AGRICULTURAL UNIVERSITY OF ATHENS
DEPARTMENT OF NATURAL RESOURCES DEVELOPMENT
& AGRICULTURAL ENGINEERING
LABORATORY OF AGRICULTURAL HYDRAULICS

PhD thesis

Development of Decision Support Systems for Water Reuse and Water Loss Reduction: Holistic and Systemic Approach for Resilience Promotion in the Context of Integrated Water Resources Management

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Development of Decision-Support Systems for Water Reuse and Water-Loss Reduction: Holistic and Systemic Approach for Resilience Promotion in the Context of Integrated Water Resources Management

Department of Natural Resources Development & Agricultural Engineering
Laboratory of Agricultural Hydraulics

ABSTRACT

Many water systems worldwide are experiencing water stress in terms of water quantity and quality due to a range of influences, leading to potential adverse effects if no adequate response is implemented. The complexity and variety of technologies and their combinations, as well as social, economic, and environmental constraints, often make it complex for stakeholders and especially decision makers to elicit relevant information about resilient systems. Water is a vital resource, and a real need exists for action in many regions that might face deficits between water demand and supply as well as water quality issues; this need is especially pronounced in fast-developing countries.

A wide range of solutions with potential positive impacts is available to decision makers and other stakeholder involved, but implementing measures sustainably is often extremely challenging in a world with an uncertain future. Plenty of knowledge, technology, success stories, and qualified experts are available, and several decision-support systems (DSSs) exist, but such systems are usually targeted for specialists, and an integrated and simplified approach remains unavailable. This thesis investigates two primary hypotheses. The first main hypothesis is that there exists a lack of managerial tools to assist and support the decision-making processes involved in the selection and planning of water-reuse systems and water-loss reduction systems. The second main hypothesis posits that the complexity involved in such decisions may be streamlined with the development of universal and comprehensive DSSs understandable by a wide range of potential users in order to support the selection of options and promote their implementation.

For water reuse, this study aims to develop a DSS (i.e., Poseidon) that supports pre-feasibility studies and promotes water reuse and capacity development in the field. The developed tool currently encompasses 37 unit processes combined into 70 benchmark treatment trains (combinations of unit processes). It also contains information on water quality standards and typical wastewater qualities. It estimates removal performances for 12 parameters, along with lifecycle costs, including distribution. The tool and all underlying data are open access and under continuous development. The underlying systemic approach of the tool allows intuitive operation even for users with limited prior knowledge in the field to identify most adequate solutions based on a multi-criteria assessment. This accessibility should help to promote water reuse and spearhead initiatives for more detailed feasibility and design commissioning for the implementation of water-reuse schemes.

For water-loss reduction, the study aims to develop an implementation-support tool (i.e., Water Utility Compass) for water utilities. The tool allows a user to assess systematically a water distribution system, calculating a water balance and performance indicators according to International Water Association (IWA) guidelines including data error calculation, defining priority areas, and developing action plans based on pre-defined measures.

Both tools have been successfully applied to several case studies in Vietnam and Lithuania and have been integrated in capacity-building activities. The open-access publication of the tools and underlying data represents a main contribution to the field of integrated water management. For water reuse, it is possible to proceed to a complex assessment by specifying only three inputs of information (quantity and quality of wastewater to be reused, intended reuse) leading to the identification of highest-ranking options and the calculation of all relevant parameters. For water-loss reduction, Water Utility Compass is the only solution offering an applied holistic approach considering baseline data, situational analysis, and action planning in a single open-access DSS. The tools should also lead to the implementation of the options they identify. Both tools are only basic instruments that should be accompanied by capacity development and other policies or economic incentives in order to enhance the resilience of water systems.

This thesis demonstrates that for any water system, technical and managerial solutions are available to make that system more resilient, even if those available solutions might not always be economically, socially or environmentally sound. Decision-support systems can be a tool to promote water reuse and water-loss reduction, but they are insufficient for successful implementation, and the willingness of local stakeholders is a prerequisite for the sustainable management of water resources.

Scientific Area: Water Management

Keywords: Integrated Water Resources Management (IWRM), Water Reuse, Water Loss Reduction, Decision Support Systems, Resilience

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ΠΕΡΙΛΗΨΗ

Πολλά συστήματα ύδρευσης σε όλο τον κόσμο υφίστανται πίεση σε ότι αφορά την ποσότητα και την ποιότητα του νερού λόγω μίας πληθώρας παραγόντων, οι οποίοι θα οδηγήσουν σε πιθανές παρενέργειες εάν δεν ληφθούν επαρκή μέτρα αντιμετώπισης. Η πολυπλοκότητα και η ποικιλία τεχνολογιών και οι συνδυασμοί τους, όπως και κοινωνικοί, οικονομικοί και περιβαλλοντικοί περιορισμοί, συχνά δυσχεραίνουν την άντληση σχετικών πληροφοριών για τα ανθεκτικά συστήματα από τα ενδιαφερόμενα μέρη και τους υπεύθυνους λήψης αποφάσεων. Το νερό είναι ένας ζωτικός πόρος, και υπάρχει πραγματική ανάγκη για δράση σε πολλές περιοχές που ενδέχεται να αντιμετωπίσουν ελλείμματα μεταξύ της ζήτησης και της παροχής νερού, όπως και ζητήματα ποιότητας νερού. Η ανάγκη αυτή είναι ιδιαίτερα έντονη στις γρήγορα αναπτυσσόμενες χώρες.

Ένα ευρύ φάσμα λύσεων με πιθανές θετικές επιδράσεις είναι διαθέσιμο στους υπεύθυνους λήψης αποφάσεων και σε άλλα εμπλεκόμενα ενδιαφερόμενα μέρη, ωστόσο η βιώσιμη εφαρμογή των μέτρων αποτελεί συχνά μεγάλη πρόκληση σε ένα κόσμο με αβέβαιο μέλλον. Υπάρχει μεγάλη προσφορά γνώσης, τεχνολογίας, επιτυχών παραδειγμάτων και καταρτισμένων πραγματογνωμόνων, και υπάρχουν και πολλά συστήματα υποστήριξης της λήψης αποφάσεων (ΣΥΛΑ), ωστόσο τα συστήματα αυτά συνήθως απευθύνονται σε ειδικούς, ενώ δεν υφίσταται μία ολοκληρωμένη και απλουστευμένη προσέγγιση. Η παρούσα διατριβή διερευνά δύο πρωτογενείς υποθέσεις. Η πρώτη βασική υπόθεση είναι ότι υπάρχει έλλειψη διαχειριστικών μέσων για να συνδράμουν και να στηρίξουν τη διαδικασία λήψης αποφάσεων που εμπεριέχεται στην επιλογή και το σχεδιασμό συστημάτων επαναχρησιμοποίησης νερού και συστημάτων μείωσης της απώλειας νερού. Η δεύτερη βασική υπόθεση θεωρεί δεδομένο ότι η πολυπλοκότητα τέτοιων αποφάσεων μπορεί ενδεχομένως να μετριαστεί μέσω της ανάπτυξης καθολικών και ολοκληρωμένων ΣΥΛΑ, τα οποία θα γίνονται κατανοητά από ένα ευρύ φάσμα πιθανών χρηστών, προκειμένου να υποστηριχθεί η επιλογή λύσεων και να προωθηθεί η εφαρμογή τους.

Σε ότι αφορά την επαναχρησιμοποίηση νερού, η παρούσα μελέτη στοχεύει στην ανάπτυξη ενός ΣΥΛΑ (π.χ. Poseidon) που θα στηρίζει τις μελέτες προκαταρκτικής σκοπιμότητας και θα προωθεί την επαναχρησιμοποίηση νερού και την ανάπτυξη των ικανοτήτων του τομέα. Επί του παρόντος, το εργαλείο που έχει αναπτυχθεί καλύπτει 37 βασικές διαδικασίες μονάδων που συνδυάζονται σε 70 βασικές ακολουθίες επεξεργασίας (συνδυασμούς διαδικασιών μονάδων). Περιέχει επίσης πληροφορίες για τα πρότυπα ποιότητας του νερού και τα τυπικά χαρακτηριστικά των λυμάτων. Υπολογίζει τις επιδόσεις αφαίρεσης ρύπων για 12 παραμέτρους, όπως και το κόστος κύκλου ζωής, συμπεριλαμβανομένης της διανομής. Το εργαλείο και όλα τα υποκείμενα στοιχεία του είναι ανοιχτής πρόσβασης και υπόκεινται σε συνεχή ανάπτυξη. Η υποκείμενη συστημική προσέγγιση του εργαλείου επιτρέπει τη διαισθητική λειτουργία ακόμα και για χρήστες με περιορισμένη προηγούμενη γνώση του τομέα για την ταυτοποίηση/ προσδιορισμό των επαρκέστερων λύσεων βάσει αξιολόγησης πολλαπλών κριτηρίων. Η προσβασιμότητα αυτή θα πρέπει να βοηθήσει την προώθηση της επαναχρησιμοποίησης νερού και να ηγηθεί πρωτοβουλιών για πιο αναλυτική μελέτη σκοπιμότητα και ανάθεση σχεδιασμού με σκοπό την εφαρμογή των σχεδίων επαναχρησιμοποίησης νερού.

Σε ότι αφορά τη μείωση της απώλειας νερού, η μελέτη αποσκοπεί στην ανάπτυξη ενός εργαλείου εφαρμογής & στήριξης (π.χ. Η Πυξίδα Χρήσης Νερού) για επιχειρήσεις υδροδότησης. Το εργαλείο επιτρέπει στο χρήστη τη συστηματική πρόσβαση σε ένα σύστημα υδροδότησης, υπολογίζοντας το υδατικό ισοζύγιο και τους δείκτες απόδοσης βάσει των οδηγιών της Διεθνούς Ορ-

γάνωσης Ύδατος (IWA) που περιλαμβάνουν τον υπολογισμό σφαλμάτων, τον καθορισμό των τομέων προτεραιότητας και την κατάρτιση σχεδίων δράσης βάσει προκαθορισμένων μέτρων.

Και τα δύο αυτά εργαλεία έχουν εφαρμοστεί επιτυχώς σε πολλές περιπτωσιολογικές μελέτες στο Βιετνάμ και τη Λιθουανία και έχουν ενσωματωθεί σε δραστηριότητες ανάπτυξης δυναμικού. Η δημοσίευση των εργαλείων με ανοιχτή πρόσβαση και τα υποκείμενα στοιχεία συνιστούν μία βασική συνεισφορά στον τομέα της ολοκληρωμένης διαχείρισης ύδατος. Ως προς την επαναχρησιμοποίηση ύδατος, είναι εφικτή η σύνθετη αξιολόγηση μέσω του προσδιορισμού τριών μόνο πληροφοριακών στοιχείων (ποσότητα και ποιότητα των λυμάτων που θα επαναχρησιμοποιηθούν, σκοπούμενη επαναχρησιμοποίηση) η οποία θα οδηγεί στον προσδιορισμό των επιλογών με τους υψηλότερους δείκτες καταλληλότητας και στον υπολογισμό όλων των σχετικών παραμέτρων. Ως προς τη μείωση της απώλειας νερού, η Πυξίδα Χρήσης Νερού είναι η μόνη λύση που παρέχει μία εφαρμοσμένη ολιστική προσέγγιση λαμβάνοντας υπόψη βασικά στοιχεία αναφοράς, αναλύσεις καταστάσεων και σχεδιασμό ενεργειών σε ένα ενιαίο ΣΥΛΑ ανοιχτής πρόσβασης. Τα εργαλεία θα πρέπει επίσης να οδηγούν στην υλοποίηση των επιλογών στις οποίες κατέληξαν. Αμφότερα τα εργαλεία είναι μόνο βασικά όργανα που θα πρέπει να συνοδεύονται από την ανάπτυξη ικανοτήτων και άλλες πολιτικές ή οικονομικά κίνητρα προκειμένου να ενισχυθεί η αντοχή των υδατικών συστημάτων.

Η παρούσα διατριβή καταδεικνύει ότι για οποιοδήποτε υδατικό σύστημα υπάρχουν διαθέσιμες τεχνικές και διαχειριστικές λύσεις για να καταστεί αυτό πιο ανθεκτικό, ακόμα και αν αυτές οι διαθέσιμες λύσεις δεν είναι πάντα οικονομικά, κοινωνικά ή περιβαλλοντικά συμφέρουσες. Τα συστήματα υποστήριξης λήψης αποφάσεων μπορούν να αποτελέσουν εργαλείο για την προώθηση της επαναχρησιμοποίησης νερού και τη μείωση της απώλειας νερού, ωστόσο είναι ανεπαρκή σε ότι αφορά την επιτυχή υλοποίηση των έργων, με την προθυμία των τοπικών ενδιαφερομένων μερών να αποτελεί προϋπόθεση για τη βιώσιμη διαχείριση των υδάτινων πόρων.

Επιστημονική Περιοχή: Διαχείριση Νερού

Λέξεις κλειδιά: Ολοκληρωμένη Διαχείριση Υδάτινων Πόρων (ΟΔΥΠ), Επαναχρησιμοποίηση Νερού, Μείωση Απώλειας Νερού, Συστήματα Υποστήριξης Λήψης Αποφάσεων, Ανθεκτικότητα.

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SYMBOLS AND ABBREVIATIONS

ALC	Active leakage control
AQUAREC	The project AQUAREC "Integrated concepts for reuse of upgraded wastewater" was funded by the Fifth Framework Program of the European Commission.
AUA	Agricultural University of Athens
BOD	Biological oxygen demand
CAPEX	Capital expenditures, capital costs based on the construction costs
COD	Chemical oxygen demand
COROADO	The project COROADO "Technologies for Water Recycling and Reuse in Latin American Context: Assessment, Decision Tools and Implementable Strategies under an Uncertain Future" was funded by the Seventh Framework Programme of the European Commission.
CUR	Currency (any currency can be substituted)
DMA	District metering area
DPSIR	Driving forces, pressure, state impact, response
DSS	Decision-support systems
EIP	European Innovation Partnership
FC	Fecal coliform
FHNW	University of Applied Sciences and Arts Northwestern Switzerland
FM	Food-to-mass
ILI	Infrastructure leakage index
IWA	International Water Association
IWRM	Integrated water resources management
MLSS	Mixed liquor suspended solids
NRW	Non-revenue water
NTU	Nephelometric turbidity units
OPEX	Operational expenditures
PI	Performance indicator
PISTLE	Political, institutional, social, technological, legal, and economic
POP	Persistent organic pollutant
RBC	Rotating biological contactor
SAT	Soil aquifer treatment
SIP	Strategic implementation plan
TC	Total coliform
TDS	Total dissolved solids

THM	Trihalomethane
TN	Total nitrogen
TOC	Total organic carbon
TP	Total phosphorous
TSS	Total suspended solids
Turb	Turbidity
UNDP	United Nations Development Program
UNIDO	United Nations Industrial Development Organisation
UP	Unit process
US-EPA	United States Environmental Protection Agency
UV	Ultraviolet
VAT	Value-added tax
WASH	Water sanitation and hygiene
WASWARPLAMO	Software tool "Waste Water Reuse Planning Model (WASWARPLAMO)" (Adewumi, 2011).
WHO	World Health Organization
WLR	Water-loss reduction
WR&R	Wastewater recycling and reuse
WSP	Waste stabilization pond
WTRNet	Decision-support software for integrated water reuse, called WTRNet (Joksimovic, Kubik, Hlavinek, Savic, & Walters, 2006)
WU-Compass	Water Utility Compass
WWTP	Wastewater treatment plant

DEFINITIONS

Adaptive capacity	The ability of a system to adjust to disturbances, to moderate potential damages, to take advantage of opportunities, or to cope with the consequences of transformations that occur (Intergovernmental Panel on Climate Change (IPCC), 2001)
Blackwater	Wastewater that contains urine and feces
Direct reuse	Direct use of reclaimed water for a specific purpose
DPSIR framework	Driving forces, Pressure, State, Impact, Response - The DPSIR framework identifies cause – effect relationships and allows for the separation of categories of issues and provides flexibility for usage and analysis (National Technical University of Athens, 2002)
Effluent	Water flow after (primary, secondary or tertiary) treatment
Exposure	The nature, degree, duration, and/or extent to which the system is in contact with, or subject to perturbations (Gallopín, 2006). In the case of water resources management, exposure is defined as whether and to what degree a geographical area will be stressed
Greywater	Wastewater from domestic activities (bathing, cleaning, laundry etc.)
Headloss	In fluid mechanics, the drop in the sum of pressure head, velocity head, and potential head between two points along the path of a flowing fluid, due to causes such as fluid friction. Used to calculate the required pumping head in distribution pipes
Indirect reuse	Reuse of wastewater, which has been previously mixed and diluted with fresh water by discharge into receiving water bodies
Primary treatment	Usually first step in the cleaning process involving removal of solids, oils and greases by flotation, sedimentation and screening
Resilience	The capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain the same function, structure, identity and feedbacks (Walker, Holling, Carpenter, & Kinzig, 2004)
Scenario	Developments, which cannot be directly influenced by Decision-Maker (e.g. Weather, Market Prices) (National Technical University of Athens, 2002)
Secondary treatment	Removal of dissolved and suspended biological matter, which typically involves biological processes by microorganisms (activated sludge, membrane bioreactors etc.)
Sensitivity	The degree to which a system can be modified or affected (adversely or beneficially, directly or indirectly) by a disturbance or set of disturbances. (Gallopín, 2006)
Strategy	The set of actions / sequence of responses to existing and emerging conditions, that is suited / available aiming at the fulfilment of a selected goal (in the case of the project the goal is that of Integrated

	Water Resources Management) (National Technical University of Athens, 2002)
Tertiary treatment	Cleaning to a high level of purity or/and removal of specific contaminants (e.g. heavy metals) and can include disinfection
Treatment trains	Series of unit processes combined in a so-called treatment train or treatment chain
Unit Process	Single water treatment technologies (primary, secondary, tertiary treatment and disinfection technologies)
Vulnerability	The degree to which a systems is susceptible to, and unable to cope with, injury damage or harm ("European Environment Agency — Environmental Terminology Discovery Service," 2015)
Wastewater	Water that has been polluted by human activities
Wastewater treatment	Improvement of water quality by applying a number of methods/technologies
Water reclamation	Cleaning of wastewater to a purity that can be used for specific purposes
Water reuse	Beneficial use of treated wastewater

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LIST OF PUBLICATIONS, ORAL PRESENTATIONS AND TRAININGS

Note: the framed publications are attached as appendix to this thesis.

WATER REUSE AND WATER MANAGEMENT

- Oertlé, E., Müller, S. R., Choukr-Allah, R., Jaouani, A., **Decision support tool for water reclamation beyond technical considerations – Egyptian, Moroccan and Tunisian case studies**. Integrated Environmental Assessment and Management, 2019 (submitted).
- Oertlé, E.; Vu, D. T.; Nguyen, D. C.; Näf, L.; Müller, S. R., **Potential for water reuse in Vietnam**. Journal of Vietnamese Environment, 2019.
- Hunter, C.; Gironás, J.; Bolster, D.; Karavitis, C.A.; Oertlé, E. **A robust decision support tool for multiple stakeholder selection of water reuse and recycling technologies**. Desalination and Water Treatment, 2019 (submitted).
- Frascari, D.; Molina Bacca, A. E.; Wardenaar, T.; Oertlé, E.; Pinelli, D. **Continuous flow adsorption of phenolic compounds from olive mill wastewater with resin XAD16N: life cycle assessment, cost-benefit analysis and process optimization**. J. Chem. Technol. Biotechnol. 2019, doi:10.1002/jctb.5980.
- Oertlé, E.; Hugi, C.; Wintgens, T.; Karavitis, C.A. **Poseidon—Decision Support Tool for Water Reuse**. Water 2019, 11, 153.
- Frascari, D., Oertlé, E., et al., **Integrated technological and management solutions for wastewater treatment and efficient agricultural reuse in Egypt, Morocco and Tunisia**, Integrated Environmental Assessment and Management, 2018.
- Oertlé, E., **The importance of resources efficiency: Swiss experience and impressions**, RECPC Final conference and awards ceremony in Kharkiv, Ukraine, November 2017.
- Oertlé, E., **Urban water supply and demand management: Selected experiences from the TRUST project and from the Strategic Alliance for Water Loss Reduction / Lesson learnt from the COROADO project on water reuse and recycling technologies**, EU-Brazil Sectorial Dialogue Workshop on Adaptive Water Management facing Climate Change: Comparing Brazilian and European Experiences, Joint Research Centre, Ispra, Italy, September 2014.
- Oertlé, E., Verzandvoort, S., **Decision-support Tools for Water Reuse in Latin America at Local and Regional Scale**, Training on Natural Systems for Water and Wastewater Treatment and Reuse, UNESCO-IHE, Delft, The Netherlands, May 2014.
- Kazner, C., Oertlé, E., Stamm, L., Das, D., Desai, T., **Training Program on "Treatment of Textile Industry Wastewater"**, facilitated by GIZ http://www.igep.in/ , Surat, Gujarat, India, March2014.
- Kazner, C., Oertlé, E., Stamm, L., Das, D., Desai, T., **Training Program on "Treatment of Pulp & Paper Industry Wastewater"**, facilitated by GIZ http://www.igep.in/ , Vapi, Gujarat, India, March2014.
- Kazner, C., Oertlé, E., Stamm, L., Das, D., Desai, T., **Training Program on "Technical Solutions and Management Aspects of Common Effluent Treatment Plants in India"**, facilitated by GIZhttp://www.igep.in/ , New Delhi, India, March 2014.

- Bello-Dambatta, A., Kapelan Z., Butler D., Oertlé E., Wintgens T.,Rozos E., Makropoulos C., Mamassis, N., **Urban Water Demand Management -Guidance for the assessment and selection of sustainable water demand management technologies**, Trust EU-Project deliverable D42.1, December 2013.
- Oertlé, E, **Panorama de tecnologías de reciclaje y reúso de agua, Coroado first workshop on water reuse and recycling**, 8 August 2012, Copiapó, Chile.
- Oertlé, E., **Cleaner Production and resource recovery**, Sino-Swiss Institutional Cooperation Workshop on Research and Education, poster and oral presentation, Nanjing, China, June 2012.
- Oertlé, E., Niewersch, C., Wintgens, T., **Im Einsatz für das Lebenselixier Wasser**, FHNW Newsletter, June 2012.

WATER LOSS REDUCTION

- Oertlé, E., **Reffnet und nachhaltiger Umgang mit Wasser**, SVGW-Wasserfachtagung – Wasserverteilung - Netzbetrieb und Löschwasserversorgung, University of Fribourg, January 2018.
- Oertlé, E., Ercolano, L., **Technical training on water loss reduction for 8 representatives from water utilities, GIZ and consultancies of 4 countries (Northern Iraq, Colombia, Egypt and Germany)**, Hamburg, Germany, April 2017.
- Oertlé, E.; Jurkienė, A.; Rimeika, M. **Application of a decision-support system for water loss reduction to the case of a water supply system in Lithuania**. In WIT Transactions on The Built Environment; WIT Press, 2016; Vol. 165, pp. 27–38.
- Oertlé, E., **Water Loss Reduction - A holistic approach through strategy, capacity building, technologies and partnerships**, conference with 40 representatives of Lithuanian water utilities, Vilnius, Lithuania, Mai 2016.
- Oertlé, E., **Strategic Alliance for Water Loss Reduction Learning Management Platform as networking and knowledge transfer tool, presentation**, GIZ event, Frankfurt, Germany, April 2016.
- Oertlé, E., **Technical training and training of trainers on water loss reduction for 15 participants from Benin and certification of 9 trainers from Burkina Faso**, Cotonou, Benin, March 2016.
- Oertlé, E., Vernickel, E.-L., **Technical training on water loss reduction for 26 representatives from water utilities, GIZ and consultancies of 8 countries (Zambia, Turkey, Bolivia, Botswana, Uganda, France, Thailand, and Germany)**, Hamburg, Germany, March 2016.
- Oertlé, E., Rémy, E., **Workshop and training on Non-Revenue Water (NRW) with a focus on Leakage detection by Helium gas tracking**, Yangon, Myanmar, February 2016.
- Oertlé, E**., Strategische Allianz für Wasserverlustreduzierung - Lernplattform als Vernetzungs- und Wissensmanagementtool**, presentation and poster, GIZ Mitarbeiter Tagung (MATA), Bad Lauterberg, Germany, July 2015.
- Oertlé, E., Ercolano, L., **Technical training on water loss reduction for 10 representatives from water utilities from 3countries (Kosovo, Botswana and Taiwan)**, Mannheim, Germany, April 2015.
- Oertlé, E., Kampues, A., **Technical training and training of trainers on water loss reduction for 25 representatives from water utilities, GIZ and consultancies of 7+ countries [Caribbean (St. Vincent, Granada,**

Dominica, St. Lucia, etc.), Uganda, Germany, France, Kosovo, Bosnia, Palestine], Hamburg, Germany, October 2014.

- Schmitt, K., Oertlé, E., **Applying IWA standards around the globe: the strategic alliance holistic approach for capacity development in water-loss reduction**, Proceedings and presentation at the IWA Water Loss conference 2014, Vienna, Austria, March 2014.
- Oertlé, E., Vreeburg, J., Roussel, A.C., Van den Hoven, T., **Roadmap to a sustainable water distribution network in Bucharest, 2 expert workshops in Romania and 1 report**, Part of Trust EU-Project deliverable D41.1, December 2013.
- Oertlé, E., Petruch, S., Bark, K., **Technical training and training of trainers on water loss reduction for 10 potential trainers from Germany and 22 representatives from water utilities, GIZ and consultancies of 7 countries (Zimbabwe, Tanzania, Burkina Faso, Lebanon, Taiwan, France and Germany)**, Hamburg, Germany, March 2013.
- Oertlé, E., Petruch, S., Bark, K., **Technical training and training of trainers on water loss reduction for 10 potential trainers from Germany and Hungary and 19 representatives from water utilities of 9 countries (Africa, Europe and Oman)**, Mannheim, Germany, November 2012.
- Oertlé, E., Vogel, M., **Training in Spanish on water loss reduction for 24 engineers and directors from different Bolivian water utilities**, Santa Cruz de la Sierra, Bolivia, November 2012.
- Oertlé, E., Vogel, M., **Training on water loss reduction for 25 engineers from the National Water and Sewerage Corporation (NWSC) from Uganda and main stakeholders**, Kampala, Uganda, October 2012.
- Oertlé, E., Eisele, T., **Water loss reduction training facilitated by GIZ, BURIMI (Newsletter of the Water Supply and Sewerage Association of Albania)**, April 2012.
- Oertlé, E., Vogel, M., Petruch, S., **Training on water loss reduction, 42 participants from 13 Albanian water utilities and main stakeholders**, Tirana, Albania, March 2012.
- Oertlé E., Knobloch A., **Réduction des pertes en eau dans les réseaux de distribution - terminologie, méthodes et instruments**, gwa, Société Suisse de l'Industrie du Gaz et des Eaux, Zürich, p.665-674, 2011.
- Oertlé, E., Vogel, M., Marinof, Y., **Management and conduction of a 4-days training for water loss reduction focusing on the establishment of IWA water balances, 27 participants from the national water utility ONEA and GIZ**, Ouagadougou, Burkina Faso, October 2011.
- Fallis P., Hübschen K., Oertlé E., Ziegler D., Knobloch A., Klingel P., Baader J., Trujillo R., Laures C., **Guidelines for Water Loss Reduction – A Focus on Pressure Management**, Book (232 pages), GIZ, VAG, KIT, FHNW, 2011.
- Oertlé, E., Knobloch, A., Marinof, Y., Bark, K., **Conduction of a 4-days stakeholder dialogue and training for water loss reduction, 50 participants from 9 West-African countries and Europe**, Ouagadougou, Burkina Faso, February 2011
- Oertlé E., **Water Loss Reduction – A Focus on Pressure Management**, Research Report HLS, FHNW, 2010.
- Oertlé, E., Trujillo, R., **Organization and conduction of a stakeholder dialogue for water loss reduction, 208 participants at the main event, representing more than 30 water utilities in Peru and Bolivia**, Lima, Peru, July 2010.
- Oertlé E., Knobloch, A., **Guidelines for Water Loss Reduction**, proceedings and oral presentation of the IWA international specialized conference Water Loss 2010, São Paulo, 2010.

CHAPTER 1 INTRODUCTION

1.1 Area of Concern and Problem Definition

Sustainable water management is one of the most challenging issues for coming generations and is on the forefront of political, social, technical, environmental, and economic concerns. The global risk 2015 report from the World Economic Forum placed water crises as the highest-ranking risk on a 10-year horizon, defined as “a significant decline in the available quality and quantity of fresh water, resulting in harmful effects on human health and/or economic activity” (World Economic Forum, 2015). In its 2017 version, the report places water crises as the third-highest risk in terms of potential impact. The Water Resources Group warns that “by 2030 under an average economic growth scenario and if no efficiency gains are assumed, the world is projected to face a 40% global water deficit between global water requirements and the current accessible and reliable supply” (Water Resources Group, Group, & Summary, 2009). This global figure, also reported in the 2015 UN World Water Assessment Report (WWAP, 2015a), is the aggregation result of a large number of local gaps between water requirement and sustainable supply, with some regions showing a gap higher than 40%. One-third of the population, concentrated in developing countries, will live in basins where this deficit is larger than 50% (Water Resources Group et al., 2009). Water risks and vulnerabilities are unevenly distributed around the globe, and 3 billion people are expected to suffer from water scarcity by 2050 (WssTP, 2010).

The field of water management is vast and complex, as it involves many disciplines and stakeholders, such as technology providers, designers and planners, financial institutions, public and private industry, policy-makers and politicians. The risks of water crises are widely acknowledged and are often among the top political concerns of affected regions. Technological or managerial solutions are often available, but their implementation can be hindered by a range of obstacles frequently rooted in misaligned objectives and poor management of interactions between stakeholders (OECD, 2012). This thesis aims first to structure the typical concerns in a generic resilience framework in order to understand the key issues of water management systemically and holistically. The heart of this thesis aims to specifically investigate the topics of water reuse and water-loss reduction in water distribution networks, and to develop decision-support systems (DSSs) in order to support the selection and implementation of the most commonly adapted solutions.

1.2 The Water Resilience Framework

A wide range of influencing factors have led to the current physical risks associated with quantity and quality of water resources, and one ingenious way to classify them follows the DPSIR (i.e., driving forces, pressure, state impact, response) framework. This thesis introduces a water resilience framework for water resources management based on the DPSIR approach, on literature review (Section 2.2) and on experience. This overarching framework serves as a means to structure and understand the problems, challenges and solutions for sustainable water management. This conceptual representation allows one to understand the overall situation holistically and offers a structure for the work developed in this thesis.

The concept of resilience has been extensively used in different fields of research, and the Organization for Economic Cooperation and Development (OECD) defines resilience as "the ability of individuals, communities and states and their institutions to absorb and recover from shocks, whilst positively adapting and transforming their structures and means for living in the face of long-term changes and uncertainty" (OECD, 2013).

The DPSIR framework has been developed for climate change but has been applied also to water resource management (Walmsley, 2002) and considers a chain of causal links starting with driving forces through pressures to states and impacts, eventually leading to responses (Kristensen, 2004). This framework, presented in Figure 1-1 (and detailed in Section 2.1), allows systematization of the context and disturbances to a water system in order to identify and prioritize the most adequate responses. Driving forces reflect pressures exerted by natural phenomena (e.g. climatic variations, climate change) and anthropogenic activities due, among other things, to global economic, demographic, technical, socio-economic, industrial, agricultural, or political development. Usually, those factors are not easily controlled, but if the framework is applied to a specific region, it allows an understanding of the regional context (Walmsley, 2002). Those driving forces lead to pressures exerted on water resources, namely on water demand, water pollution, or water supply. Because of these pressures, the state of the water resources is affected through water quantity and water quality in different water compartments (groundwater, rivers, wetlands, estuaries or reservoirs). This change in the physical, chemical, or biological state of the water resources may have social, environmental, or economic impacts on the functioning of ecosystems, on their ability to support life, and ultimately on human health and on the economic and social performance of societies (Kristensen, 2004). Responses by society or policy makers deal with undesired impacts, either already happening or predicted to happen, and they can address any part of the chain via different possible measures (e.g., policies, laws, infrastructure financing, education) (Kristensen, 2004). The responses can be divided into facilitation activities and implementation.

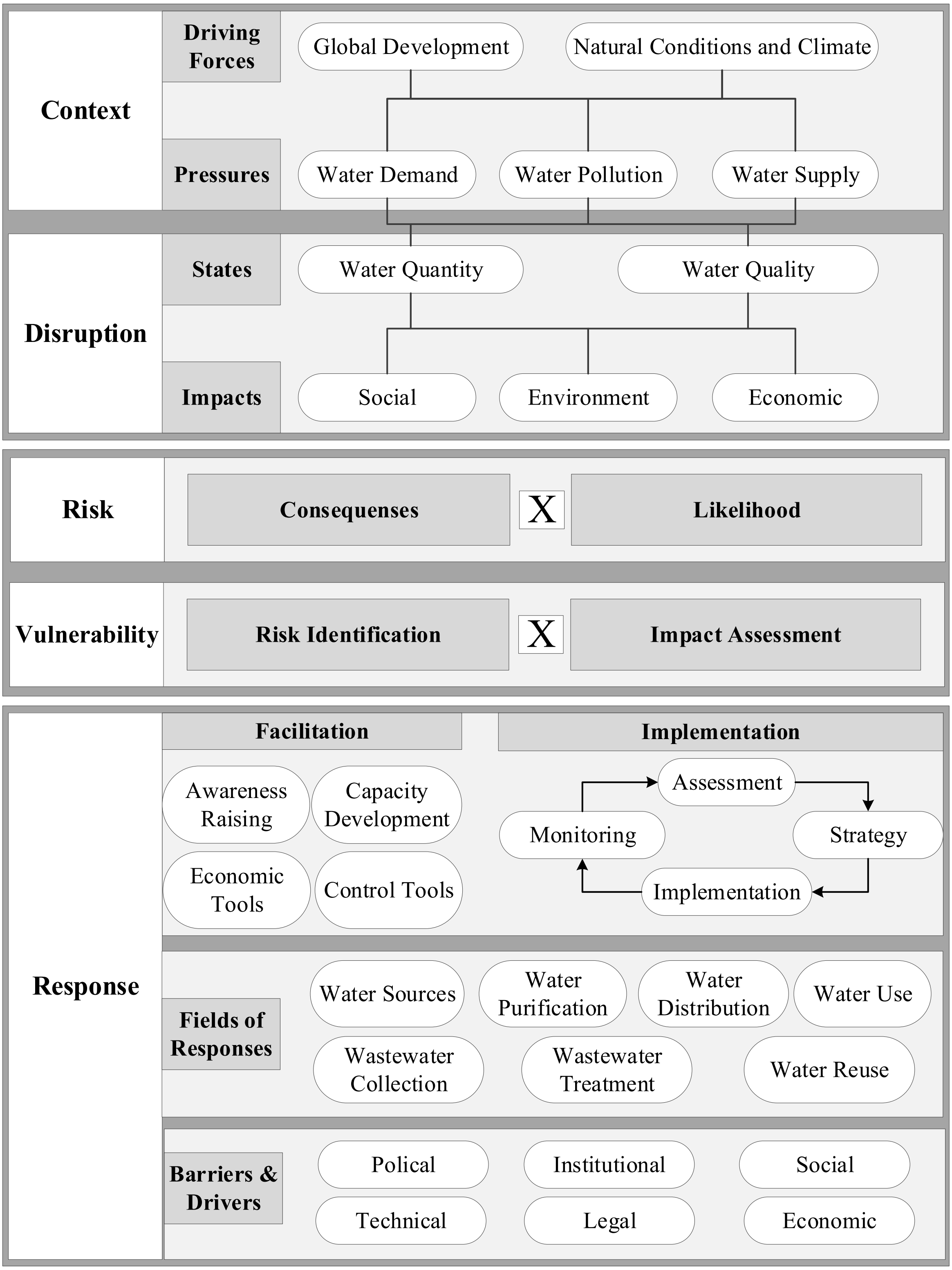


Figure 1-1: The framework of resilience for water resources management is composed of 5 main components: context, disruption, risk, vulnerability and response (adapted from Walmsley 2002).

Figure 1-1 also presents two additional concepts: risk and vulnerability. Depending on the intensity of those influencing factors in discrete countries or river basins, different ecological systems will be able to deal with the disturbance or not. A risk assessment, composed of the magnitude of the consequences of a potential impact occurring and the likelihood of its occurrence, can also be included when analyzing a region. This concept is linked to the notion of vulnerability, which has different definitions and expressions depending on its field of application. One expression has a functional form composed of exposure, sensitivity, and adaptive capacity (see DEFINITIONS) (Stathatou et al., 2015). In general, regions with a high adaptive capacity and low sensitivity will be less vulnerable and can therefore better tolerate disturbances than can regions with low adaptive capacity and high sensitivity to perturbation (Figure 1-2).

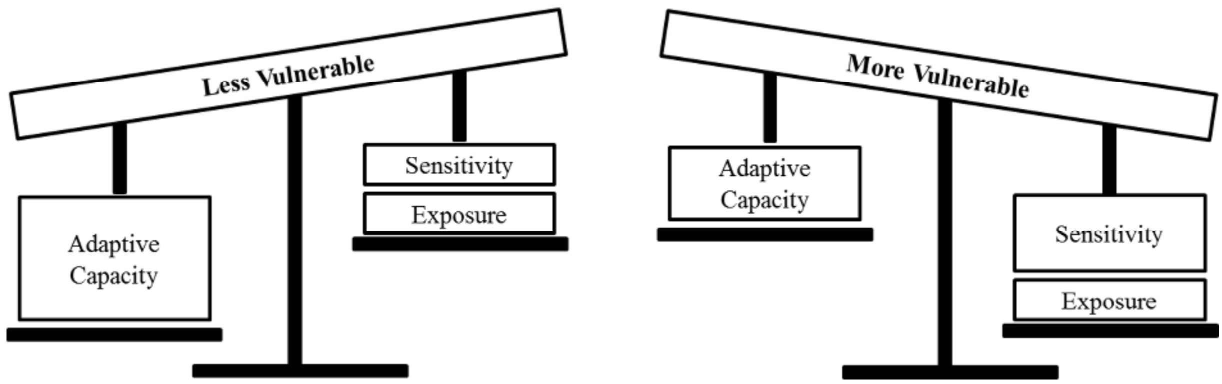


Figure 1-2: Vulnerability is in general determined by the relationship among three components: exposure, sensitivity and adaptive capacity (San Francisco Bay Conservation and Development Commission, 2012).

Karavitis et al. (2014) propose definitions of “vulnerability” focusing primarily on the technical and engineering elements, rather than the more comprehensive or general versions. A proposed sense of the term “vulnerability” may be expressed by two basic elements: hazards and impacts, as such described by the following equation:

$$\text{Vulnerability} = \text{Risk identificaton x Impact assessment.} \tag{1}$$

The combination of vulnerability and risk assessment allows one to prioritize the adequate responses given present and future situations. With the concept of resilience as a widely recognized framework to understand a specific region, the object of this thesis is to provide responses, and implementation facilitation for the most adequate solutions, in the fields of water reuse and water-loss reduction in water distribution networks.

1.3 Water Reuse and Water-Loss Reduction as Responses to Enhance Resilience

1.3.1 Water Reuse

The objective of wastewater recycling and reuse is the treatment of wastewater to be pure enough for direct use for specific purposes (i.e., the 'fit-for-purpose' concept) (WWDAP, 2017). Water reuse has received growing attention with regard to the mitigation of water scarcity and as an opportunity to avoid high first-use water prices. Wastewater reuse can be classified as direct or indirect, as shown in Figure 1-3 (Wintgens & Hochstrat, 2006):

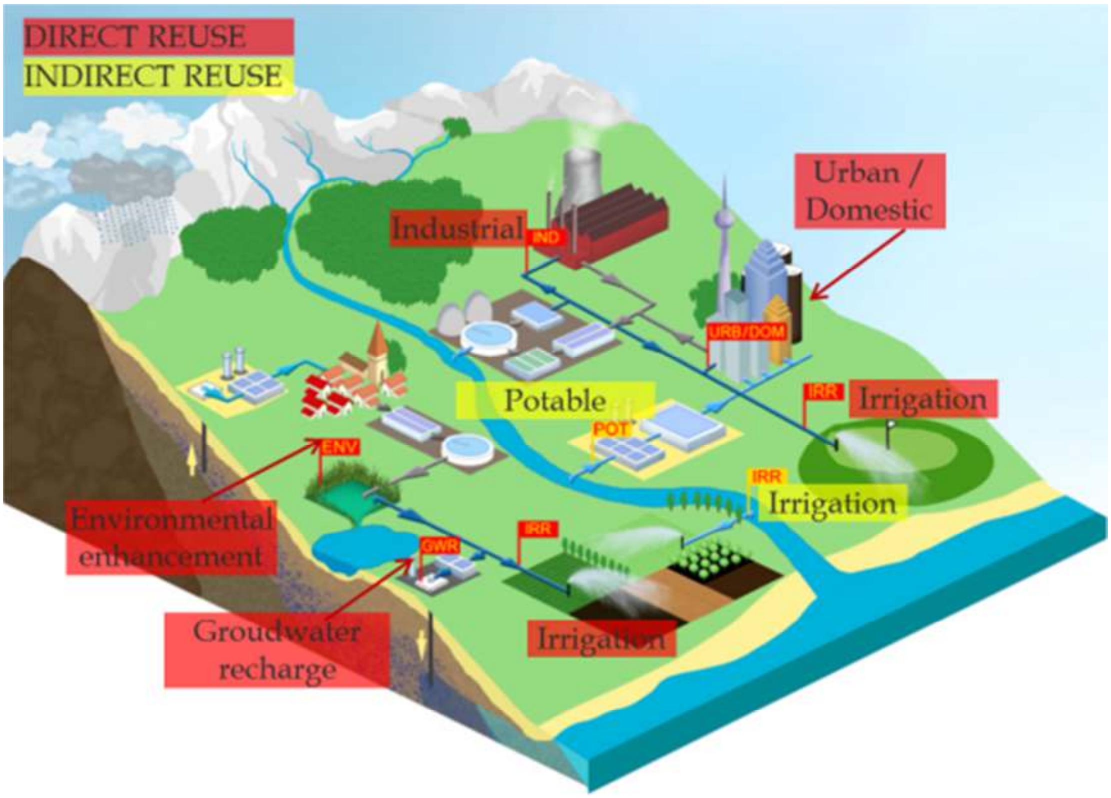


Figure 1-3: The anthropogenic water cycle with direct and indirect reuse (Wintgens & Hochstrat, 2006).

Direct reuse refers to the direct use of reclaimed water for a specific purpose. Direct water reuse can supply applications such as agricultural irrigation, industrial uses such as cooling and process water, urban and recreational uses such as garden irrigation and street washing, groundwater recharge and ecological uses.

Unintentional indirect reuse refers to the use of water downstream from a discharge of (treated or untreated) wastewater into a water body. The effluent from wastewater treatment plants (WWTPs) is mixed, diluted and further cleaned by naturally occurring chemical and biological processes in the receiving water body, which is the most common practice of indirect water reuse worldwide.

Intentional indirect reuse is the planned linkage between the discharge of treated wastewater into an environmental water body and further usage (Levine & Asano, 2004). An example of intentional indirect reuse is groundwater (aquifer) recharge of effluents for further reuse. For both direct and indirect reuse, the specific reuse application (purpose) together with the relevant legislation determines the required level of purity.

Water reuse is one of the most promising integrated solutions to improving access to water and may present an alternative to exploiting new water sources, as it performs two fundamental functions that appear to be the primary incentives for implementing water reuse schemes (Davide Bixio et al., 2006) (Urkiaga et al., 2006; Wintgens & Hochstrat, 2006):

- Treated wastewater can be reused as a water resource for beneficial purposes.
- Wastewater is kept out of receiving environments thus reducing pollution.

Water reuse can both improve water management in general and help people to better cope with drought management (Karavitis, 1998). A significant part of this thesis deals with water reuse and the development of a DSS for the selection of the most effective technologies. The work on this topic was integrated within the Coroado project ("Coroado Project Website," 2017), which aimed to develop new and adapt existing concepts and operational frameworks and to produce a web-based toolbox for reuse and recycling technologies in the context of integrated water resources management; simultaneously, the project sought to account for long-lasting changes and address environmental and ecosystem integrity.

1.3.2 Water-Loss Reduction

Drivers such as the demographic and economic growth and development, migration and fast urbanization are not only placing new strains on water resources, but also on water infrastructure. In big cities, such as Mexico City or Cairo, up to 70% of the water is lost due to leaks in water-supply networks (Parmentier, 2007) and the World Bank estimated in 2006 that an average of 40–50% of the water produced in developing countries was non-revenue water (NRW) (Kingdom, Liemberger, & Marin, 2006). Non-revenue water is composed of both real water losses (e.g., physical leaks) and apparent losses (e.g., metering and data handling errors or illegal connections).

In a context of water scarcity, loosing so much water in the distribution network is a top concern for many water utilities and associations, such as the International Water Association (IWA), which has been leading many initiatives to tackle this issue. Many solutions and methods to limit water losses to a sustainable level, but water losses are often only the most noticeable part of the problem, with more complex institutional matters being less obvious. The four principal methods to prevent real water losses according to the IWA Water Loss Task Force are infrastructure management, active leakage control, efficient and effective repairs, and pressure management. For apparent losses, the four standard tools are improvement of meter reading and data transfer, reduction of unauthorized consumption, reduction of customer meter inaccuracies, and improvement of data handling (Thornton, Sturm, & Kunkel, 2008).

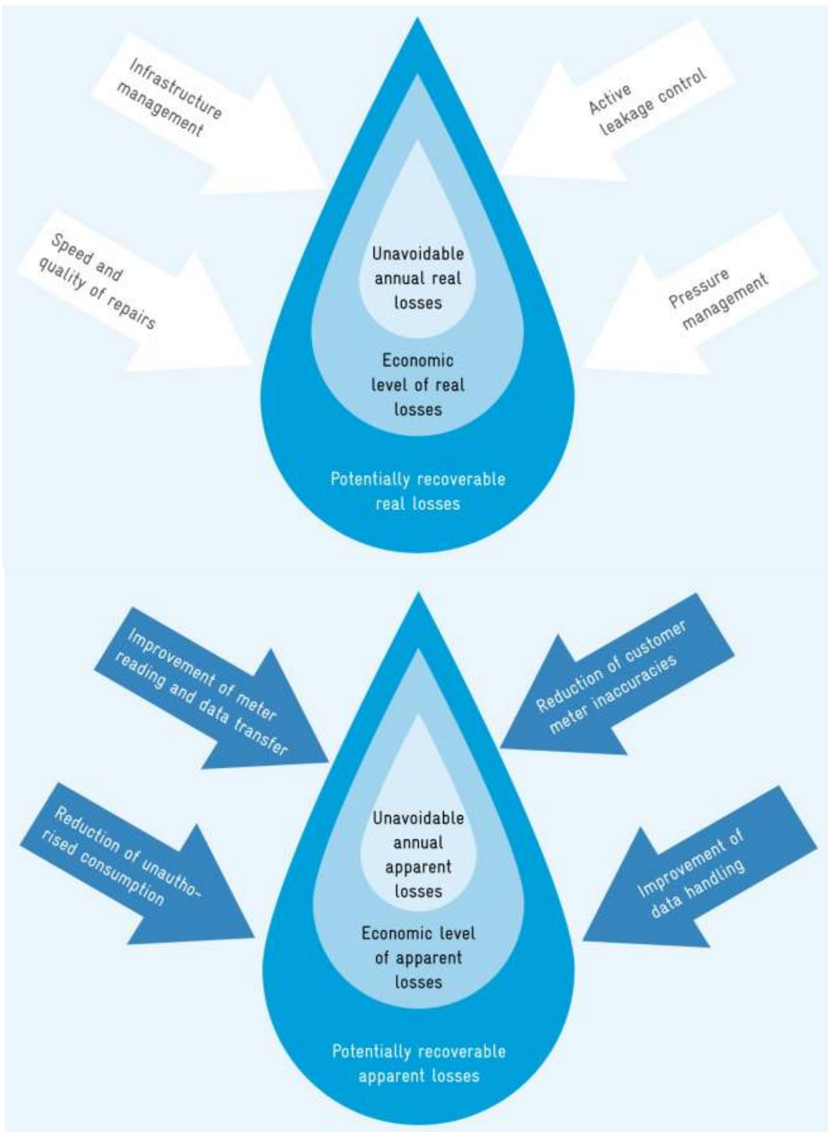


Figure 1-4: Intervention tools for real and apparent loss reduction programs (Fallis et al., 2011a).

The second significant part of this thesis deals with water-loss reduction, and work on this topic was linked with the Strategic Alliance for Water Loss Reduction. It was a public–private partnership that provided fundamental contributions toward the improvement of water-loss reduction in its partner countries, including guidelines, technology implementation and training for water-loss reduction (Strategic Alliance for Water Loss Reduction, 2016). For many water utilities, tackling water-loss reduction remains part of an event-driven strategy and sometimes due to lack of staff and resources, the long-term planning and strategic approach is complicated. Because the topic of water-loss reduction is complex, engineers and managers face complexity in gaining a comprehensive understanding of water systems to support sound and efficient decisions. Water utilities in emerging economies and developing countries are often too overwhelmed to tackle the issue of water-loss reduction. One objective of this thesis is to develop a tool to facilitate the analysis of water loss in a given water system, the identification of the most appropriate measures and subsequent mitigation strategies.

1.3.3 Water Reuse, Water-Loss Reduction and the Water Resilience Framework

If one considers the resilient framework (Figure 1-1), it can be seen that both water reuse and water-loss reduction can improve the resilience of water systems:

Water reuse can immediately increase the water quantity available, improve its quality and reduce pollution by treating wastewater. In the long-term, water reuse also decreases the vulnerability of water systems and the related risks of water shortages. Water reuse can be implemented for theoretically any kind of end-use (domestic, industrial, agricultural and environment).

Water-loss reduction concerns water from distribution networks from the perspective of water utilities. The effective reduction of water losses mainly has an effect on the volume of the water supply but can also positively affect water quality, as empty and deteriorated pipes can lead to infiltrations of wastewater within the network.

If water reuse and water-loss reduction are undoubtedly pertinent responses that can contribute to enhancing the resilience of water systems worldwide, both can also be very complex issues, requiring knowledge of a wide range of possible technologies and a favorable environment to enable successful implementation.

1.4 Hypothesis and Research Objectives of This Thesis

1.4.1 Summary of the Problem

The previous chapters and the literature review of this thesis stated that globally, many water systems are experiencing water stress due to a range of influences, leading to potential adverse effects if no adequate response is implemented. The complexity involved not only of the technologies but also in the broader environment—considering political, social, economic, legal and environmental constraints—often means that stakeholders face difficulty working together towards resilient systems and water basins. Water is a vital resource, and a real need for action exists for many regions that might face a water deficits between demand and supply and might face water quality issues. The necessity of this resource is reflected in Sustainable Development Goal 6: "ensure availability and sustainable management of water and sanitation for all" (United Nations, 2017). Even if many solutions with potentially positive impacts are available to decision makers and other stakeholders involved, decision support is crucial, especially in developing countries and emerging economies.

1.4.2 Main Hypothesis and Objectives

This thesis investigates two primary hypotheses. The first main hypothesis is that there exists a lack of managerial tools to assist and support the decision-making processes involved in the selection and planning of water-reuse systems and water-loss reduction systems. The second main hypothesis posits that the complexity involved in such decisions may be streamlined with the development of universal and comprehensive DSSs understandable by a wide range of potential users in order to support the selection of options and promote their implementation.

This thesis aims to identify the gaps in the available managerial tools and to facilitate decision making with the development of two DSSs for water reuse and water-loss reduction, in order to facilitate and promote the implementation of sound measures to improve water systems. Two main approaches are presented in this thesis, embedded within the water resilience framework, in order to facilitate and promote implementation.

- This work develops a DSS for water reuse (i.e., Poseidon) addressed to a wide range of users at the stage of pre-feasibility in order to select and propose feasible treatment trains (i.e., combinations of unit processes) for water reuse and foster more detailed feasibility studies.

- This work further develops a DSS for water loss reduction (i.e., Water Utility Compass) addressed to water utilities and consultants in order to support the assessment, strategic planning and continuous-action planning and implementation of water-loss reduction measures.

The first approach for water reuse covers the facilitation of the response and aims at developing a tool to perform pre-feasibility studies. This approach aims to promote the concept of water reuse in regions where it is still an emerging concept.

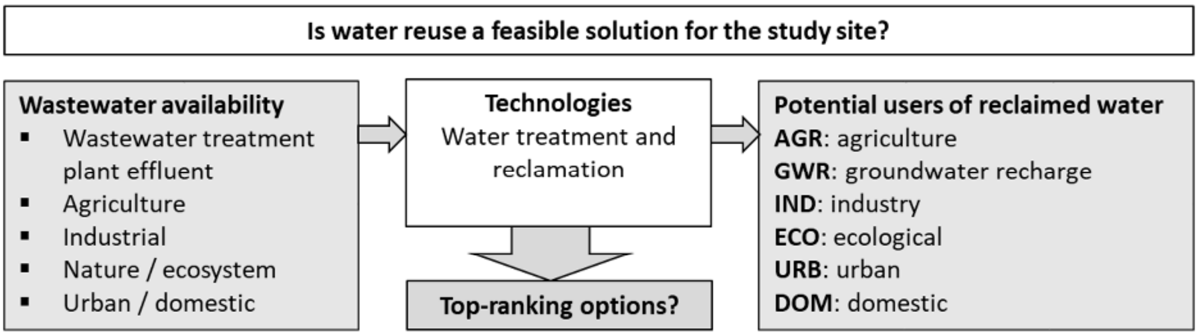


Figure 1-5: Main purpose of the decision-support system for water reuse (i.e., Poseidon).

For this task, the objective is first to show that water reuse would be technically possible or feasible, and then propose options (Figure 1-5). As the DSS is addressed to a large audience, it requires simplification from expert-level discourse to more accessible explanation. It should also include some capacity-building component for users unfamiliar with water-reuse technologies. Its scope of application starts with awareness raising and the potential for water reuse and ends just before detailed feasibility studies and design of water-reuse schemes.

For the second DSS, on water-loss reduction, a different approach is applied, and both facilitation and implementation components of response are considered.

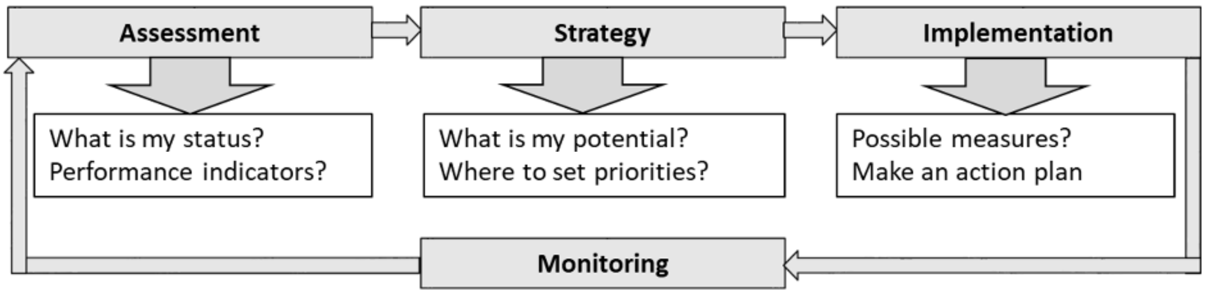


Figure 1-6: Main purpose of the decision-support system for water-loss reduction (Water Utility Compass).

This DSS aims to put the whole process of assessment, strategy, implementation and monitoring in a single place with a participatory approach of the users (Figure 1-6). It is targeted to water utilities staff and experts from the water sector who can select for themselves, with the help of reasonable estimates, what the most suitable responses to their challenges are. It should also involve some capacity-development components and should principally aim at establishing an action plan.

1.4.3 Specific Research Objectives

Based on the main hypothesis and objectives presented in Section 1.4.2, this thesis has the following specific research objectives:

1. *Identify needs for DSSs*: Identify the needs in the fields of water reuse and water-loss reduction, as well as the main limitations of existing DSSs. This objective is treated in the literature review, and the results are presented in Section 2.5.
2. *Develop two DSSs for two different applications*:
    a. *Poseidon to be applied at a pre-feasibility stage*: As many expert tools for the design are already available, a solution for the pre-feasibility stage is necessary.
    b. *Water Utility Compass as an implementation-support tool for water utilities*: As many tools consider only the analysis of the present situation, it is also necessary to include possible measures in the DSS.
3. *Apply the DSSs to different case studies* in order to validate and demonstrate possible applications, uses and benefits, the tools should be critically applied to a case study in order to demonstrate it is working and offers the expected results. Poseidon should be tested for plausibility, and its reliability should be assessed.
4. *Contribute to the field of integrated water management* through the open-access publication of key underlying data collected and developed during the development of the DSS.

1.5 Thesis Outline

The general structure of the thesis presented in Table 1-1 follows a classical PhD dissertation canvas based on Harvard University standards (Harvard University, 2017). In Chapter 2, the literature review analyses the contexts and vulnerabilities of sustainable water management, as well as responses to those vulnerabilities. It also reviews the state of the art of DSSs for water reuse and water-loss reduction, and it identifies knowledge gaps. In Chapter 3, the methodology presents the development of both DSSs and describes both systems in detail. Chapters 4 and 5 present the application of the DSSs to case studies and their main results, and it discusses the outcomes. In Chapter 6, the conclusions and recommendations provide a summary of all research conducted and tools developed and state the main conclusions and recommendations for future research. After the references, different appendixes provide all database and additional information linked with the DSSs developed.

Table 1-1: Main chapters of the thesis and short description of main content

Development of Decision-Support Systems (DSSs) for Water Reuse and Water-Loss Reduction Holistic and Systemic Approach for Resilience Promotion in the Context of Water Resources Management	
CHAPTER 1 – INTRODUCTION	Problem definition, key challenges and the water resilience framework, water reuse and water-loss reduction, hypotheses and research objectives, structure of the thesis
CHAPTER 2 – LITERATURE REVIEW	DSSs for water reuse and water-loss reduction, state of the art, substantial aspects relevant for this thesis, knowledge gaps
CHAPTER 3 – METHODOLOGY	Methodology and development of two DSSs for water reuse (Poseidon) and water-loss reduction (Water Utility Compass)
CHAPTER 4 – CASE STUDIES AND APPLICATIONS	Description of the case study areas, presentation of the resulting DSSs, accuracy and application to case studies
CHAPTER 5 – RESULTS AND DISCUSSION	Results of the application, analysis of the outcomes and discussion
CHAPTER 6 – CONCLUSIONS AND RECOMMENDATIONS	Summary of all research conducted and tools developed, main conclusions, and future research recommendations
APPENDIXES	Database tables, lists of technologies and treatment trains considered, handbook, etc.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

This chapter first reviews current literature related to water management through the resilience framework (Section 2.2) and then considers key concepts related to the development of both DSSs for water reuse (Section 2.3) and water-loss reduction (Section 2.4). This chapter closes with a summary that indicates the requirements for DSSs development to progress beyond the state of the art in the field of water resource management (Section 2.5).

2.2 Context, Vulnerability and Responses for Sustainable Water Management

Water stress index is a widely applied indicator that measures the ratio of total annual water withdrawals to total available annual renewable supply, accounting for upstream consumptive use (World Resources Institute, 2014). Figure 2-1 represents the projected value of water stress in the year 2040 under a business-as-usual scenario. The scarcity of water and the increased demands of the various economic sectors have become one of the most prominent challenges faced by the government and a focal task for many multi- and bilateral donor agencies. Water scarcity can be divided by type. First, *physical water scarcity* affects 1.2 billion people (United Nations, 2015), where the demand outstrips the land's ability to provide fresh renewable water; these conditions usually arise in dry and arid regions of the world or where the human demand exceeds the capacity of the natural environment. A second type is economic water scarcity, which presently affects 1.6 billion people; in this case, water is physically available, but the lack of investment and infrastructure does not allow access to the required water. The following sub-chapters depict key issues related to water management, to the resilience framework presented in Figure 1-1 and their relationships with water reuse and water-loss reduction.

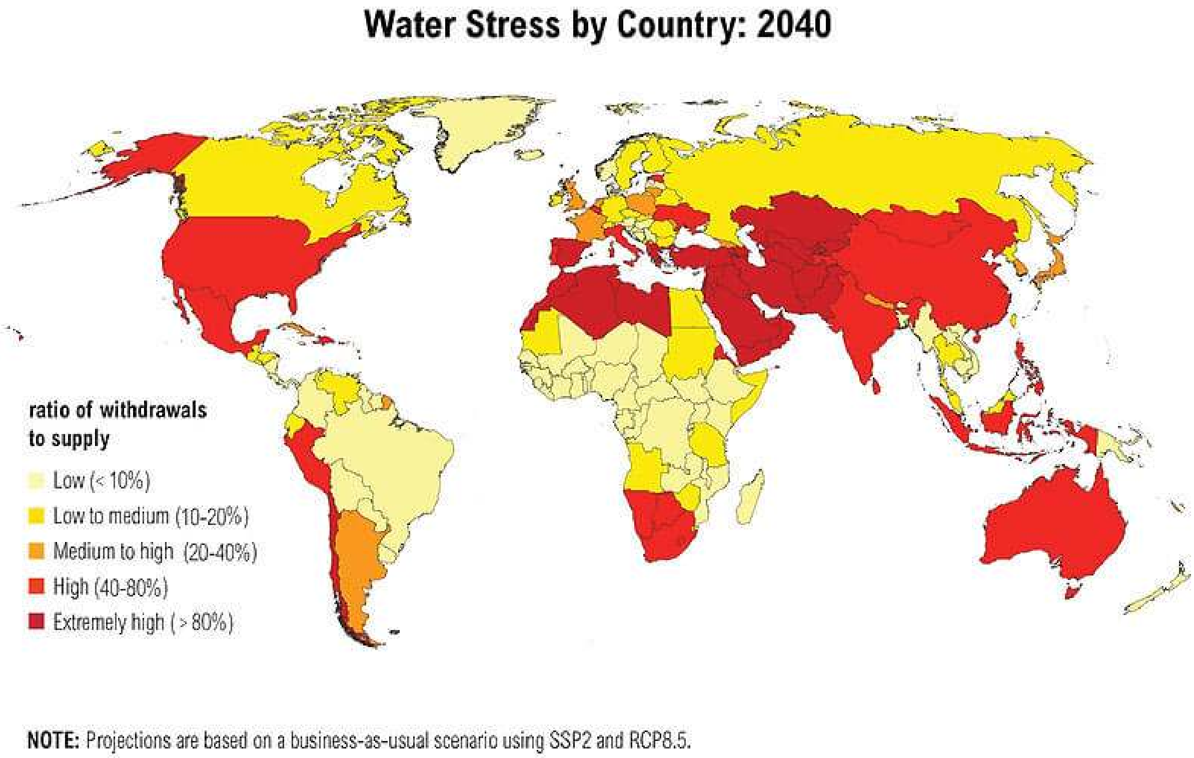


Figure 2-1: Water stress values in 2040 with a projected change under the business-as-usual scenario (World Resources Institute, 2014).

2.2.1 Global Development as a Driving Force of Water Stress

The tremendous demographic and economic growth that has occurred in recent decades is mainly responsible for human vulnerability concerning water crises. The population is growing (not linearly, but by about 80 million people yearly, predicted to reach 9.7 billion by 2050; United Nations and Social Affairs 2015), implying increased freshwater demand of around 64 billion m^3 per year. The distribution and availability of freshwater resources and population around the world is not uniform; some areas of the globe receiving different quantities of water over any given year. Additionally, different climates can vary considerably, especially over wet and dry seasons. Most population growth will occur in developing countries, mainly in regions that are already experiencing water stress and in areas with limited access to safe drinking water and adequate sanitation facilities (WWAP, 2009). This trend may lead to migrations, and it is expected that water scarcity in some arid and semi-arid places will displace between 24 million and 700 million people (United Nations, 2015).

The phenomenon of urbanization also has an impact on access to safe drinking water or adequate sanitation services, causing specific and often highly localized pressures on the availability of freshwater resources, especially in drought-prone areas (UN Water, 2015). In 2008, the world population was estimated to be equally split between urban and rural areas, with 30% of all city dwellers residing in slums; however, the urban population is expected to increase to more than 65% with a total of 6.3 billion by 2050 (WWAP, 2012). Furthermore, 93% of the increase in urban population is expected in developing countries, 40% of which will likely be the expansion of slums (UN-Habitat, 2010). Together, India, China and Nigeria will account for 35% of the projected growth of the world's urban population between 2018 and 2050. This growth of small and mid-size cities will have an impact on water resources, especially in informal urban areas. In 2006, 54% of the world's population had a piped connection of drinking water to their dwelling, plot or yard, and 33% used other improved sources of drinking water. The remaining 13% relied on unimproved sources. One should also be aware that coverage is much higher in urban than in rural areas (WWAP, 2009).

Another influencing factor affecting water resources is dependence on water inflow from neighboring countries (cross-boundary use of water resources). As many countries rely on other nations for the quantity and quality of their water supply and discharge, some more vulnerable areas will have to cope with additional transboundary political issues. The rules governing global economics increasingly influence local and national governance, affecting the sustainability of water resources at the basin level (UNDESA, 2012).

2.2.2 Water Demand

The main factors affecting water use are population growth, economic growth, urbanization, technological change and changing consumption patterns. Water withdrawals have tripled over the past 50 years (explained by the rapid increase in irrigation development and by the growth of agriculture-based economies). Due to demographic growth, agriculture is the largest user of water resources and has had to increase the amount of irrigated surfaces used to irrigate diverse crops, representing now 70% of all freshwater humanity withdraws annually. Nineteen percent is for industrial use, and 11%, for municipal and domestic needs (Aquastat, 2015). The agricultural sector withdraws over 90% of freshwater used in most of the world's least-developed countries (WWAP, 2014). These numbers, however, are biased strongly by the few countries that have very high water withdrawals. Averaging the ratios of each individual country, we find that, for any given country, these ratios are 59% for agricultural use, 23% for industrial use, and 18%, for domestic use (Aquastat, 2015). Agriculture will have an increase of water demand of 60% worldwide and 100% in developing countries (WWAP, 2015b). Demand for water is expected to increase in all sectors of production (WWAP, 2012). Increasing industrial production will also affect water quantity and quality. In some areas with poor regulation and enforcement, water pollution could increase dramatically. Freshwater withdrawals for energy production, which currently account for 15% of the world's total (WWAP, 2014), are expected to increase by 20% through 2035 (IEA, 2012). Drinking water consumption increased six fold in the 20th century, while the population has increased only threefold. A European consumes, on average, 300 L of water per day and an African 30 L. Strong income growth and the rising living standards of a growing middle class have also led to an increase of direct and indirect water use.

2.2.3 Natural Conditions and Climate

Additional factors will further influence the water supply in the near future, and any current forecast must be looked at very critically. One prominent factor that has to be considered more seriously is the impact of climate change, reducing precipitation and groundwater recharge. Water has been identified as the primary medium through which society and the environment will be impacted by climate change (Bates, Kundzewicz, Wu, & Palutikof, 2008). Climate change will lead to increasing variability in precipitation patterns that many countries have already begun to experience with direct and indirect effects on the hydrological cycle, with changes in runoff and aquifer recharge and in water quality (Alavian et al., 2009). In addition, higher water temperatures are expected to intensify many forms of pollution, with possible negative impacts on ecosystems, human health, water system reliability and operating costs (Bates et al., 2008). Furthermore, since the Rio Earth Summit in 1992, floods, droughts and storms have affected 4.4 billion people (95% of all people affected by all disasters) and caused US$2 trillion of damage (UNISDR, 2012; WWAP, 2015b).

2.2.4 Water Pollution and Water Quality

In addition to water scarcity, water quality and pollution are also affecting water availability. Intensive agriculture, industrial production, mining and untreated or badly treated urban runoff and wastewater create environmental and health risks (WWAP, 2015b). This degraded water quality is often due to human activities and lack of infrastructure treating the wastewater. Figure

2-2 represents physical risks related to water quality and identifies areas of concern regarding water quality that may affect short or long-term water availability.

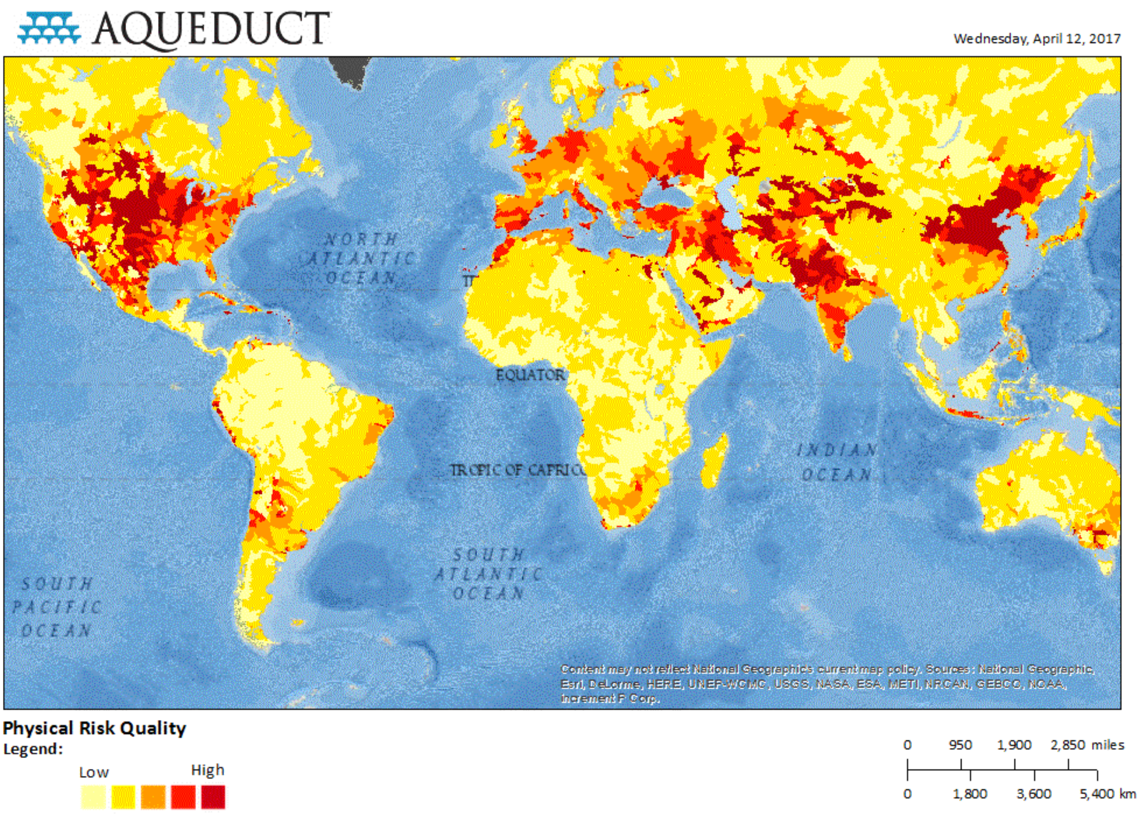


Figure 2-2: Physical Risk Quality (World Resources Institute, 2014).

2.2.5 Water Supply and Water Quantity

At least half of the global population's drinking water and 43% of all water used for irrigation is supplied by groundwater (Groundwater Governance, 2015). It plays a capital role and is often subject to overexploitation, leading to diminishing supplies: it is estimated that 20% of the world's aquifers withdrawals are overexploited (Gleeson, Wada, Bierkens, & van Beek, 2012; WWAP, 2015b). In some regions, such as the Arabian Peninsula, withdrawals were five times more than the internal renewable water resources in 2011 (Aquastat, 2015). As a consequence, the levels of groundwater are declining around many mega-cities and in several of the world's agriculture intensive countries (Groundwater Governance, 2015). In addition, land subsidence and saltwater intrusion are direct consequences of over-exploitation (U.S. Geological Survey, 2015).

2.2.6 Vulnerability of Water Systems

These different influencing factors describe the global context and disturbances related to the quantity and quality of water resources. Each region considered has a specific context with its own driving forces and pressures and also specific disturbances to its water resources, as well as social, environmental and economic impacts. Depending on the intensity of those factors, different systems will be able to deal with the disturbance or not, a concept captured by the notion of vulnerability. There is no consensus on the meaning of "vulnerability," as it has been used in different research traditions (Gallopín, 2006), but a functional form for vulnerability composed of hazards and impacts can be considered in the context of water resources management as described by Equation (2) (Karavitis et al., 2014). Vulnerability assessments of water systems tend to evaluate whether the exposure to a disturbance would impair the system physically or functionally and whether the system would be able to cope with the perturbation. The combination of vulnerability and risk assessment allows one to prioritize the adequate responses, given present and future situation.

$$\text{Vulnerability} = \text{Risk identificaton x Impact assessment} \tag{2}$$

2.2.7 Global Call for Actions

The confluence of those main influences (population growth, economic growth, urbanization, technological change, changing consumption patterns, climate change, and water pollution) has led to the vulnerable and challenging situation the world faces today. Some regions are most exposed to water vulnerability than others, but in the age of a globalized world, everybody is affected directly or indirectly by potential water crises. All reports and studies have shown that under business-as-usual conditions, the situation will worsen, and many multi-lateral organizations have called for action.

In 1992, The Dublin principle stated that fresh water is a finite, vulnerable and essential resource that should be managed in an integrated manner (Global Water Partnership, Solanes, & Gonzalez-Villarreal, 1999). Access to water is at the core of many policies' targets, most recently within the United Nations Millennium Development Goals, where target 7.C was to halve the proportion of the population without sustainable access to safe drinking water and basic sanitation between 1990 and 2015. The world has met the target of halving the proportion of people without access to improved sources of water five years ahead of schedule.

Between 1990 and 2012, 2.3 billion people gained access to improved drinking water sources. However, in 2012, 748 million people remained without access to an improved source of drinking water, and 2.5 billion in developing countries still lack access to improved sanitation facilities ("United Nations Millennium Development Goals," 2015). During the 2012 United Nations Conference on Sustainable Development (Rio+2012), member states committed to markedly improve wastewater treatment and reuse and to enhance water use efficiency.

In Europe, the 2020 Resource Efficient Europe Roadmap for Water states that water withdrawals should stay below 20% of the available renewable resources. The Blueprint to Safeguard Europe's Water Resources stresses the need to enhance the water storage potential of soils and ecosystems. The European Innovation Partnership's Water Strategic Implementation Plan also states that the EU must thus find creative solutions that contribute to tackle these water-related challenges while stimulating economic growth and job creation. Actions towards the achievement of the water-related goals can lead to a marked growth of the European water sector that provides 600,000 direct jobs and several more indirect ones. Furthermore, the water framework directive 2000/60/EC establishes a framework for community action in the field of water policy (European Parliament and European council, 2000).

The post-2015 Sustainable Development Goals follow the Millennium Development Goals and are part of the 2030 Agenda for Sustainable Development, adopted by Heads of State and Governments in September 2015. The 2030 Agenda is a new plan of action for people, planet and prosperity, with 17 Sustainable Development Goals and 169 associated targets at its core (United Nations, 2017). Sustainable Development Goal 6 (SDG 6) is to "Ensure availability and sustainable management of water and sanitation for all" by 2030 (WWAP, 2015b). SDG 6.A proposes to expand international cooperation and capacity-building support to developing countries in water- and sanitation-related activities and programs, including water harvesting, desalination, water efficiency, wastewater treatment, recycling and reuse technologies (WWAP, 2015b).

A possible 40% water shortfall in freshwater supplies by 2030 could be avoided if the international community takes recommended action, according to the UN 2015 World Water Development report (WWAP, 2015b). The main driving forces between 2011 and 2050 are as follows: (1) water resources, (2) infrastructure, (3) climate change, (4) agriculture, (5) technology, (6) demography, (7) economy and security, (8) governance, (9) politics, and (10) ethics (Cosgrove & Cosgrove, 2012). Since water is necessary to sustain life, development and the environment

(Dublin principle) (Global Water Partnership et al., 1999), actions must be taken to bridge the foreseen gap between demand and supply.

2.2.8 Response

Previous sections of this chapter have reviewed several aspects helping to explain the factors influencing water systems, their vulnerability and the risks associated with current or future disturbances. With these different factors presented, the rest of the thesis will focus on responses to increase the adaptive capacity of water systems in reaction to influencing factors and disturbances of the systems presented.

2.2.8.1 The challenge of implementation in developing countries and emerging economies

The capacity to adapt and cope with vulnerability does not guarantee capacity will be used, and this lack of action is an underlying problem often encountered. If a disturbance with high risk and potentially high consequences has been identified in a system that theoretically has the adaptive capacity to react, it can happen that no reaction occurs. Sometimes, everything is available to cope with a water-related issue (identified measure, available technology, possible financing, knowledgeable and competent staff, favorable institutional framework, willingness of stakeholders), but no action is taken usually due to misaligned objectives and poor management of interactions between stakeholders (OECD, 2012). The systems having to cope with water-related stress, disturbance, vulnerability and risk are comprised of various stakeholders and organizations that are not necessarily resilient. According to the Rockefeller Foundation, five main factors make some systems more resilient than others (Rockefeller Foundation, 2013):

- standby capacity ensuring an alternative if an essential component of a system fails,
- flexibility allowing change, progress or adaptation when facing a stress or disturbance,
- limited occurrences of failure that could lead to a cascade of failures across a system,
- fast reaction to re-establish functions in order to avoid long-term disruptions, and
- perpetual learning and capacity development.

The resilience framework also includes the reaction and the ability of local stakeholders to respond to a disturbance by different means (Figure 2-3). The reaction component is composed of facilitation and implementation. The facilitation is composed of awareness raising, capacity development, economic tools and control tools. Implementation follows a classical cycle of assessment, strategy definition and action planning, implementation, and monitoring, returning again to assessment.

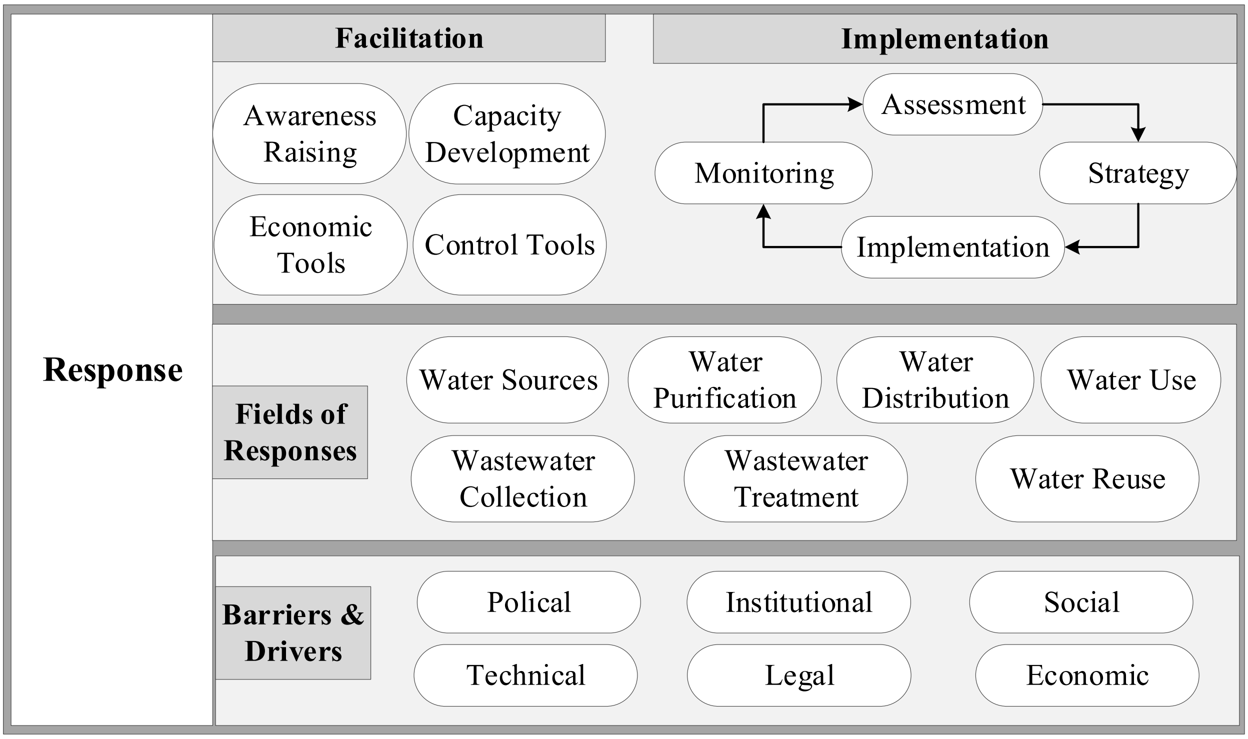


Figure 2-3: The reaction or responses within the water resilience framework.

2.2.8.2 Technical options

Both for water reuse and for water-loss reduction, a range of technologies and solutions (hardware) are available to implement strategies. These solutions are reviewed in Sections 2.3 and 2.4. However, in many developing countries and emerging economies, the challenges are often overwhelming and even if solutions are available, and there are some key elements are missing for implementing the most adequate strategies. The successful implementation of water-reuse schemes, for example, is not effortless and involves knowledge of technologies and people able to operate the chosen scheme; it also requires a good planning, design and organization, as well as adequate selection of technologies based on local requirements. These are just some of the factors involved, and as this is a relatively new approach in some regions, there is a need for expertise and decision-making support. Apart from the hardware, there is a requirement for software tools, defined as "instruments and set-ups with aim to change the behavior and attitudes of different actors" (Conradin, Kropac, & Spuhler, 2010). These software tools are divided into awareness raising, capacity development, economic tools and control tools.

2.2.8.3 Awareness raising and institutional framework

As many different issues are usually part of the daily business of decision-makers, the first step required is usually to increase the awareness or consciousness of a problem and the need for responses. This process not only addresses politics and decision-makers, but it can also be targeted to wider target groups. The tools to help raise awareness are manifold and can include, among others, media campaigns, empowerment of young people, advocacy to influence leaders and lobbying, school campaigns, information events, reports and trainings.

Regarding wastewater and water reuse, one of the main reasons wastewater has been largely neglected is that many water utilities have not realized the value of investing in wastewater infrastructure (WWAP, 2015b): "Improving wastewater governance therefore requires the alignment of varying interests in ways that allow people and organizations to collaborate towards meeting basic common needs while maximizing benefits across the various stages of wastewater management" (WWDAP, 2017).

2.2.8.4 Capacity development and enabling environment

In order to improve water management, it is essential to ensure that the appropriate levels of human capacity are available (WWDAP, 2017). The United Nations Development Program (UNDP) defines capacity development as "the process through which individuals, organizations and societies obtain, strengthen and maintain the capabilities to set and achieve their own development objectives over time" (UNDP, 2008). It is composed of four levels of capacities:

- *Individual competencies* refer to human resources development through skills, experience and knowledge of people usually gained by trainings and work experience.
- *Organizational development* considers the union of individual capacities to work together and achieve the goals and mandates of organizations. The capacities involved are internal policies, arrangements, procedures and frameworks that should allow organizations to work better than the sum of their employees.
- *Enabling environment* refers to broader systems where organizations and individuals cohabitate and interact. The enabling environment can be divided into *system and network development* (Figure 2-4). Capacities at this level facilitate or hinder the existence and performance of an organization's entities and involve system development in the policy field, legislation power relations and social norms.

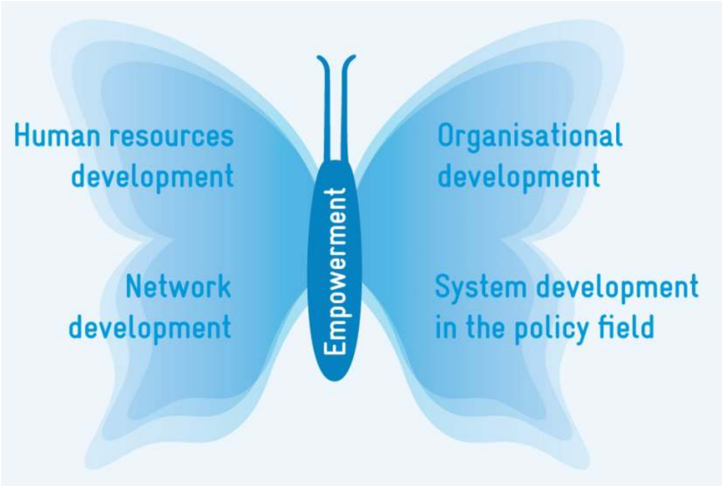


Figure 2-4: Interconnection between various elements of capacity development (Fallis et al., 2011a).

The CapDev butterfly metaphor (Figure 2-4) illustrates the importance of each of the dimensions of the individual, the network, the organization and the system by assigning one of the four wings to each dimension: “The butterfly orients itself on potentials and opportunities, and flies only when it moves its wings in a coordinated way” (SDC, 2006). Furthermore, a butterfly cannot fly forward with a single wing. In other words, all those aspects should be adapted, coordinated, strengthened and improved to allow success, independence and empowerment of the water systems.

2.2.8.5 Economic tools

Potable water remains generally undervalued and underpriced when compared to the actual cost of providing the service; nevertheless, investments in water reuse and water-loss reduction generally compare well to the costs of dams, desalination, inter-basin transfers and other options to increase water supplies (WWDAP, 2017). Market-based instruments and water prices can encourage changes of behavior and facilitate the implementation of solutions using financial incentives. Such tools involve, for example, water pricing (tariffs), subventions, charges and tradable water rights (Conradin et al., 2010).

2.2.8.6 Control tools

Control tools are instruments that oblige water users, businesses or service providers to comply with a regulation. Such instruments are usually set up by government bodies and include prohibitions and restrictions, permits, standards, directives and more. Water use restrictions or rationing are examples of control tools that can be applied in case of droughts and that water users are obliged to follow (Conradin et al., 2010). Regulation and enforcement of the pollutant concentration limits for wastewater discharges from industries into the receiving water bodies are another example of such instruments.

2.2.8.7 Implementation and necessity of decision-support systems

In many cases, the classical virtuous cycle of "assessment, strategy and action planning, implementation and monitoring to go back to assessment" is not always straightforward to put into practice, and support tools are required to assist this exercise. In addition, DSSs can also simplify sustainable management and help prioritize most adequate options among the plethora of available solutions. For water reuse applied in developing and emerging economies, it appears that the facilitation step should be tackled, whereas for water-loss reduction, the key gap primarily concerns the implementation of measures and support for water utilities managers.

2.3 Water Reuse

This section first reviews the state of the art related to DSSs for water reuse, aiming to understand the progress so far as well as the gaps and needs addressed. The second objective is to review the various components required for the development of an innovative DSS.

2.3.1 Decision-Support Systems Review

The main goal of wastewater treatment is to remove the harmful or negative effects that the relevant constituents could have on the local environment, at the lowest cost (Srinivas Krovvidy, Wee, Summers, & Coleman, 1991). In order to remove the pollutants, many *unit processes* are available, grouped together to provide the following (Tchobanoglous et al., 2013):

- *primary treatment*: physical processes, such as grits or rags;
- *secondary treatment*: chemical or biological processes to remove biodegradable organic matter;
- *tertiary treatment*: for example, filters or disinfection to remove residual suspended solids; and
- *advanced treatment*: removal of additional dissolved and suspended materials sometimes required for water-reuse applications/

In general, a so-called treatment train comprises the several unit processes that have to operate in series in order to achieve a desired level of treatment (it is also called a "treatment process flow diagram" or "treatment chain"). A treatment train is a sequence of unit processes where the effluent of one process becomes the influent of the next process (Srinivas Krovvidy et al., 1991). It has been reported that as many as 50,000 possible alternatives need to be considered to determine which is the most sustainable wastewater treatment option; this multiplicity demonstrates the complexity of process engineering (Chen & Beck, 1997; Hamouda, Anderson, & Huck, 2009).

Historically, designing wastewater treatment schemes was a kind of art based on heuristic knowledge (based on experts' experience), dominated by linear end-of-pipe infrastructure design (Chamberlain, Carenini, Öberg, Poole, & Taheri, 2012). Over the time, several DSSs emerged including more and more sophisticated mathematical algorithms with numerical optimization methods to support the complex task of wastewater treatment design (Srinivas Krovvidy et al., 1991). In their 2009 literature review of DSSs in water and wastewater treatment process selection and design, Hamouda et al. classify several tools into three main categories of analysis (Hamouda et al., 2009):

- *technical design*: outdated approach due to the importance of non-technical factors in the assessment;
- *technical and economic analysis*: includes cost minimization to determine the optimum treatment; and
- *system analysis*: integrated approach considering cost, technical performance, social, legal, and environmental interactions.

Most existing DSSs are oriented primarily to experts, including wastewater researchers and practitioners (i.e., wastewater engineers and operators), and most also focus on the technical design (Castillo et al., 2016; Hamouda et al., 2009). Some of those design tools are extremely sophisticated, sometimes even including artificial intelligence, but they are inaccessible to non-experts or non-specialists in the field of water-reuse technologies and have a different purpose than the DSS to be developed in this thesis, which aims at a system analysis at a pre-feasibility stage.

A list of referenced DSSs is presented in Table 2-1, where the initial entry relies on a review from Hamouda et al. (Hamouda et al., 2009), which is then complemented with more recent

DSSs encountered during this literature review. If several publications can be found presenting many DSSs, it is difficult to obtain the mentioned software and eventually get access to them. It is not clear whether the DSSs have been commercialized or further developed since the background research was published. Most wastewater management modelling software including a high level of detail is not openly shared, with some exceptions, such as the computer software "Water and Wastewater Treatment Technologies Appropriate for Reuse (WAWTTAR)" (Finney & Gerheart, 2004), which includes a database of wastewater system components that can be openly accessed (Chamberlain et al., 2012). This free software has many similarities with the DSS developed in this thesis, but it was not possible to make it run correctly due to a range of errors, and apparently this tool has not been continuously updated.

Table 2-1: Selected list of main decision-support systems reported in literature (based on Hamouda, Anderson, and Huck 2009)

Name of tool or authors	Reference	Scope		Key methods	Open source
		Technical & economic	System analysis		
Krovvidy et al.	(Srinivas Krovvidy et al., 1991)	X		Rule-based, heuristic search, neural networks, certainty factors for the developed rules	-
Kao et al.	(Kao, Brill, Pfeffer, & Geselbracht, 1993)	X		Process modeling, mathematical programming, solves mass balance on a treatment train, graphical display of designs	-
Krovvidy et al.	(Srinivas Krovvidy & Wee, 1993)	X		Case-based reasoning, heuristic search, define cost per unit removal of contaminant	-
SOWAT	(S. Krovvidy et al., 1994)	X		Rule-based, heuristic search, fuzzy logic, fuzzy functions for technology performance, ability to check a user-defined train	-
Yang et al.	(Yang & Kao, 1996)	X		Expert system, fuzzy logic, certainty factor for technology treatability, user-defined fuzzy preference of technologies	-
MEMFES	(Heller, Garlapati, & Aithala, 1998)		X	Industrial wastewater, expert system, simulation, analytical hierarchy process, a reviewer provides justification for outcome. Surveyed the system's user-friendliness	-
Rodriguez-Roda et al.	(Rodriguez-Roda, Poch, & Bañares-Alcántara, 2000)	X		Simulation, issue-based information systems, reports describe the deliberation over a decision, searching design records using key-words	-
SANEX	(Loetscher & Keller, 2002)		X	Conjunctive elimination, multi-attribute utility technique, multi-disciplinary set of sustainability indicators, multi-level amalgamation used for rating	-
Wukovits et al.	(Wukovits, Harasek, & Friedl, 2003)	X		Knowledge-based system, heuristic search, easy update of process database, possible communication with other programs	-
WAWTTAR	(Finney & Gerheart, 2004)		X	Modeling and simulation, screening, multi-criteria decision analysis,	X

Name of tool or authors	Reference	Scope		Key methods	Open source
		Technical & economic	System analysis		
				output: lowest-cost alternative, assesses risk, and more, community specific data considered in the decision	
WASDA	(F. M. Sairan, Z. Ujang, M. R. Salim, 2014)	X		Technical design, rule-based, design equations, friendly user interface, process design calculation module	-
WADO	(Ullmer, Kunde, Lassahn, Gruhn, & Schulz, 2005)	X		Industrial wastewater, rule-based, mixed integer non-linear programming, investigates regeneration opportunities from water used in industrial processes	-
WTRNet	(Joksimovic et al., 2006)	X		Modeling & simulation, linear & nonlinear programming, genetic algorithm, provides user guidance for treatment train selection through either an expert or a stepwise approach	-
Zeng et al.	(Zeng, Jiang, Huang, Xu, & Li, 2007)		X	Analytical hierarchy process, grey relational analysis, allows comparison between alternatives considering the entire criteria	-
Zhu et al.	(Zhu & McBean, 2007)		X	Drinking water, Bayesian probability networks, considers performance uncertainty, variables measuring impact on public health	-
MOSTWATAR	(Dinesh & Dandy, 2003)	X		Genetic algorithms, fitness score, techno-economic feasibility investigation	-
MEDAWARE	(Hidalgo, Irusta, Martinez, Fatta, & Papadopoulos, 2007)	X		Existing wastewater facilities, online tool, multi-criteria analysis	-
WASWARPLAMO	(Adewumi, 2011)	X		Modeling & simulation, linear & nonlinear programming, genetic algorithm, provides user guidance for treatment train selection through either an expert or a stepwise approach	-
Chamberlain et al.	(Chamberlain et al., 2012)		X	Integrated model, logic programming, explicit ontology, selection based on stated values and priorities	-
NOVEDAR_EDSS	(Castillo et al., 2016)		X	Intelligent or expert screening of process technologies	X for aca-

Name of tool or authors	Reference	Scope		Key methods	Open source
		Technical & economic	System analysis		
					demic purposes
Huang et al.	(Huang, Dong, Zeng, & Chen, 2015)	X		Integrated model, urban wastewater, genetic algorithm, multi-objective optimization, non-dominated sorting	-

Two remarkable DSSs that could be partially examined are the decision-support software for integrated water reuse, called WTRNet (Joksimovic et al., 2006) and the software tool "Waste Water Reuse Planning Model (WASWARPLAMO)" (Adewumi, 2011). Both systems apply an approach between techno-economic assessment and system analysis, including algorithms with a set of rules to assemble unit processes into treatment trains. Several data and much information for the development of the DSS presented in this thesis is gathered from the project AQUAREC "Integrated concepts for reuse of upgraded wastewater", which was funded by the Fifth Framework Program of the European Commission. That project led to the development of WTRNet. Several work colleagues were involved in this project and could kindly support for data review and recommendations. One of the main output of the AQUAREC project was the water-reuse system management manual. For decision makers initiating, implementing or improving water reclamation and reuse schemes, addressing structural, non-structural and managerial conditions, this tool helps them to implement and operate water-reuse schemes in ways that are safe, publicly acceptable and economically, financially and environmentally feasible (Davide Bixio et al., 2006). In addition to this manual, this literature review recommends the following two books that could be considered as main references in the field of wastewater engineering and water reuse: *Water Reuse: Issues, Technologies, and Applications* (Asano, Burton, & Leverenz, 2007) and *Wastewater Engineering: Treatment and Resource* (Tchobanoglous et al., 2013).

Based on this review and its related investigation, the following needs in the field of water reuse and main gaps of existing DSSs have been identified. Those aspects should be considered in the development of the DSS presented in this thesis, in order to produce a tool that substantially advances the state of knowledge on the subject:

- The DSS should be accessible to a wider audience than only technical experts from the field. It should be possible to perform analysis without prior expert knowledge for the design of treatment trains, and the DSS should already include most common treatment trains. Nevertheless, it should also be transparent and offer experts the possibility to perform a more detailed analysis with a possibility to add more options if further expertise is on hand.
- Capacity building should be integrated within the tool and within additional required basic knowledge and information (e.g. technologies descriptions, typical water quality classes, typical treatment trains).

- There is a need for accessible tools at a pre-feasibility stage, with scoping options that can quickly demonstrate the solutions available based on local economic, social and ecological conditions. The objective should not be to propose the best option, but rather to show that water reuse is feasible and provide simple estimates on cost, performance and additional indicators. More detailed design studies can be done at a later stage by experts or by using one of the already existing DSS. Guidelines for feasibility studies are beyond the scope of this thesis and are provided in detail by Urkiaga et al. (2006a).
- A system analysis is needed, and the DSS should consider not only technical aspects, but also a broader range of information, modules and assessment criteria (integrated system analysis). Many DSSs focus on wastewater treatment technologies, and there is a need to focus more on the concept of water reclamation and reuse on a systemic approach, also including the water distribution and not only the treatment technology.
- The DSS should be flexible. It should be possible to adapt the variables locally in order to apply the tool anywhere.
- The DSS should be publicly available and allow further development and integration within follow-up projects, ensuring that the tool does not suddenly "disappear" or become obsolete. It should use spreadsheets (e.g. Microsoft Excel) rather than sophisticated software quickly becoming outdated or out of service. If the background skeleton is developed, it can be adapted to other interfaces in the future.

2.3.2 Components Required for the Development of an Innovative Decision-Support System

The second objective of this review is to identify the different components required for the development of an innovative DSS. This section discusses the following:

- *Water quality and constituents of concern*: What are the key components and corresponding measurement parameters to be considered, review of key aspects for each component?
- *Typical wastewater quality and reclaimed water quality requirements*: What should be the concentration of different constituents in order to reuse the reclaimed water for different intended purposes, what are typical wastewater qualities encountered in typical effluents that can potentially be treated and reused?

- *Unit process technologies*: What are most common and relevant unit processes to be considered?
- *Treatment trains*: How to assemble unit processes into treatment train, how to deal with the complexity of process design in the DSS to be developed?

2.3.3 Water Quality: Constituents and Guidelines

Note: Section 2.3.3 has been written in the frame of the COROADO project ("Coroado Project Website," 2017) and was included in the public project deliverable 4.2 (Verzandvoort et al., 2015); only minor edits have been made. The project COROADO "Technologies for Water Recycling and Reuse in Latin American Context: Assessment, Decision Tools and Implementable Strategies under an Uncertain Future" was funded by the Seventh Framework Programme of the European Commission.

2.3.3.1 Wastewater constituents of concern for water recycling and reuse

In order to decide on the level of treatment required to clean wastewater of a sufficient quality for specific reuse, it is important to identify constituents of concern and their concentration. In untreated wastewater, a range of constituents (Table 2-2) can be found that can negatively affect public health, the environment and infrastructure (e.g., corrosion). According to the US Environment Protection Agency (US-EPA, 2012a), all reuse systems should at least have secondary treatment (following a primary one) that addresses suspended solids, most dissolved organic matter, some nutrients and other inorganics. The specific reuse will determine whether secondary treatment is sufficient or if more stringent cleaning of the wastewater is necessary. This section provides an overview of the most commonly found wastewater constituents. Table 2-2 provides an overview of measured parameters with a focus on those included in this document.

Table 2-2: Wastewater constituents, their concerns regarding wastewater reuse and commonly measured parameters for water reclamation water quality, adapted from (US-EPA, 2004a, 2012a) *and* (Levine & Asano, 2004)

Constituents of concern	Measured parameters	Acronym / unit
Turbidity is the measure of relative clarity of a liquid. The more total suspended solids in the water, the murkier it seems and the higher the turbidity.	Turbidity (Turb)	Turb / Nephelometric Turbidity Unit [NTU]

Constituents of concern	Measured parameters	Acronym / unit
Total suspended solids. Organic contaminants, heavy metals, etc. are absorbed on particles. Suspended matter can shield microorganisms from disinfectants. Excessive amounts of suspended solids cause plugging in irrigation systems.	Total suspended solids (TSS)	TSS / [mg/l]
Organic chemicals. Aesthetic and nuisance problems. Organics provide food for microorganisms, adversely affect disinfection processes, make water unsuitable for some industrial or other uses, consume oxygen, and may result in acute or chronic effects if reclaimed water is used.	Biochemical oxygen demand (BOD)	BOD / [mg/l]
	Chemical oxygen demand (COD)	COD / [mg/l]
	Total organic carbon (TOC)	TOC / [mg/l]
Inorganic chemicals and persistent organic chemicals. Some of these organics tend to resist conventional methods of wastewater treatment. Some organic compounds are toxic in the environment, and their presence may limit the suitability of reclaimed water for irrigation or other uses.	Specific compounds (e.g., pesticides, pharmaceutical compounds etc.)	
Nutrients. Nitrogen, phosphorus, and potassium are essential nutrients for plant growth and their presence normally enhances the value of the water for irrigation. When discharged to the aquatic environment, nitrogen and phosphorus can lead to the growth of undesired algae (eutrophication).	Total nitrogen (TN)	TN / [mg/l]
	Nitrate (NO_3)	NO_3 / [mg/l]
	Total phosphorus (TP)	TP / [mg/l]
	Phosphate (PO_4)	PO_4 / [mg/l]
Pathogens. Infectious microorganisms and viruses (pathogens) are present in untreated wastewater according to the prevalence in population and animals connected to the sewer system. Various disinfection methods exist to reduce pathogen loads.	E. coli	No/100 ml (log)
	Fecal coliform	No/100 ml (log)
	Intestinal nematode eggs	No/100 ml (log)

2.3.3.2 Chemical compounds

The composition of chemical contaminations in wastewater depends on its origin and co-determines the level of treatment required to produce reclaimed water for a specific application. Inorganic compounds include nutrients, heavy metals and salts while organic compounds include organic matter, organic detergents, and so on.

2.3.3.3 Organic chemicals

Organic pollution originates from fecal matter, kitchen wastes, detergents, oil, industrial wastes and so forth. Both chemical and biological processes acting on organic chemicals in the wastewater stream require oxygen, and the level of organic pollution can be determined through biological oxygen demand (BOD) and chemical oxygen demand (COD). Total organic carbon (TOC) and, indirectly, total suspended solids (TSS) and turbidity are commonly used measures of organic pollution in the wastewater stream. Biological oxygen demand refers to the amount of dissolved oxygen (usually milligrams of oxygen per liter of wastewater) required to degrade organic material by aerobic organisms in a given wastewater at a standard temperature over a standard time (e.g. BOD_5 over five days at 20°C). The COD uses strong oxidizing agents instead of aerobic microorganisms and is thus a measure for the overall content or organic chemical compounds. Chemical oxygen demand is also usually measured in milligrams of oxygen per liter of wastewater. Total organic carbon refers to the fraction of total carbon, which is bound in organic compounds and includes natural organic matter and synthetic sources such as detergents, fertilizers, herbicides, industrial chemicals, and more. All these measures are used as indicators of the overall removal efficiency of sewage treatment plants (Salgot & Huertas, 2006) measured before and after treatment. The effects of high organic chemical loads include coloration and odor problems of the water, possible soil contamination if used for irrigation, depleted oxygen content in the receiving environmental waters (lakes and streams) through decomposition processes by microorganisms, and use limitation (many industrial applications require water with low organic contents). Furthermore, since organic contaminations are often associated with suspended solids, high turbidity can reduce the effectiveness of disinfection involving chlorine, ultraviolet (UV) light or other disinfectants. High BOD in streams and rivers may reduce dissolved oxygen to levels that are inadequate to support aquatic organisms and is thus a limiting factor for environmental reuse (e.g., in stream regulation or as pond water).

2.3.3.4 Inorganic chemicals and persistent organic pollutants

Inorganic chemicals such as total dissolved solids (TDS), nutrients (nitrogen and phosphorus compounds, see Section 2.3.3.5) and heavy metals, along with persistent organic pollutants such as pesticides and some by-products of chemical industries, can affect the reuse potential of secondary effluents from WWTPs and the need to install further cleaning stages. Inorganic chemicals and persistent organic pollutants are not readily removed by conventional water treatment, since they are often dissolved and in many cases not biologically degraded (Salgot & Huertas, 2006). Many of these substances are harmful to aquatic organisms and are thus problematic for environmental reuse. Some substances are directly harmful to humans and can accumulate in organs.

2.3.3.5 Total dissolved solids, salts

Various inorganic chemicals are of particular concern for agricultural reuse, especially salts. Irrigation water with high salinity can degrade soils over time and cause leaf burn. High boron and sodium concentrations of more than 0.4 mg L^{-1} have detrimental effects on some crops such as citrus plants (Salgot & Huertas, 2006). In urban and industrial applications, scaling and corrosion can be concerns. While salinity removal is possible in water treatment, it is quite expensive and energy intensive (US-EPA, 2012a).

2.3.3.6 Heavy metals

Heavy metals are metals with densities higher than 5 g cm^{-3} (Ravazini et al., 2006) and include copper, nickel and zinc. They may accumulate in soils, later into plants and consequently the human food chain. In wastewater from certain industries, especially mining, heavy metals can be an issue to consider specifically. Treatment options to remove heavy metals from wastewater include for instance reverse osmosis and ion exchange.

2.3.3.7 Persistent organic pollutants and micropollutants

Typical examples of contaminations that have only recently received growing attention in wastewater treatment, drinking water production and water reuse are the residues of pharmaceuticals, hormone-active substances, pesticides and personal care products. Most of these contaminations are not removed by conventional water treatment, and more advanced treatment is required. Advanced methods include advanced oxidation processes and soil-aquifer treatment.

2.3.3.8 Nutrients

Nutrients are compounds that provide essential energy for organisms. Nutrients found in wastewater include phosphorus and nitrogen compounds mainly originating from human and animal excrements, industrial processes and discharge from agricultural areas. Depending on the reuse application, nutrients in the reclaimed water can be beneficial or undesirable. For agricultural reuse, the soil nutrient status can be positively affected by nutrients in the reclaimed water. For environmental or ornamental reuse, however (e.g., stream water regulation or pond water.), nutrient load should be minimized since otherwise algae growth will be enhanced through nutrient enrichment, leading to oxygen deficits and consequently the decay of fish and other animals (a process called eutrophication). The need to remove nutrients during treatment for reuse therefore depends on the intended use of the reclaimed water. Conventional secondary (activated sludge) treatment processes do not significantly remove phosphorus and nitrogen compounds. Since activated sludge treatment is based on microbial degradation of organic substances, nutrients may even be released in more plant-accessible forms (US-EPA, 2004b). Treatment options to remove nutrients from wastewater include enhanced biological phosphorus removal, P-precipitation and ion exchange.

2.3.3.9 Pathogens

Microorganisms such as bacteria and protozoa are omnipresent in nature and urban environments. In the environment, microorganisms are important decomposers of organic matter and therewith provide necessary nutrients. Most microorganisms are not dangerous to humans, and some are even directly beneficial (e.g., intestinal 'flora'). In wastewater engineering, microorganisms help to decompose organic matter and are essential in most secondary unit processes, such as activated sludge and trickling filters. Apart from harmless microorganisms, raw wastewater can contain high concentrations of infectious microorganisms or pathogens, which originate primarily from the feces of infected humans. Pathogens that can be present in urine include those causing schistosomiasis (disease caused by parasitic flatworms called *schistosomes*), typhoid fever, leptospirosis (infection caused by corkscrew-shaped bacteria called *Leptospira*) and certain sexually transmitted infections (although the latter do not survive for long in wastewater) (US-EPA, 2012a). Waterborne diseases can be transmitted by various pathways, which include the consumption of contaminated water or food via hand-to-mouth contact and the breathing of mist or aerosols from water containing suspended pathogens (e.g., during irrigation).

Since microorganisms and viruses in generally appear in very high concentrations, a logarithmic scale is usually used to report concentrations and the removal efficiencies of wastewater treatment processes. For instance, a removal rate of 1log for *E. coli* means that 90% of the concentration is removed and is calculated according to the following formula:

For $x$log: $100 - 10^{-x} \times 100$= removal efficiency [%]. (3)
E.g., 1log: $100 - 10^{-1} \times 100 = 99.9\%$.
E.g., 2log: $100 - 10^{-2} \times 100 = 99.99\%$.

In general, the presence or absence of microorganisms and viruses in the effluent is analyzed through indicator species. These indicators are used to search for contamination of the water by feces, indicating a high probability of the presence of pathogens (Davide Bixio et al., 2006). The most common types of microorganisms are discussed in Sections 2.3.3.9.1–2.3.3.9.3.

2.3.3.9.1 Bacteria

Bacteria are microorganisms of 0.2–10 µm in length. Many types are present in municipal wastewater. The number and type of bacteria are proportional to their prevalence in the human and animal community from which the wastewater originates (US-EPA, 2012a). Bacteria can be effectively removed from wastewater. Removal efficiencies vary with the level of treatment. A proportion of the bacteria are removed by sedimentation (after adsorption to particulate matter) in primary clarification, secondary clarification and various advanced treatments such as coagulation, flocculation and sedimentation. Bacteria can further be removed by filtration including sand filters or membrane processes. In a last step, bacteria can also be inactivated by disinfection. The most commonly used indicator organisms include fecal coliforms and *E. coli*.

2.3.3.9.2 Protozoa and helminths

In feces, parasites can be present in various life stages (i.e., as adult organisms, spores, cytes, oocysts or eggs) ranging in size from 1 µm to over 60 µm (US-EPA, 2012a). Eggs are the most robust against stressors such as heat, freezing and sunlight. In wastewater, helminths (parasitic worms) can be present as adults, larvae, eggs or ova ranging from 10 µm to more than 100 µm (US-EPA, 2012a). Physical removal by sedimentation or filtration for water reclamation is efficient due to the large size of the organisms. However, both protozoa (informal term for single-celled eukaryotes, either free-living or parasitic) and helminths can be resistant to disinfection by chlorination or other chemicals. Ultraviolet light can effectively induce mutations of the DNA of these parasites and deactivate their pathogenicity (US-EPA, 2012a). Commonly used indicators for helminths and nematodes (also called roundworm, any worm of the phylum Nematoda) are nematode eggs. There are no known indicators for protozoa and analytical tools are not yet well developed (Davide Bixio et al., 2006).

2.3.3.9.3 Viruses

Viruses occur within size ranges of 0.01–0.3 µm (US-EPA, 2012a). Many enteric viruses can cause infections or diseases, and these viruses can be released in feces. They are generally better adapted to environmental stressors than bacteria. Compared to bacteria and other microorganisms, viruses are less effectively removed by sedimentation and microfiltration processes, due to their small size. Ultrafiltration, nanofiltration and reverse osmosis can achieve significant virus removal. Deactivation of viruses by UV radiation is also efficient, but requires higher doses of UV than does the deactivation of bacteria and protozoa (US-EPA, 2012a). No accepted indicator for viruses has yet been established.

2.3.4 Typical Wastewater Quality and Reclaimed Water Quality Requirements

2.3.4.1 Guidelines

The objective of water reclamation and reuse is to treat wastewater to a level of purity that can be used for different reuses, such as agricultural, industrial, urban, potable, environmental or recreational uses or for groundwater recharge. The reclaimed water has to reach different quality levels, depending on the intended reuse purpose. Furthermore, those quality levels' requirements often differ from country to country. Reaching the required quality is the main objective of wastewater treatment technologies, and the DSS to be developed should propose feasible treatment trains that can meet the relevant quality standards. It is therefore crucial to define reclaimed water quality requirements and to utilize the several guidelines that currently govern the management of wastewater (Table 2-3).

Table 2-3: Overview of most common international guidelines and standards for treated wastewater reuse

Guidelines / Reference	Description
US-EPA, Guidelines for water reuse 2012 / (US-EPA, 2012a)	This update from the 2004 US-EPA guidelines (US-EPA, 2004a) is an exhaustive reference report considering all type of water reuse.
WHO, Guidelines for the safe use of wastewater, excreta and greywater. 2006 / (WHO, 2006b, 2006e, 2006d, 2006a)	In 2006, the WHO published four volumes of a third edition of its guidelines for the safe use of wastewater, excreta and greywater in agriculture and aquaculture. The revised guidelines reflect a strong focus on disease prevention and public health principles.
WHO, Guidelines for drinking-water quality: Fourth edition / (WHO, 2017)	The fourth edition of the WHO's guidelines for drinking-water quality builds on over 50 years of guidance from the WHO on drinking-water quality, which has formed an authoritative basis for the setting of national regulations and standards for water safety in support of public health.
ISO Guidelines for treated wastewater use for irrigation projects (2015)	ISO 16075-3:2015 covers the system's components needed for the use of TWW for irrigation.
FAO Water quality for agriculture 1994 / (Ayers, Westcot, & Food and Agriculture Organization of the United Nations., 1985)	The FAO suggests various water quality criteria for general irrigation. The guidelines are practical and have been used successfully in general irrigated agriculture.
Proposal by the Aquarec project, 2006 / (Davide Bixio et al., 2006; Salgot & Huertas, 2006)	The Aquarec project proposes seven quality categories for different types of reuses and compiled microbial and chemical limits for each category.
California code of regulation title 22 / (California Code of Regulations, 2017)	The DHS establishes water quality standards and treatment reliability criteria for water recycling under Title 22 and establishes requirements for use of recycled water not addressed uniformly statewide (Salgot & Huertas, 2006). These quality standards are often used as reference or used as a model to establish national water standards in other states or countries.

Notes: "US-EPA" stands for "United States Environmental Protection Agency", "WHO" stands for "World Health Organization", "ISO" stands for "International Organization for Standardization", and "FAO" stands for "Food and Agriculture Organization of the United Nations".

Most of the guidelines presented in Table 2-3 are recommendations, and only a very limited number of countries have guidelines or regulations on wastewater reclamation and reuse, with the southernmost countries usually having national regulations (Salgot & Huertas, 2006). Furthermore, every guideline has a different approach and use different parameters for water quality standards. It is therefore not possible to provide a universal table with quality standards that could be applied worldwide, and the DSS should be flexible and offer the possibility to select which guideline should be applied. A detailed overview of all encountered guidelines during the literature review is presented in Appendix V (Table 8-3).

2.3.4.2 Input quality: Typical wastewater quality

If reaching the water quality standards governing the intended reuse is the main objective of water-reuse schemes, it is important to consider the water quality of the wastewater to be treated (input). Several types of wastewater are potential candidates for reclamation and reuse, for example, effluent from an existing WWTP, industrial wastewater or even untreated domestic wastewater. The different water quality criteria will be a variable of the DSS to be developed, and flexibility should be offered to the user to define those parameters if known. If they are not available, a list of the most common types of wastewater, with integrated quality criteria, should be included. For this reason, a study was conducted, and the resulting tables of typical wastewater quality are presented in Appendix V.

2.3.5 Technologies: Unit Processes and Treatment Trains

In Appendix VI, most common unit processes are presented in the form of fact sheets, presenting for each technology a process description, and in many cases a diagram or picture, to visualize the process, its main advantages and its disadvantages. Normally, treatment trains are divided in several stages of treatment with different purposes of removal. In wastewater treatment and reclamation, generally the following treatment stages can be distinguished:

- *Primary treatment* involves unit processes, which involve quiescent temporary storage tanks where heavier solids settle to the bottom, and lighter wastewater constituents (e.g., oil, grease and solids with a low specific weight) float to the surface. Settled and floating wastewater constituents are removed, and the remaining primary effluent is either discharged or input into secondary treatment.
- *Secondary treatment* focuses on the removal of biological matter through degradation by microorganisms that are normally present in wastewater. The microorganisms can grow either suspended in the treatment tank (i.e., suspended growth, such as in activated sludge processes and membrane bioreactor) or attached to a medium (i.e., attached growth, such as in trickling filters, rotating biological contactors (RBCs) and

submerged aerated filters). Prior to discharge or tertiary treatment, microorganisms are usually removed from the treated wastewater.

- *Tertiary treatment* can focus on different pollutants depending on constituents in the wastewater stream, the intended discharge area for wastewater treatment (e.g., nutrient sensitive areas) and intended reuse application for reuse schemes.
- *Disinfection* occurs in two primary forms. Depending on the discharge or specific re-use application, treated wastewater can be chemically (e.g., by chlorine) or physically (e.g., by UV radiation) disinfected.

In order to decide which treatment is required to produce water that fits a specific application from a given effluent, the water quality of the effluent and the water quality required by the intended reuse have to be known. Based on the removal efficiencies of unit processes, treatment trains can be proposed. The available water quality and the required water quality for a reuse application is the key to propose applicable unit processes and to design appropriate treatment technology. In general, it is recommended that at least secondary treatment is applied if water is to be reused for various purposes (US-EPA, 2004a). Furthermore, a disinfection step is necessary for reuse with potentially high contact use. Assembling unit processes into treatment trains is a complex task that is central focus of the DSS.

If the option for expert users of the DSS developed in this thesis to define their own treatment train should be left open, the task is outside of the scope of the activities of main stakeholders who might use the DSS. For this reason, a selection listing typical treatment trains should be included in a database. Such a list is presented in Appendix VIII and provide examples from global water-reuse and reclamation practices.

2.4 Water-Loss Reduction

This section reviews the state of the art related to DSSs for water-loss reduction in water distribution systems and various related components. It aims to understand the progress made so far as well as the gaps and needs addressed.

2.4.1 The Challenge of Water-Loss Reduction

In the field of drinking water supply and efficient water management, the topic of water-loss reduction is crucial for a sustainable management of water resources. For many water utilities, tackling water losses is still part of an event-driven strategy, and the long term planning and implementation of a strategic approach is challenging. The topic of water-loss reduction is complex, so gaining an overview and making sound and efficient decisions can be complicated. In effect, analyzing the NRW of a water utility and NRW's causes quickly leads to examination of further underlying aspects, such as related organizational aspects, data, metering and knowledge of the network, human resources, equipment, water tariffs, budgets and managerial commitment, as well as public awareness. Developing a sound strategy for water-loss reduction often involves actions and measures involving crosscutting issues that should be implemented in a coordinated manner.

2.4.2 International Water Association Guidance and the Guidelines for Water-Loss Reduction

The International Water Association (IWA) has developed a wide range of guidance notes and technical documents presented and discussed during international conferences. However, most of the recommendations take time to be applied, as changes in habit are difficult to enforce. For example, a percentage of NRW is still widely used to set performance targets rather than the Infrastructure Leakage Index (ILI) or other more appropriate indicators. Also, the IWA provides its recommendations only in English language, and there is no official translations into other languages (Emmanuel Oertlé & Knobloch, 2011). In this regard, the Strategic Alliance for Water Loss Reduction (Strategic Alliance for Water Loss Reduction, 2016) developed a handbook translated into several languages that supports water utilities around the world to apply the IWA best practices (Fallis et al., 2011b; Schmitt & Oertlé, 2014). The field of water-loss reduction differs from that of water reuse in the sense that it is mostly based on a heuristic approach, and academic research or scientific papers are less important than in the field of wastewater treatment and reuse. This thesis does not propose to review the underlying theory of water-loss reduction; all necessary information is very well documented in the guidelines for water-loss reduction (Fallis et al., 2011b; Emmanuel Oertlé & et al., 2012). The guidelines have become a reference, and they are accompanied by an integrated training concept. Regular trainings for water utilities are conducted around the globe. After several years of experience training staff of water utilities on the topic, a lack of DSSs to support the action planning and implementation of measures was found.

2.4.3 Decision-Support Systems Review

In order to support water utility managers to analyze their present situation of NRW and to develop an adequate strategy, several DSSs and help for calculation are available (Table 2-4). Many DSSs support the calculation of a water balance and main performance indicators based on IWA or other recommendations (EU, national regulations), sometimes including the error calculation according to the 95% confidence limit method. Some DSSs focus on certain water-loss reduction measures, such as pressure management or active leakage control or a more exhaustive list of measures (European Union, 2015; Liemberger, 2017). Other DSSs provide support for auditing water utilities and for the management and development of a strategy (e.g. defining the economic level of leakage). If most listed DSSs (Table 2-4) have useful features for different purposes, there is no DSS with a holistic approach, including everything in a single tool that can be applied worldwide. Furthermore, many of the existing tools require expert knowledge to be correctly applied and analyzed or require the involvement of a consultant.

Table 2-4: Most prominent decision-support system

Name	Main features
ALCCalcs (ILMSS, 2019a)	Active leakage control
AWWA Free Audit Software (AWWA, 2019)	Spreadsheet-based water audit tool designed to help quantify and track water losses associated with water distribution systems and identify areas for improved efficiency and cost recovery; founded upon the principles of the M36 Water Audit methodology (AWWA, 2016)
AZPandNDFCalcs (Lambert, 2019a)	Free software that explains how to identify and record the location of the average zone point and how to calculate the night day factor by analyzing pressure measurements taken at the average zone point
CalcuLEAKator (Koldzo, 2019)	A tool for calculation of water balance and performance indicators in accordance with IWA methodology using a “bottom-up" approach
Checkcalcs (ILMSS, 2019b)	Leakage and pressure management opportunities
ELLCalcs (ILMSS, 2019c)	Economic leakage levels
EurWB&PICalcs (Lambert, 2019b)	Software designed to be used in the “getting started” methodology to provide a quick assessment of current leakage management and “fit for purpose” leakage performance indicators for any utility system or sub-system, with quick and simple sensitivity testing; calculation is based on the EU reference document (European Union, 2015)
PIFastCalcs (ILMSS, 2019d)	Water balance & performance indicators
PressCalcs (ILMSS, 2019e)	Pressure management
Waterloss DSS (Aristotle	Decision-support tool and a prioritized list of measures for con-

Name	Main features
University of Thessaloniki, 2019)	trolling water losses, adapted to regional conditions
WB-Easycalc (Liemberger, 2019)	Multi-lingual water balance and water-loss performance indicator software

2.5 Progress beyond the State of the Art

Several gaps were identified in this literature review, confirming the hypothesis of a lack of available managerial tools, especially for specific aspects where the development of DSS should contribute to those research fields. Based on those identified gaps, several main objectives and key directions for the development of Poseidon and Water Utility Compass can be defined. Those key aspects listed below address the main areas in which the two DSSs developed and will show novel features and progress beyond the state of the art.

1. *Straightforward solutions with clear representation of results*: Decision-support tools are required to assist and simplify handling decision-making with the complexity of sustainable management and help prioritize most adequate options among the plethora of available solutions. For Poseidon, the most adequate solutions should be selected from an uncomplicated assessment. The DSS should assemble and compare treatment trains to propose best-adapted solutions. For Water Utility Compass, the purpose is to present a clear integrated assessment of the water utility, including situation analysis, WU-efficiency, strategy and priorities definition, selection of measures and action planning.
2. *Simple user interface, flexibility and expert mode*: The DSS should be accessible to an audience broader than only technical experts from the field. The user interfaces should be simple to understand even for users not familiar with the field for both DSSs developed in this thesis. The DSS should allow experts to make changes and to add their own input for more detailed studies (especially for Poseidon). It should use spreadsheets (e.g. Microsoft Excel) rather than sophisticated software, which can quickly become outdated or go out of service.
3. *Systemic and holistic approach*: A systemic and holistic approach should be applied to the design of both DSSs. Detailed calculation should be performed in the background (black box) with simple input and output for the user.
4. *Data transparency, local specificities and universality*: The data in the tools should be transparent and allow expert users to fine-tune their results. The DSS should be able to cope with local variables, and it should be possible to adapt the variables in order to ap-

ply the tools anywhere in the world. The tools should include a database of key input required to allow quick assessments (e.g. water quality classes and a list of measures and options). All data used should be shown transparently.

5. *Capacity building*: A capacity-development module should be integrated to the tools or within accompanying material.
6. *Foster implementation*: Poseidon should create and enable the environment and create momentum for more advanced feasibility design studies to lead to the implementation of environmentally sound solutions. The tool Water Utility Compass should create an enabling environment and create momentum for action leading to implementation of adequate solutions.
7. *Availability and future development*: The DSS should be publicly available and allow further development and integration within follow-up projects for continuous development.

2.6 Chapter Summary

Based on the literature review on the context, vulnerability and responses for sustainable water management, the analysis of water reuse and water-loss reduction needs and the DSSs available, the state of the art and progress so far have been assessed. This chapter has reviewed key aspects involved with sustainable water management in order to foster the implementation of solutions for water reuse and water-loss reduction in water distribution networks. It satisfied the first main hypothesis by investigating the lack of managerial tools and gathered the main information required for the development of two innovative DSSs.

CHAPTER 3 METHODOLOGY

3.1 Methodology and Main Hypothesis

This thesis investigates two primary hypotheses that can be decomposed into six main aspects (Figure 3-1). The first main hypothesis suggests that (1) there exists a lack of managerial tools to assist and support the decision-making processes involved in the selection, planning of water reuse and water-loss reduction systems. The second main hypothesis posits that the complexity involved in such decisions may be streamlined with the development of (2) universal and (3) comprehensive DSSs understandable by (4) a wide range of potential users in order to support (5) the selection of options and (6) promote their implementation.

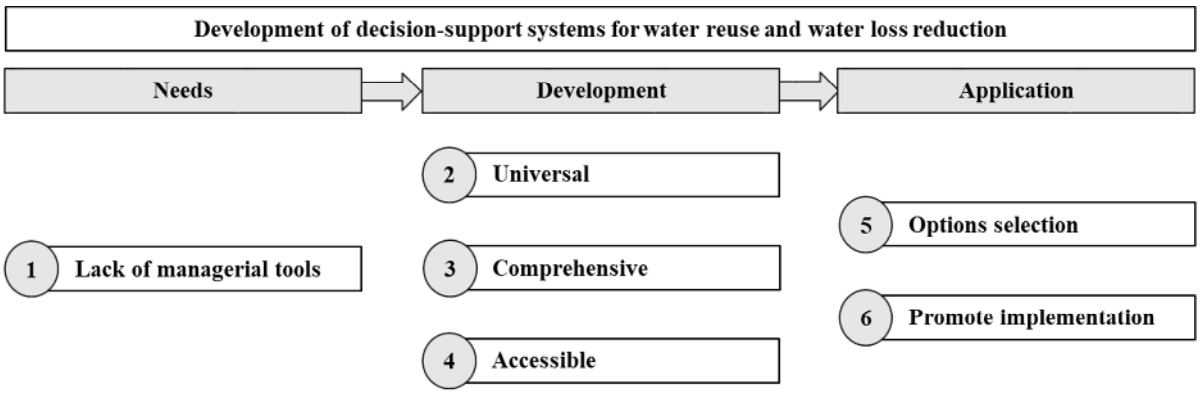


Figure 3-1: Representation of six main aspects of the thesis hypothesis.

In this research, the main hypothesis and its six main aspects are proven as follows:

1. *Lack of managerial tools*: The literature review confirmed the lack of existing managerial tools and identified how to fill the gaps encountered (Section 2.5). Furthermore, the DSS will be published as an open-access resource, addressing the lack of managerial tools available.
2. *Universal*: The universality of the DSSs is considered in this chapter. During the development phase, country profiles where local parameters can be specified and the possibility to apply the DSSs everywhere will be considered, as well as translations to different languages (i.e., for Water Utility Compass). Furthermore, the DSSs will be applied to several different countries with different characteristics and contexts (CHAPTER 4).

3. *Comprehensive*: To develop comprehensive tools, the content and background calculations will be based on reliable published scientific references and expert tools. In order to assess and prove the reliability of the developed DSS, a plausibility check will be conducted in order to compare the simulated results with case studies referenced in the literature (Section 4.2) and will be published in peer-reviewed publications (E. Oertlé, Jurkienė, & Rimeika, 2016; Emmanuel Oertlé et al., 2019).
4. *Accessible to a wide range of users*: To ensure wide accessibility, the user interface will be simple. To prove this accessibility, the DSS will be applied during workshops and capacity-development events, so that the ease of use can be confirmed if participants manage to apply the DSS successfully (CHAPTER 4).
5. *Options selection*: A list of options, measures, technologies and combinations of technologies will be included in the DSS. The application of the DSS will prove that this information can be used to identify and select options for specific cases, making use of options screening and multi-criteria evaluation (Sections 3.2.12 and 3.3.5).
6. *Promote implementation*: The inclusion of aspects beyond technological aspects, such as political, economic, social and legal considerations, should enable the environment to foster implementation of sound options. The application of the DSS will prove that DSSs can play a role in implementation promotion through the development of an action plan for a Lithuanian case study (Section 4.5) and through its application to a Vietnamese case study (Section 4.3).

3.2 Development of a Decision-Support System for Water Reuse: Poseidon

The present section considers the research objectives described in Section 1.4.3 and the gaps identified and summarized in Sections 2.3.1 and 2.5 in order to develop a decision-support system (DSS) for water reuse called “Poseidon.” This section first defines the main objectives of the tool and then presents the background of the tool developed.

3.2.1 Purpose and Objectives Specification

It is supposed that for any case study with a potential for water reuse, a possible treatment train that can meet the requirements exists. As the number of possible technologies and treatment trains is important and requires expertise, the development of a DSS is proposed in order to select possible treatment trains for a given case study with a minimum of input requirements. The concept is that the user should provide data only on the quantity and quality of the foreseen input (wastewater to be treated), the foreseen type of reuse and some information on the local specificities. Based on this input, the DSS should provide three adequate candidate treatment trains that can meet the requirements based on a series of assessment criteria. For this purpose, the DSS has to simplify and minimize the required input by the user to a minimum and provide enough information and flexibility to support capacity-development activities. If this first possible application of the DSS should be very simple and be usable by anybody, the DSS also requires the possibility of more advanced application for experts, where options can be assessed in more detail.

One of the main objectives of Poseidon is to promote water reuse and to show that several treatment trains can achieve the requirements to match the supply and demand of wastewater in zones at risk of water scarcity. The assessment system also contains a wide range of content, descriptions, figures and resources, and it can therefore also be used for capacity-building purposes as well. The assessment should be considered a pre-feasibility study, where options are proposed and can be compared. This pre-feasibility study should lead to awareness-raising among users and stakeholders addressed by this assessment, specifically concerning the potential of water reuse compared, for example, to the exploitation of new water sources. However, the system should not be seen as a design-support system. For further in-depth feasibility studies and designs of treatment trains, more sophisticated models are available (Hamouda et al., 2009) and the intervention of experts, engineers and planners is normally mandatory.

The present research focuses on the pre-feasibility stage and considers potential water-reuse schemes in a systemic approach (Figure 3-2). This focus allows the determination of whether an identified area with potential for water reuse could lead to a feasible reclamation scheme with the current resources, technologies, and available information. A typical pre-feasibility assessment starts with the identification of potential reclaimable water or wastewater (1) and evaluates whether this water could be treated and reused for different purposes (2). Depending on the quality and quantity of available and required water, adequate treatment technologies can be identified and assessed (3). These assessments can include assessing costs, requirements, and impacts, pollutant-removal performance, and additional technical criteria such as reliability, ease of operation, and maintenance to propose the most promising solutions and support the decision to proceed with or abandon reuse options.

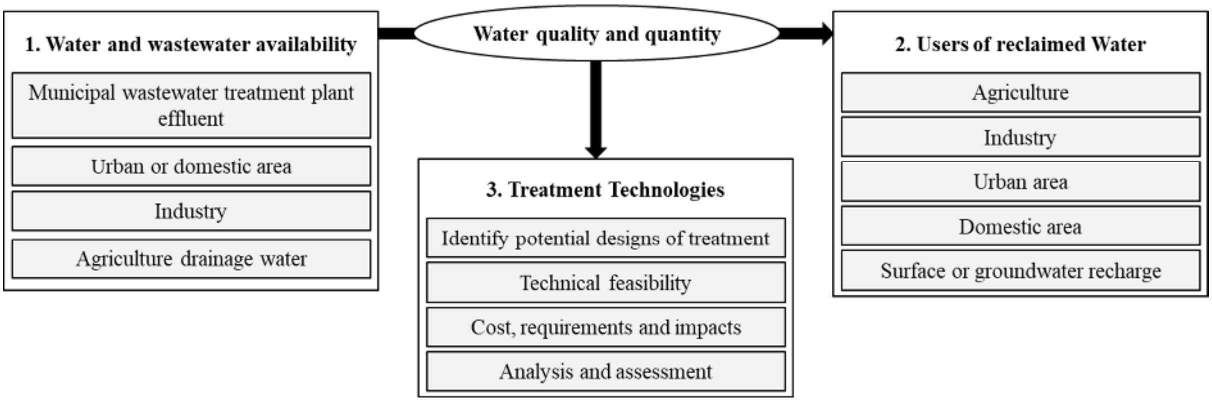


Figure 3-2: Water reuse for pre-feasibility in a systemic approach: (1) wastewater for reuse, (2) type of intended reuse, and (3) identification and assessment of technology.

The system developed in this chapter is intended to cover a very broad range of scenarios for water reuse with results that are understandable by a wide range of users, including non-experts. However, the reality of the implementation of a water-reuse scheme implies additional local specificities and technical details that cannot be included in a system as holistic as the DSS developed. The results obtained should therefore always be considered with care, mostly because of the resulting uncertainties.

3.2.2 Architecture of the Decision-Support System

The architecture of the DSS (Figure 3-3) is an aggregation of several components. The DSS is versatile and offers additional possibilities for expert users.

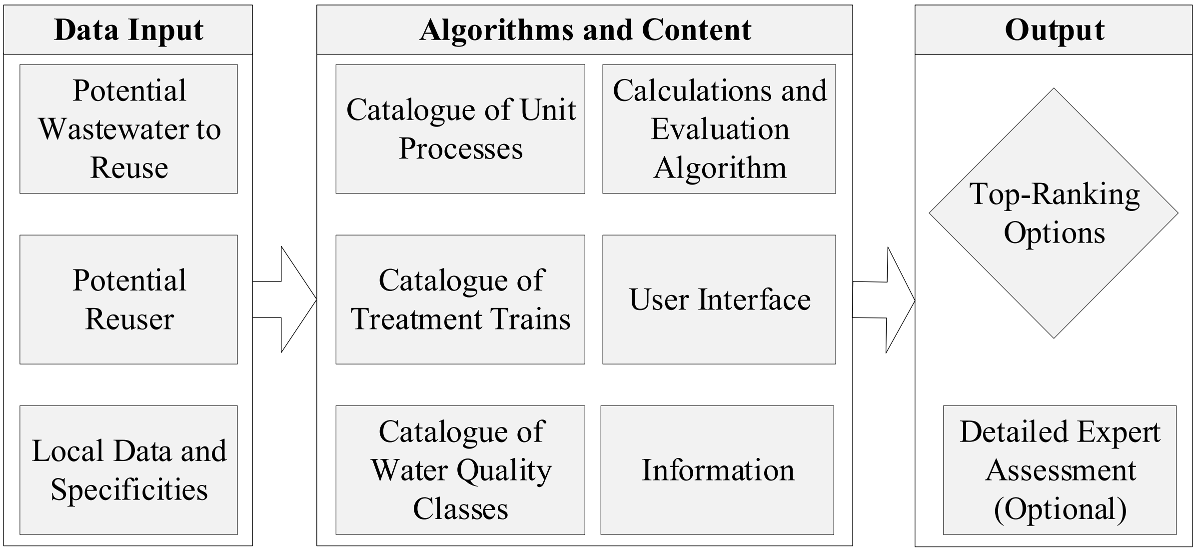


Figure 3-3: Architecture of the proposed decision-support system.

This section presents all the background information required for integration within the DSS (Table 3-1). The different calculations are presented in the following chapters, and the raw data included in the system are presented in Appendix VII.

Table 3-1: Overview of sections describing the development of the decision-support system (DSS) for water reuse

Section (with hyperlinks)	**Content**
3.2.3 Starting Point and Strategic Questions for Application of Decision-Support System :	Required data and typical cases for the application of the DSS
3.2.4 Unit Processes	Unit processes included in the system (Table 3-2)
3.2.5 Treatment Trains	Presentation of the approach, categorization of treatment trains and calculation of pollutant removal performance
3.2.6 Water Quality Parameters and Water Quality Classes	Water quality parameters and water quality classes included in the DSS (Table 3-4)
3.2.8 Lifecycle Cost Estimation	Methodology for the calculation of estimated lifecycle costs
3.2.9 Calculation of Annualized Treatment Costs	Methodology for the calculation of annualized treatment costs
3.2.10 Calculation of Annualized Distribution Costs	Methodology for the calculation of annualized distribution costs
3.2.11 Assessment Criteria	Presentation of assessment criteria included in the DSS
3.2.12 Assessment of Different Water-Reuse	Assessment algorithms included in the DSS

Options or Treatment Trains	
3.2.13 User Interface	Short presentation of the user interface
Appendix V Poseidon – Water Quality Classes Tables	Tables with all water quality classes included, presenting the values for every parameter considered
Appendix VI Poseidon – Unit Processes Factsheets	Description of all unit processes included with figure and key aspects
Appendix VII Poseidon – Unit Process Data	Tables with all data for all unit processes included regarding technical performance and assessment criteria
Appendix VIII Poseidon – Treatment Trains Tables	Table with all treatment trains included in the system, short description and reference
Appendix IX Poseidon – Cost Estimation Tables	Table with coefficients in order to calculate estimate treatment costs component for any unit process and any flow rate
Appendix III Poseidon – Handbook	Short handbook with screenshots presenting the resulting DSS

3.2.3 Starting Point and Strategic Questions for Application of Decision-Support System

Before starting an analysis, preliminary information should be available for the assessment of water-reuse options. For a user who does not know the parameters for certain information, such as water quality parameters or electricity costs, databases with typical values are included in the decision-support system (DSS). The different pieces of information required for a user to perform a quick assessment are as follows:

- available water to be reused (quality, quantity and location);
- intended reuse(s) (quality and quantity required, location);
- community profile composed of several locally-specific information (e.g. electricity costs, labor cost, water tariff, etc., as described in Section 3.2.8.4); and
- several strategies to be analyzed; for example, consider the following:
    1. Given 2,000 m^3/day of wastewater of medium quality at a known location in an Argentinian city, it is envisaged to treat this water in order to reuse it for irrigation of non-food crops. What are the three top-ranking options available, what will be the performance of different options and how much will it cost?
    2. It is planned to reclaim the secondary effluent of a WWTP treating wastewater of about 5,000 inhabitants and to treat its effluent in Mexico for two potential reuses:

one industry that needs water of medium quality no more than 1 km away from the WWTP, and a fruit producer next to the WWTP needs high-quality water. What are the most preferable options available, and what are the foreseen costs of distribution?

3. In Chile, it is foreseen to draw from a new source of freshwater 200 km away from a city of 10,000 people to complement the lack of water availability. On the other hand, it would be feasible to reclaim the wastewater from the city to cover the needs. Which solution would be most cost-efficient? What assessment criteria could be considered in the choice?

For each strategy to analyze and based on the input data provided (available wastewater to be reused, intended reuse and several locally specific characteristics required for the calculation), the system will calculate several parameters:

- *pollutant removal performance* of every treatment train included in the system (Section 3.2.5),
- *lifecycle treatment and distribution costs* (Sections 3.2.8, 3.2.9 and 3.2.10), and
- *assessment criteria* (Section 3.2.11).

3.2.4 Unit Processes

To proceed to the intended type of water reuse, myriad technological options are available. Usually only experts from the field of wastewater treatment and sanitary engineering can rely upon wide knowledge of the set of technologies and their combinations. Water reclamation technologies can be classed as primary, secondary, and tertiary treatments, as well as disinfection. Individual technologies are called “unit processes.” The 37 selected unit processes in the system are shown in Table 3-2 (the selection is based on Adewumi 2011; Joksimović 2006; and personal communications with water-reuse experts).

Table 3-2: List of unit processes considered in the decision-support system

Primary treatment (P)	**Disinfection (D)**
Bar screen	Ozonation
Coarse screen	Chlorine gas
Grit Chamber	Chlorine dioxide
Equalization Basin	Ultraviolet disinfection
Sedimentation without coagulant	
Sedimentation with coagulant	

Anaerobic stabilization ponds	
Secondary Treatment (S)	**Tertiary Treatment (T)**
Activated sludge Low loaded activated sludge without denitrification and secondary sedimentation Low loaded activated sludge with denitrification and secondary sedimentation High loaded activated sludge with secondary sedimentation Extended aeration Trickling filter with secondary sedimentation Rotating biological contactor (RBC) Stabilization ponds: Aerobic Stabilization ponds: Facultative Membrane bioreactor (MBR)	Constructed wetland Enhanced biological phosphorus removal Phosphorous Precipitation Denitrification Dual-media filter Microfiltration Ultrafiltration Nanofiltration Reverse osmosis Activated carbon Ion exchange Advanced oxidation process Soil-aquifer treatment (SAT) Maturation pond Flocculation Electrodialysis

Poseidon – Unit Processes Factsheets provides a description of all included unit processes, and the information is included in the DSS (Appendix VI). Those factsheets are intended as a support for capacity building of users who are not familiar with the different technologies and provide a brief description of each technology as well as a figure that helps explain the basics, so that the user can understand the suggestions made by the DSS.

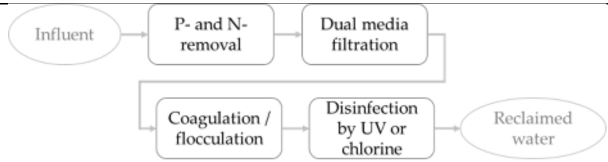
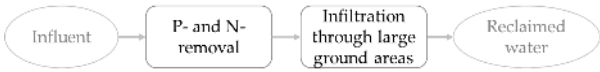
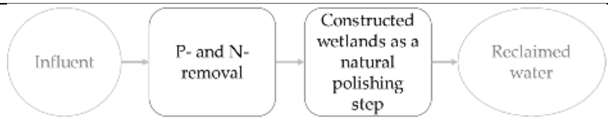
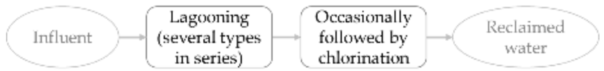
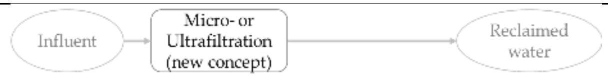
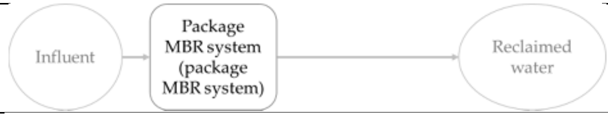
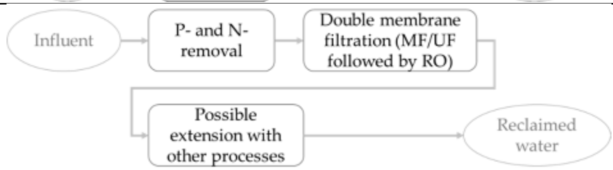
3.2.5 Treatment Trains

As mentioned in the literature review, these unit processes will also be combined and commonly referred to as treatment trains (TTs). For each identified case study with a potential for water reuse, many feasible combinations of technologies may be available to can meet the required pollutant-removal target at the desired treatment cost. Under the applied concept, a water-reuse option has to be composed of a feasible treatment train that fulfills the water quality requirements of the intended uses. The DSS developed contains a list of treatment trains with characteristics such as technical performance on pollutant removals, several assessment criteria, requirements and impacts, and a quantitative cost module to estimate the foreseen costs of treatments. Data is included for each unit process and when assembling a treatment train, those data are combined and the calculation is made in series. The system calculates which of those treatment trains would comply with the requirements defined by the user and presents the top-ranking options to the non-expert user based on the various already-defined characteristics. The term "top-ranking options" should be understood as representing the most adequate feasible solutions based on the assessment criteria included in the DSS, and more detailed design and feasibility studies should be conducted at a later stage.

In the implemented DSS, the combination of those 37 unit processes (Table 3-2) can lead to series of a maximum 10 unit processes per treatment train. If one considers that every single unit process can be a starting point and that every unit process could be used several times, the result statistically leads to about 10^{16} possibilities. Chen and Beck (Chen & Beck, 1997; Hamouda et al., 2009) have noted that if one compiles all possible treatment trains, as many as 50,000 options should be considered as possible trains to identify promising options. Indeed, most of those possibilities are not relevant, and many can be directly eliminated. However, this breadth of possibility shows the complexity of the process to establish an ideal treatment train, given the local situation.

Most existing DSSs are primarily oriented to experts and are already design programs (Hamouda et al., 2009). Those systems are hardly usable and understandable by non-experts or non-specialists in the field of water-reuse technologies. As the developed DSS addresses a broader range of users and aims at promoting water reuse, the approach chosen in the present DSS is to propose a list of the most representative treatment trains. This list is based on best-practice examples and case studies from the literature, as well as from expert interviews. Local water-reuse schemes from Latin America are also included in the DSS, due to the geographical focus of the European project COROADO, which partially funded the current research (“Coroado Project Website,” 2017). At the time of this writing, the list is composed of almost 70 treatment trains. With this approach, the user does not need to be an expert in wastewater treatment technologies to proceed with an analysis, as the non-exhaustive list already provides an overview of the most common possibilities. The system also provides certain features for experts, where it is possible to create up to three user-specific treatment trains and assess the calculated results. A review of benchmark treatment trains leads to a list of treatment trains as examples from global water-reuse and reclamation practices, as detailed in tables the provided in Appendix VIII (Emmanuel Oertlé, 2018b). This appendix includes a list of all treatment trains with the unit processes and the corresponding reference. All treatment trains are categorized in typical basic treatment schemes categories according to van der Graaf et al. (2005) (Table 3-3). The name of the Title 22 benchmark technology originates from the homonymous Californian regulation. If applicable, the specific reuse purpose has been indicated: drinking water, agricultural and environmental purposes, industrial purposes or urban purposes.

Table 3-3: Benchmark treatment trains (Van Der Graaf et al., 2005)

Category	Processes	Possible applications	Treatment trains present in Poseidon (from literature and case studies)
1—Title 22		Reuse variation from urban applications and green landscaping to industrial uses	Benchmark Technology, Italy, Australia, Cyprus, Greece, Spain, USA I, Brazil I, Belgium, Brazil II, Mexico, South Africa
2—Soil aquifer treatment (SAT)		Final water reused for unrestricted irrigation	Benchmark Technology, Israel, USA
3—Wetlands		Reuse in nature conservation or agriculture	Benchmark Technology, Nicaragua, Peru, Brazil, USA, Spain, Mexico, Senegal
4—Lagooning		Reuse of the effluent by (very) restricted irrigation	Benchmark Technology, Israel, France, Australia I, Australia II, South Africa, Argentina, United Arab Emirates
5—Disinfection only		Treated water reused for irrigation under restricted conditions	Benchmark Technology, USA, Chile, Brazil
6—Direct membrane filtration		Treated water reused for agricultural applications	Benchmark Technology, USA, Australia
7—Local membrane bioreactor (MBR)		Reuse of the water in the direct neighborhood (e.g., as toilet flush water)	Benchmark Technology, USA, Brazil, China, Japan
8—High wastewater quality		Treated water of such high quality that many applications (industrial, households, etc.) are possible	Benchmark Technology, Belgium, Singapore, Namibia, The Netherlands, United Kingdom, USA I, USA II

Appendix VII presents the different removal efficiencies (in percentages) of each unit process for each parameter considered (see Table 3-2 and Table 3-4). For each parameter, the removal performance is provided by three percentages: minimum removal efficiency, average removal, and maximum removal efficiency. These data points are used in the DSS to calculate the foreseen water quality after treatment. The different percentages used are set based on the literature (Adewumi, 2011; Joksimović, 2006) and several meetings conducted with experts in the field of water reuse.[1] A unit process is a simplified concept, to be clear, and many different types of technologies fit within the same unit process (different brands and models); furthermore, each technology from each different supplier, applied in different contexts, will perform uniquely. However, those estimated removal performances already provide a good estimate for the pre-feasibility stage intended by the DSS developed. The following equation is used for the calculation of the pollutant-removal efficiency:

$$C_{eff} = C_{inf} \cdot (1 - R_i), R \epsilon \{R_{min}, R_{avg}, R_{max}\}, \quad (4)$$

where,

C_{eff} *is effluent concentration [water quality parameter unit],*

C_{inf} *is influent concentration [water quality parameter unit], and*

R_i *is removal efficiency [%].*

For the pollutant removal calculation of treatment trains, Equation (4) is used in series, the effluent of the first unit process being the influent of the second unit process. It should be noted that this equation uses percentage removal as a simplification and that other DSSs use more advanced models, for example calculating the effluent quality as a function of BOD removed, considering retention time, temperature, or pH (Joksimović, 2006). Nevertheless, this equation is supposed to offer satisfying results for the objectives of the DSS.

[1] Several personal communication was made with selected experts. An important workshop for water reuse technologies experts took place on 6 November 2013 in Muttenz, Switzerland with the participation of Thomas Wintgens, Christian Kazner and Rita Hochstrat and aimed at reviewing, updating and validating unit processes performance and evaluation criteria, typical treatment trains to be considered and general recommendations. The three participating experts have been extremely active in the field of water reuse in the past years through many projects and publications (Davide Bixio, Wintgens, & Bixio, 2006; US-EPA, 2012a).

3.2.6 Water Quality Parameters and Water Quality Classes

Water quality can be defined by an almost indefinite number of parameters: the topic of water quality is immense and has been the subject of many books (Asano et al., 2007; Davide Bixio et al., 2006; Tchobanoglous et al., 2013). The most recent literature on the subject has been reviewed in Section 2.3.4, and two prominent publications on the topic include the World Health Organization (WHO) guidelines and the United States Environmental Protection Agency (US-EPA) guidelines (US-EPA, 2012a; WHO, 2006b; WHO, 2017). The concentration of any substance or constituent potentially present in wastewater could be a parameter to be analyzed, in addition to all physical, chemical and biological parameters that can be measured. This vast subject required a selection of most relevant parameters to be included in the system, and this selection has been based on

- the relevance of several parameters for different intended reuse,
- ease of measuring and monitoring the parameter,
- parameters included in the different quality standards and recommendations,
- selection of parameters from similar studies,
- data availability for removal performance of the different technologies considered, and
- recommendation by water-reuse experts.

After several organized workshops with experts in the field of water reuse (Wintgens, Kazner, Hochstrat, Gross, & Oertlé, 2013), 12 key water quality parameters were considered as most appropriate for the identification and initial assessment of the potential of water-reuse options and were integrated into the DSS (Table 3-4). Future versions of the tool might address more specific types of contaminants, such as microplastics, organic contaminants, emerging pollutants, or specific pollutants of industrial wastewater (e.g., dyes and bleach from textile industry, fungicides and pesticides from agricultural food processing).

Table 3-4: Water quality parameters included in the decision-support system

Water quality parameter	**Acronym**	**Unit**
Turbidity	Turb	[NTU]
Total Suspended Solids	TSS	[mg/l]
Biological Oxygen Demand	BOD	[mg/l]

Water quality parameter	Acronym	Unit
Chemical Oxygen Demand	COD	[mg/l]
Total Nitrogen	TN	[mg/l]
Total Phosphorous	TP	[mg/l]
Fecal Coliform	FC	[CFU/100 ml]
Total Coliform	TC	[CFU/100 ml]
Total Dissolved Solids	TDS	[mg/l]
Nitrate	Nitrate	[mg N-NO_3/l]
Total Organic Carbon	TOC	[mg/l]
Virus	Virus	[PFU/100 ml]

3.2.7 Water Quality Classes

The user of the DSS can independently specify the values of each parameter for the reclaimable wastewater and the requirements for the intended reuse, but if the user is not a specialist or needs support, descriptive water quality classes have been established for the DSS. Appendix X (Emmanuel Oertlé, 2018c) includes the quality classes with the corresponding parameters (from Table 3-4). Please note that some references do not provide limits of constituents for each of the 12 considered parameters. If no value is specified or if no data could be found, a dummy value of "−1" is set in the tables. Three types of water quality classes are considered:

- typical wastewater quality that is intended for reuse (e.g., effluent from a WWTP),
- recommended water quality for and intended use based on international guidelines, such as the WHO or US-EPA (US-EPA, 2012b; WHO, 2006c; WHO, 2017); and
- additional guidelines and regulations, such as local legislation from different countries, considered for the water quality required for different types of intended reuse (e.g., Argentina, Brazil, Chile, Mexico, US-Texas, US-California, Jordan, Eastern Mediterranean regions based on WHO, and the Aquarec project)

As an additional option for the user, it is possible to establish standard quality classes A–E that can be defined by the user. Those classes account for the national legislation and regulations. However, in some cases, different parameters are not specified in the local regulations, and in those cases, it is suggested to use the recommendations from the WHO and from the AQUAREC project. The approach proposed is to define water quality classes for a given region at the beginning of an assessment. In the DSS, these classes are left blank, and water quality parameters can be specified by the user. The quality classes A–E are defined as follows:

- *Class A*: Water quality is *very low*. Water cannot be reused for any purpose, cannot be discharged, and needs treatment.
- *Class B*: Water quality is *low*. Water cannot be reused for any purpose but can be discharged according to the national regulations.
- *Class C*: Water quality is *medium*. Water could be reused for restricted agricultural (food crops not consumed uncooked) or industrial purposes.
- *Class D*: Water quality is *good*. Water could be reused for agriculture and other non-potable uses in industry or in the urban network.
- *Class E*: Water quality is *excellent*. Water could be reused for potable uses.

3.2.8 Lifecycle Cost Estimation

To assess and identify promising options, a typical user initially wants to know whether the proposed technology will meet the technical requirements and achieve the required water quality. If the treatment train achieves the water quality, the next piece of information is the costs of treatment and distribution. It is important to include the costs of distribution from the beginning, as these costs are often significantly higher than are the treatment costs (Figure 3-4) (Hochstrat, Joksimovic, Wintgens, Melin, & Savic, 2007).

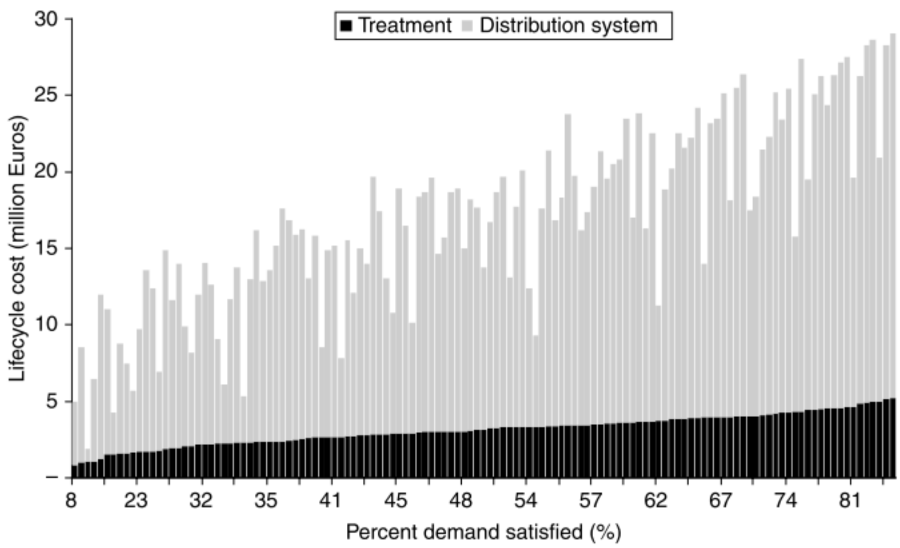


Figure 3-4: Life cycle cost of different water-reuse schemes (Hochstrat et al., 2007).

For this purpose, a cost component has been developed and results in quantitative figures for the total cost of treatment in local currency per cubic meter of reclaimed water, as well as the distribution costs expressed in the same unit. The user can select or define several local parameters, such as the local currency, electricity costs, land costs, labor costs, and reclaimed water-selling price. On this basis, the DSS will estimate overall specific costs automatically.

As costs are sometimes difficult to estimate for such a wide range of technologies considering local specificities and market prices, the uncertainty of the estimation is evidently high (a similar study estimates reasonable accuracy between −30% and +50% of actual costs; Stanford et al. 2013). Nevertheless, the range of calculated values with the DSS provides initial approximations, allowing comparisons between different options at the pre-feasibility stage.

3.2.8.1 Simulations of the program WTRNet conducted as a basis reference for the elaboration of regressions

The cost component is based on the program WTRNet, from the Aquarec Project[2] (Joksimović, 2006). Several flows presented in Table 3-5 with standard pollutant limits defined in Table 3-6 have been tested with the program. A total of 336 simulations have been conducted (i.e., 8 different flows over 42 unit processes), and for each simulation the following results have been collected: construction costs [EUR], land requirement [ha], energy required [kWh/y], labor requirement [person-hour/month], sludge production [ton/y], concentrate production [m^3/y] as well as total annual operation and maintenance cost [EUR/y].

Table 3-5: Different flows considered for the regressions of the cost curves

Average flow [m^3/day]	**Serviced Population [capita]**	**Peak flow [m^3/h]**
10	50	1
20	100	2
200	1,000	20

[2] The project Aquarec has been funded by the European commission and most project results and deliverables are publicly available, such as the manual for water reuse (Davide Bixio et al., 2006).

1,000	5,000	100
2,000	10,000	200
4,000	20,000	400
10,000	50,000	1,000
20,000	100,000	2,000

Table 3-6: Water quality parameters considered for the regressions of the cost curves

Parameter	Unit	Raw Wastewater	Potable reuse
Turbidity	NTU	225	10
Total suspended solids (TSS)	mg/l	250	10
Biological oxygen demand (BOD)	mg/l	220	20
Chemical oxygen demand (COD)	mg/l	600	70
Total nitrogen (TN)	mg/l	55	10
Total phosphorous (TP)	mg/l	9	0.2
Fecal coliforms (FC)	mg/l	1E6	200
Intestinal nematodes eggs (IN Eggs)	No/100 ml	800	0.1

3.2.8.2 Regressions conducted for the elaboration of cost curves

The data collected from the different simulations has been converted to USD from 2006 with a conversion factor of 1.1825[3] and classified in the following categories: construction costs [1,000 USD2006], land requirement [ha], energy required [kWh/y], labor requirement [person-hour/month], as well as total annual operation and maintenance cost including sludge and concentrate production [1,000 USD2006/y]. Sludge and concentrate production have been included within total operation and maintenance costs, for simplification purposes and because few unit processes are concerned. After the conversion and classification step, a total of 336 regressions were performed. Power regressions were applied, as the cost equations from the WTRNet program also follow an exponential pattern. The use of power regressions also makes sense from an economic perspective (i.e., with the concept of economies of scale).

[3] It has been assumed that 2006 is the reference year. It would be possible to include inflation and Construction Cost Index and Building Cost index but this is not in the scope of the present assessment. The currency exchange rate is taken from the European Commission monthly accounting rate of Euro available at http://ec.europa.eu/budget/contracts_grants/info_contracts/inforeuro/inforeuro_en.cfm

In order to simplify the task and not to perform 336 graphics in Excel, a linearization has been performed, and the Excel function LINEST has been applied.

These regressions lead to a database of regression coefficients for every unit process and every cost component category as a function of the average flow rate, as presented in Appendix IX. Each cost factor considered is calculated with an equation in the form of

$$y = a \cdot Q^b, \tag{5}$$

where

Q = average flow [m^3/day];

y = any cost component calculated (construction cost [1,000 USD2006], land requirements [ha], energy requirements [kWh/y], labor requirements [person-hour/month], and other operations and maintenance [1,000 USD2006/y]; and

a, b = resulting coefficients listed in Poseidon.

Only flows with a corresponding cost component value other than 0 have been considered, and inconsistencies have been removed from the regressions. Appendix IX provides all coefficients a and b for all unit processes considered, and Equation (5) can be applied with those coefficients to obtain any cost component for any unit process for any flow between 10 and 20,000 [m^3/day].

3.2.8.3 Deviations from WTRNet database and additional data

Some unit processes are not included in WTRNet, and the following has been added to the database:

- *Equalization tank:* The total annual costs from a concrete tank have been used and calculated as described in Section 3.2.10.2. A retention time of 1 day has been applied.
- *General process activated sludge and extended aeration:* Cost data from high loaded activated sludge + sec. sedimentation have been used.
- *Dual media filter:* Cost data from filtration over fine porous media have been used
- *Denitrification:* Cost data from P-precipitation have been used.

- *Electrodialysis:* Data from ion exchange have been used for the time being, and electricity requirements of 2.9 kWh/m^3 have been applied (Lazarova, Choo, & Cornel, 2012).

3.2.8.4 Community profiles for cost analysis

The developed cost component allows adapting the results to the local conditions by adapting several parameters in so-called “community profiles.” Those parameters are used in the cost calculation to obtain locally specific results. By assembling results obtained with Equation (5) and parameters from Table 3-7, every cost component for any location can be calculated. For each community or study site, the following criteria can be specified.

Table 3-7: Parameters considered in the community profiles for the calculation of the cost component

Parameter	Unit	Default value	Comment
Currency	[CUR]	USD	The reference community is based on USD from 2006.
Exchange rate to USD2006	[CUR / USD2006]	1	To define the exchange rate, it is recommended to use the exchange rate from 2006[4] and to eventually include inflation rate or other evolution factors since 2006.
Land cost	[CUR/ha]	10,000	Acquisition costs and the unit costs for land have to be merged into this overall land cost factor.
Electricity cost	[CUR/kWh]	0.05	Average electricity cost should be used.
Personal cost	[CUR/p-h]	20	Average labor cost should be used covering a mix of different types of personnel (blue and white collar).
Water tariff – households	[CUR/m^3]	2	Selling price of reclaimed water may be indicated.
Water tariff – industry	[CUR/m^3]	2	
Water tariff - agriculture	[CUR/m^3]	2	

[4] The following website from the European Commission offer a currency exchange module for different years:
http://ec.europa.eu/budget/contracts_grants/info_contracts/inforeuro/inforeuro_en.cfm

Parameter	Unit	Default value	Comment
Discount rate	%	8%	
Piping	%	8%	
Controls & Instrumentation	%	8%	
Site electrical	%	9%	
Site development	%	8%	
Site works	%	6%	
Engineering	%	12%	
Contingency	%	12%	

3.2.9 Calculation of Annualized Treatment Costs

For comparable and easily understandable results, we calculated every cost in the local currency per cubic meter (CUR/m^3) of reclaimed water based on the annual lifecycle costs. For this, we calculated every cost component independently as annual cost, and then we summed them to determine the total lifecycle costs for the whole treatment train. The different cost components are calculated for each unit process independently. Then, dividing the "total lifecycle costs for the whole treatment" by the annual volume of reclaimed water, we obtained the annualized treatment costs in (CUR/m^3) of reclaimed water:

$$Treatment\ Cost_{Ann} = \sum_{i=1}^{N} \left(CAPEX_{Ann} + O\&M_{Ann} + Land_{Ann} + Energy_{Ann} + Labour_{Ann}\right) \Big/ V_{Ann}, \tag{6}$$

where

Treatment Cost_{Ann} = annualized unit cost of treatment per m^3 of reclaimed water (CUR/y/m^3),
N = number of unit processes i in the treatment train considered (-),
$\text{CAPEX}_{\text{Ann}}$ = annualized capital cost of unit process i (CUR/y),
$\text{O\&M}_{\text{Ann}}$ = annualized operation and maintenance cost of unit process i (CUR/y),
Land_{Ann} = annualized land cost of unit process i (CUR/y),
$\text{Energy}_{\text{Ann}}$ = yearly energy cost of unit process i (CUR/y),
$\text{Labour}_{\text{Ann}}$ = yearly labor cost of unit process i (CUR/y), and
V_{Ann} = volume of reclaimed water produced annually (m^3/y).

3.2.9.1 Annualized capital costs calculation

In order to calculate the total capital costs for every unit process, the standard capital cost algorithm presented in Table 3-8 has been used. All equipment costs are first calculated with the regressions for the different cost components described before and depending on the flow. It has to be noted that the flow takes into account the recovery percentage of each unit process. For example, if a sequence of two unit processes is considered, with the first unit process having a recovery of 50%, if the inflow in the first unit process is 1,000 [m^3/day], the inflow in the second unit process considered for cost calculation will be 500 [m^3/day].

Table 3-8: Standard capital cost algorithm applied (adapted from US-EPA 2000a; Joksimović 2006)

Factor	**Used in the system**	**Default value**
Equipment cost (EC)	Technology-specific cost from the regressions defined in Section 3.2.8.2.	EC
Installation	Site electrical	9% of EC
	Site development	8% of EC
	Site works	6% of EC
Piping		8% of EC
Instrumentation and controls		8% of EC
Total construction cost (CC)	Equipment + installation + piping + instrumentation and controls	39% of EC
Engineering	12% of total construction cost	12% of CC
Contingency	15% of total construction cost	15% of CC
Total indirect cost	Engineering + contingency	27% of CC
Total capital expenditure (CAPEX)	Total construction cost + Total indirect cost	CAPEX = (1.39*EC)*1.27

Equipment costs and therefore total capital cost for every unit process can be calculated independently for, theoretically, every possible flow between 10 and 20,000 [m^3/day][5]. The resulting total capital costs have to be annualized based on the useful life of every unit process considered. For the annualization, the following capital recovery factor is used:

$$CRF = \frac{r \cdot (1+r)^n}{(1+r)^n - 1} = \frac{r}{1-(1+r)^{-n}}, \qquad (7)$$

where

[5] This is the range of the regressions carried out and described in section 3.2.8.2. The application range might be wider but has not been tested neither validated. It is expected that results are mostly subject to error for very low and very high flows mostly because of the economy of scale effect.

CRF = capital recovery factor [y^{-1}],
r = discount rate[6] [-], and
n = useful life of the unit process [y].

The discount rate is defined by the Fisher equation:

$$r = \frac{1+i}{1+p} - 1 \approx i - p, \tag{8}$$

where
r = discount rate (default value of 8%) [-],
i = interest rate [-], and
p = actual inflation rate [-].

The total capital cost multiplied by CRF results in annualized capital costs.

3.2.9.2 Operation and maintenance costs (OPEX)

The operation and maintenance costs used in the cost component are from the different regressions carried out and costs for sludge and concentrate disposal have been integrated to those costs. Therefore the costs consist in the following (US-EPA, 2000a):

- maintenance (usually 4% of total capital costs),
- taxes and insurance (usually 2% of total capital cost),
- chemicals (lime or calcium hydroxide, polymer, sodium hydroxide, sodium hypochlorite, sulfuric acid, cationic polymer, ferrous sulfate, hydrated lime, sodium sulfide),
- residual management (technology-specific costs),
- sludge disposal, and
- concentrate disposal.

[6] Discount rate takes into account the interest rate and the inflation. Default value of 8% is used.

The land costs, energy costs and labor costs are calculated separately and are not included in operation and maintenance costs. This method allows simplification of the calculations in order to vary those costs to local situations and various electricity, land and labor costs.

3.2.9.3 Land, energy and labor costs

The following parameters are calculated for every unit process:

- land requirement [ha],
- electricity requirement [kWh/year], and
- labor requirements [person-hour/month].

In order to obtain land, energy and labor costs, it is necessary only to multiply those parameters with the corresponding ones from Table 3-7. One obtains electricity and labor costs per year, and for the land costs, an annualization is also necessary. The calculation applied is the same as for the annualization of the total capital costs described in Section 3.2.9.1. An annualization period of 30 years was chosen for the land, and as well as for the application of corresponding land unit costs. This timeframe has been chosen because most unit processes considered have a useful life of 30 years. In practice, this consideration means that if the total cost of land is 100,000 USD with a discount rate of 8% and an annualization period of 30 years, the annual costs would be

$$100{,}000\ [USD] * CRF\ (0.089)\ [y^{-1}] = 8{,}883\ [USD/y], \quad (9)$$

where
CRF = capital recovery factor [y^{-1}].

Using a fixed period of 30 years is a simplification, and the user should be aware that the residual value of the land after 30 years is not considered in the calculation. Furthermore, depending on whether the capital used for buying the land is public or private, differences might ensue; another factor is that the period might be longer. If the period is rather 100 years, the resulting annual land costs would be 8,000 [USD/y], a difference of around 11%. The influence of this difference on the final cost of treatment is insignificant compared to the expected uncertainty of the final cost of treatment calculated with this model. However, the user should be aware of this fact and, for example, if the land is already owned by the user, one should enter that land costs = 0 [CUR/ha].

3.2.10 Calculation of Annualized Distribution Costs

3.2.10.1 Pumps

The calculation for the distribution component have been taken over from Joksimović 2006, based on Heaney, Sample, and Wright (1999) and Oron (1996). The below two main equations are used for the pumping costs calculation.

Pumping capital costs

$$CAPEX = (21{,}715 * H * Q^{0.52}), \tag{10}$$

where

CAPEX = pumping station capital cost [CUR],

H = required pumping head [m], and

Q = design flow rate [l/s].

Note: In addition, 5% of the capital cost is used for annual maintenance. For the annualization of the capital costs, a useful life of 15 years is used, and the same procedure with the capital recovery factor is applied.

Pumping energy required

$$CE = \theta_{hp} \cdot C_e \cdot \frac{V_{ann} \cdot H}{2.7 \cdot \eta}, \tag{11}$$

where

CE = annual cost of energy required for pumping [CUR],

θ_{hp} = conversion factor to kWh (θ_{hp}= 0.746),

C_e = unit cost of energy [CUR/kWh],

V_{ann} = volume of water pumped annually [m^3],

H = pressure head required at the pump [m], and

η = pump efficiency [%], (default value of 65%).

3.2.10.2 Storage facilities

Four different types of storage are considered: reservoir, concrete tank, covered concrete tank, and earthen basin. The following equation is applied for cost calculation:

$$UCS = C_1 \cdot V^{C_2}, \tag{12}$$

where

UCS = unit cost of storage facility [CUR],

C_i = cost coefficients from Table 3-9, and

V = storage volume [m^3],

Note: In addition, 0.5% of the capital cost is used for annual maintenance. For the annualization of the capital costs, a useful life of 30 years is used, and the same procedure with the capital recovery factor is applied.

Table 3-9: Storage facilities cost coefficients (Joksimović 2006)

Storage type	C_1	C_2
Reservoir	15,093	−0.60
Concrete tank	1,238	−0.19
Covered concrete tank	5,575	−0.39
Earthen basin	128	−0.24

3.2.10.3 Pipe

The cost curves for the pipe cost also come from (Joksimović, 2006) that derived the equations from data on the costs of installed pipes provided by United Kingdom water companies, reported in Stone et al. (2002). The model proposes pipe costs coefficients for three different types of land use: grassland, rural or suburban, and urban. The following equation is applied:

$$CP = C_1 \cdot e^{C_2 \cdot D}, \tag{13}$$

where

CP = pipe unit cost [CUR/m],

C_i = cost coefficients from Table 3-10, and

D = pipe diameter [m].

Note: In addition, 3% of the capital cost is used for annual maintenance. For the annualization of the capital costs, a useful life of 50 years is used, and the same procedure is applied with the capital recovery factor.

Table 3-10: Pipe unit cost coefficients (Joksimović 2006)

Land use	**C_1**	**C_2**
Grassland	47.47	3.51
Rural/suburban	96.19	3.07
Urban	129.42	2.72

3.2.10.4 Required parameters

Based on the cost curves equations described in previous chapters, the parameters presented in Table 3-11 are required in order to calculate all incurred distribution costs.

Table 3-11: Input parameters required for the calculation of the distribution costs

Parameter	**Unit**	**Note**
Length of pipe	[m]	Defined by the user
Pipe diameter (D)	[mm]	Calculated by the simple design model presented in Section 3.2.10.7
Elevation (+uphill, -downhill)	[m]	Defined by the user; please note that a negative elevation will not bring revenue to the model but will only annihilate the head due to friction and result in costs of zero.
Volume of water pumped annually (V_{ann})	[m^3]	Calculated by the system based on the flow (if the distribution is before the treatment the inflow is used, if it is after the treatment, the flow calculated with the treatment train recovery is used)
Pressure head required at the pump (H)	[m]	Calculated with the Hazen–Williams equation as described in Section 3.2.10.6
Design flow rate (Q)	[l/s]	Calculated by the system based on the flow (if the distribution is before the treatment the inflow is used, if it is after the treatment, the flow calculated with the treatment train recovery is used)
Storage volume (V)	[m^3]	Defined by the user

The biggest challenge in estimating costs for distribution is to estimate the appropriate design, namely the diameter of the pipes that will influence the velocity, pumping costs and piping costs. Once the design is fixed, the head loss can be calculated and added to the elevation in order to calculate the pressure head required for pumping.

3.2.10.5 Calculation of the frictional head loss

In order to calculate the pressure head required for pumping, the Hazen–Williams equation is used (see Equation (14)). Note that the Hazen–Williams formula is empirical and lacks a theoretical basis. Be aware that the roughness coefficients are based on "normal" conditions with approximately 1 m/s (Engineering Toolbox Website, 2017).

$$h_f = L \cdot \left(\frac{10.67 \cdot Q^{1.85}}{C^{1.85} \cdot d^{4.87}} \right), \tag{14}$$

where
h_f = head loss over the length of pipe [m],
L = length of pipe [m],
Q = volumetric flow rate [m^3/s],
C = pipe roughness coefficient (default value of 140), and
d = inside pipe diameter [m].
Note: In the DSS, the equation using imperial units is used and converted to metric units.

3.2.10.6 Calculation of the pressure head required for pumping

$$H = h_f + Elevation, \tag{15}$$

where
H = pressure head required at the pump [m],
h_f = head loss over the length of pipe [m], and
Elevation = altitude difference between the beginning and end of the pipe, positive or negative [m].

3.2.10.7 Simple design model for the definition of the pipe diameter

One can see that the only unknown parameter is the inside pipe diameter. In order to determine this parameter, the assumption has been made that the velocity of the fluid should be 1 m/s. If the water velocity is fixed, one can obtain the internal diameter using the following equation:

$$d = 2000 \cdot \sqrt{\frac{Q}{v \cdot \pi}}, \tag{16}$$

where

d = inside pipe diameter [m],

Q = volumetric flow rate [m^3/s], and

v = flow velocity [m/s] (default value of 1).

3.2.10.8 Calculation of the total annual distribution lifecycle costs

For comparable and easily understandable results, the distribution costs were also calculated in costs per cubic meter of reclaimed water based on the annual lifecycle costs. The calculation of the total annual distribution of lifecycle costs allows the consideration of one transport pipe from the wastewater source to the treatment scheme, a storage tank, and another transport pipe to the end-use location (Figure 3-5). Equation (16) is applied for the calculation of the annualized distribution costs per cubic meter of reclaimed water.

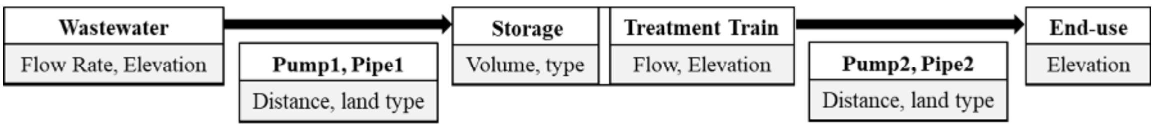


Figure 3-5: Schematic representation of the distribution components and information required for the cost calculation (grey).

$$Dist_{Ann} = Pump1_{Ann} + Pipe1_{Ann} + Storage_{Ann} + Pump2_{Ann} + Pipe2_{Ann}, \tag{17}$$

where

$\mathrm{Dist_{Ann}}$ = total annual distribution cost [CUR/y],

$\mathrm{Pump1_{Ann}}$ = annualized pumping costs [CUR/y],

$\mathrm{Pipe1_{Ann}}$ = annualized piping costs [CUR/y],

$\mathrm{Storage_{Ann}}$ = annualized storage costs [CUR/y],

$\mathrm{Pump2_{Ann}}$ = annualized pumping costs [CUR/y], and

$\mathrm{Pipe2_{Ann}}$ = annualized piping costs [CUR/y].

Then, in order to obtain the annualized distribution costs in [CUR] per cubic meters of reclaimed water, the following equation is applied:

$$Distribution\ cost_{Ann} = \frac{Dist_{Ann}}{V_{Ann}}, \tag{18}$$

where

$\text{Distribution cost}_{\text{Ann}}$ = annualized unit cost of distribution per cubic meter of reclaimed water [CUR/y/m^3],

Dist_{Ann} = total annual distribution cost [CUR/y], and

V_{Ann} = volume of reclaimed water produced annually [m^3].

3.2.11 Assessment Criteria

In addition to the pollutants removal performance and the quantitative cost component, the DSS also considers additional assessment criteria, requirements and impacts described in this chapter. As for the other components, for this component a database assigns the different values for each unit process independently, and the treatment train assessment criteria are calculated as described below. Some criteria are fixed per unit process based on work by Urkiaga et al. (2006), and some are derived from quantitative results (e.g. cost of treatment) and therefore dependent on the condition specified by the user (e.g. volume of water treated, cost of electricity, etc.). This section is divided by the following subjects:

- technical assessment criteria of the treatment trains (Section 3.2.11.1),
- requirements and impacts (Section 3.2.11.2), and
- normalized costs component (Section 3.2.11.3).

3.2.11.1 Technical assessment criteria

In addition to the pollutant removal, technical assessment criteria refer to desired effects from the installation of a certain process (see Table 18). Important factors include the reliability of the process, the ease of upgrading if the wastewater stream increases (e.g. population growth), adaptability to varying wastewater flows (e.g. seasonal differences), adaptability to varying influent wastewater quality, ease of operation and management (e.g. requirements for specially trained personnel, dosing of certain substances), ease of construction (e.g. overall estimate of the ease to install a unit process based on additional installations required, human resources and specialists needed, etc.), and ease of demonstration. These 7 indicators are qualitative, and a value is provided for each unit process in a database presented in Appendix VII.

Table 3-12: Technical assessment criteria

Assessment criteria (AC) (0 = nil, 1 = low, 2 = medium, and 3 = high)						
Reliability (Qualitative)	**Ease to upgrade** (Qualitative)	**Adaptability to varying flow** (Qualitative)	**Adaptability to varying quality** (Qualitative)	**Ease of operations and maintenance** (Qualitative)	**Ease of construction** (Qualitative)	**Ease of demonstration** (Qualitative)

The calculation of an average assessment criteria score for different treatment trains is made using the following equation:

$$AC_i^{TT} = \frac{\sum_j^N AC_{ij}^{UP}}{N}, \tag{19}$$

where

AC_i^{TT} = treatment train average assessment criteria score for criteria i [-],

AC_{ij}^{UP} = assessment criteria i value for unit process j [-], and

N = number of unit processes in the treatment train [-].

3.2.11.2 Technical and environmental requirements and impacts

Significant operational requirements and environmental impacts are evaluated for each unit process (see Table 19). These requirements and impacts include differences in energy demand (which is often the most important operational cost), chemical demand (e.g. chloride), land requirements (area needed to install a certain unit process), and effects on groundwater, odor generation, and quantity of sludge production (depending on available area and transport infrastructure, generated sludge can lead to significant cost for transport and disposal).

Table 3-13: Requirements and impacts assessment criteria

Requirements and impacts (RI) (0 = nil, 1 = low, 2 = medium, and 3 = high)						
Power demand (Semi-quantitative)	**Chemical demand** (Qualitative)	**Odor generation** (Qualitative)	**Impact on groundwater** (Qualitative)	**Land requirement** (Semi-quantitative)	**Cost of treatment** (Semi-quantitative)	**Quantity of sludge production** (Semi-quantitative)

For the requirements and impact based on qualitative data, every unit process has an assigned value provided in Appendix VII. For the semi-quantitative ones, the value is based on regressions presented in Appendix IX, based on the flow. Each value is calculated individually and depends on values entered by the user. The treatment train aggregated score is calculated with the following process (and described in Equation (20)):

- summing up the scores of every unit processes involved in the treatment train,
- *normalization*: dividing the sum by the highest criteria value from all treatment trains considered, and
- multiplication by 3 in order to obtain values in the range [0;3];

$$RI_i^{TT} = 3 * \left(\frac{\sum_j^N RI_{ij}^{UP}}{MAX \overbrace{\left\{ \sum_j^N RI_{ij}^{UP} \right\}}^{i}} \right) \tag{20}$$

where

$\mathrm{RI}_i^{\mathrm{TT}}$ = treatment train average requirements and impacts criteria score for criteria *i* [-],

$\mathrm{RI}_{ij}^{\mathrm{UP}}$ = requirement and impact criteria *i* value for unit process *j* [-], and

N = number of unit processes in the treatment train [-].

3.2.11.3 Costs

Table 3-14: Costs assessment criteria

Costs (0 = nil, 1 = low, 2 = medium, and 3 = high)						
Annualized capital cost (Semi-quantitative)	**Land cost** (Semi-quantitative)	**Energy cost** (Semi-quantitative)	**Labor** (Semi-quantitative)	**Operations & maintenance: others** (Semi-quantitative)	**Total annualized costs** (Semi-quantitative)	

The calculation for cost assessment criteria (Table 3-14) is the same as the one used for the requirements and impacts:

$$C_i^{TT} = 3 * \left(\frac{\sum_j^N C_{ij}^{UP}}{MAX \overbrace{\left\{\sum_j^N C_{ij}^{UP}\right\}}^{i}} \right), \tag{21}$$

where

C_i^{TT} = treatment train average requirements and impacts criteria score for criteria i [-],

C_{ij}^{UP} = requirement and impact criteria i value for unit process j [-], and

N = number of unit processes in the treatment train [-].

3.2.12 Assessment of Different Water-Reuse Options or Treatment Trains

Based on those assessments, the DSS proposes an assessment algorithm that calculates the three best possible candidates, as presented in Figure 3-6. Every parameter is calculated for every treatment train included in the system and the three treatment trains that can be defined by the user. The algorithm proposes three different assessment methods to select the three best candidates within the list. The first possibility (1) eliminates all treatment trains that do not comply with the quality requirements (based on the maximal removal performance of each unit process). Then, a ranking is made based on the weights for each single indicator defined by the user. The second possibility (2) first eliminates all treatment trains that do not comply with the required quality and then ranks the three options with the lowest lifecycle treatment costs calculated. The user can then evaluate the three options by analyzing the whole set of assessment criteria calculated. The third possibility (3) is primarily intended for experts and allows a manual selection of the top-ranking options based on a subjective assessment of all assessment criteria presented. The details of the methodology applied and calculations involved are presented in Section 3.2.12.1.

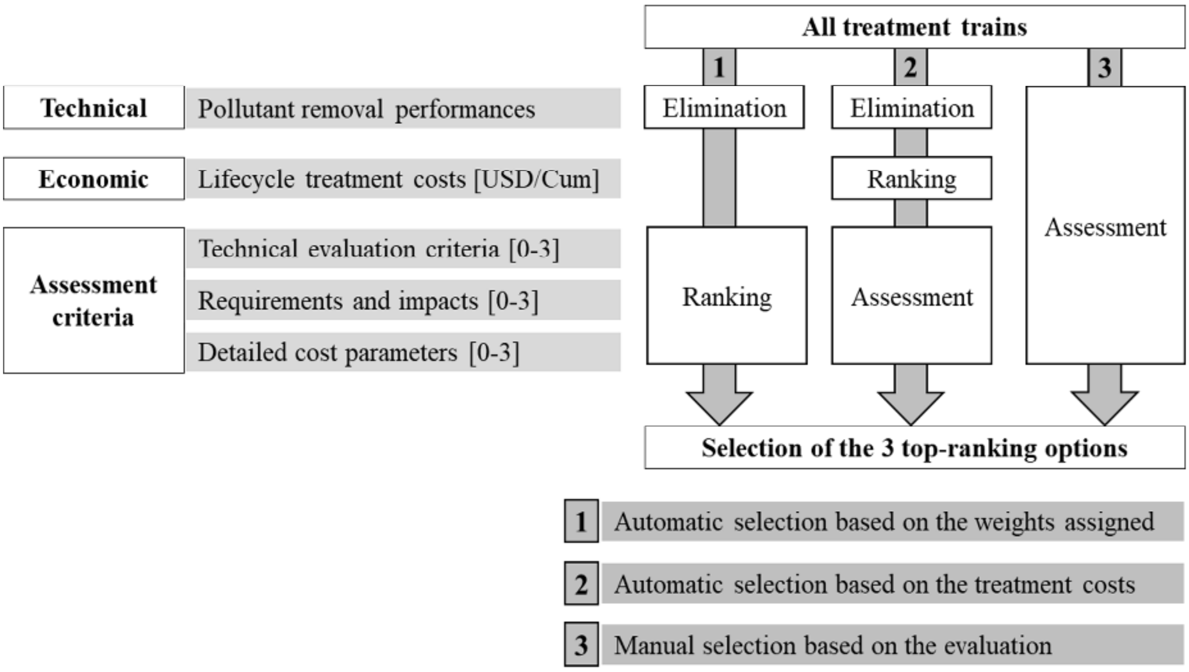


Figure 3-6: Assessment algorithm proposed.

3.2.12.1 Ranking, filtering, assessment and selection

Water-reuse systems and applicable unit processes cannot be selected based only on removal efficiencies of wastewater constituents and costs. In order to choose reuse systems, which are adapted to the local environmental, economic and social conditions, different systems and their unit processes should be compared based on defined selection criteria, such as energy requirements, land requirements, ease of construction or any of the assessment criteria included in the system. At a preliminary stage, different options need to be discussed between different stakeholders, and often a community consultation process is either required or recommended. It is therefore useful to have a strong knowledge not only regarding removal efficiencies, but also environmental, economic and social aspects.

3.2.12.2 Calculation of an overall treatment train assessment score

For the calculation of a treatment train's overall assessment score, the weights that can be user defined are used, and the following process is applied:

- The user specifies the importance of the different assessment criteria and requirements and impacts in the following range (0–4):
  0. *not important (not considered),*
  1. *not very important,*

2. *regular,*
3. *important, or*
4. *very important.*

- The following criteria are normalized to a value between 0 and 1 (The criteria defined before between 0 and 3 are divided by 3 and the quantitative criteria, divided by the highest value of the list of treatment trains considered).
- For the criteria evaluated as negative (requirement and impacts, costs), the formula 1-NC_i^{TT} is applied in order to make every value in positive for the overall assessment score.

The calculation of the treatment train overall assessment score is made using the following equation:

$$OA^{TT} = 3 \cdot \left(\frac{\sum_{i=1}^{M} W_i \cdot NC_i^{TT}}{\sum W_i} \right), \tag{22}$$

where

OA^{TT} = treatment train overall assessment score [-] (range 0–3),
W_i = weight of criteria *i* [-] (range 0–4, user-defined),
NC_i^{TT} = normalized criteria *i* score [-] (range 0–1), and
M = number of assessment criteria [-].

3.2.13 User Interface

Information presented in Section 3.2 has been integrated in a user-friendly interface based on Microsoft Excel. More details and guidance for use are presented in Appendix III.

3.2.14 Chapter Summary

The methodology presented in the previous sections for the development of the DSS results in a database of unit processes and treatment trains with corresponding parameters. This database allows calculation and presentation of pollutant-removal efficiencies, quantitative lifecycle treatment and distribution costs, assessment scores (based on a range of criteria and factsheets and information on technologies), typical treatment trains, quality classes, and additional general topics. The algorithm applied calculates everything for any case to be assessed and then proposes a screening-ranking methodology in order to present three most adequate solutions based on results and weighting applied. Furthermore, some further assessment is offered to expert users, for example the possibility to add additional treatment trains, add more unit processes, define water quality of influent and requirements for effluent, customize the distribution design, or make a personalized assessment of results. The whole tool is embedded in a user-friendly interface based on Microsoft Excel, and the background information and calculation algorithms can be potentially integrated in other programs and interfaces.

3.3 Development of a Decision-Support System for Water-Loss Reduction: Water Utility Compass

3.3.1 Introduction

This thesis presents the development of a decision-support system (DSS) aiming to apply a holistic approach for water-loss reduction and includes most relevant features in a single Microsoft Excel File, whose results can be easily understood by non-experts and managers of the water utility. As the topic of water-loss reduction involves more considerations than only isolated and uncoordinated measures, this innovative approach considers main business areas of water utilities influencing water losses in a systemic way in order to identify priority areas. The DSS should also support the calculation of key performance indicators, including error calculation, and propose a list of measures in order to support the elaboration of an adequate and realistic action plan.

3.3.2 Architecture of Water Utility Compass

The DSS Water Utility Compass follows the steps presented in Figure 1-1: assessment, strategy development, implementation, monitoring and back to assessment. It is split into four sections, each with a different focus (Table 3-15).

Table 3-15: Structure and components of the Water Utility Compass

Water Utility Compass		
Data Input	**Situation Analysis**	**Action Plan**
▪ Water utility data ▪ Self-assessment questionnaire	▪ IWA water balance ▪ Water utility efficiency compass ▪ Performance indicators ▪ What-if analysis	▪ Suggested priorities and measures ▪ Development of a simple action plan
Knowledge Base ▪ Glossary, references ▪ Performance indicators formula and benchmarks		

The first section (Data Input) contains most of the forms for user input, including a tab that collects the most important statistics about the water supply company and a self-assessment questionnaire composed of 14 main categories influencing the efficiency of a water utility and its NRW. The second section (Situation Analysis) presents some analytical results based on the data from the first section. The computation of the water balance included is based on the IWA standard as well as several performance indicators, and the error is calculated with the 95% confidence limit method for every value and performance indicator (Helena Alegre et al., 2016). The second section also includes the possibility of varying the value of several performance indicators and some of the input values to analyze potential changes, identify the potential for improvement, and set targets. Those two sections together allow the users to analyze their current status in the area of water-loss reduction as well as identify the remaining potential for improvement and priority areas.

The third section guides the user in the right direction regarding possible future actions to take. First, the user has to choose several areas to focus on; the program then lists suitable measures to tackle each of those areas based on the self-assessment questionnaire. This list allows the user to create a simple tailor-made action plan. In addition, commonly used and more detailed measures are also included, which can support the user to gather supplementary ideas. The last tab creates and compiles a simple action plan for the user containing the selected measures as well as measures entered manually by the user. All output from the DSS can be copied and exported to either create a presentation or a report using the generated data, calculation, analysis, charts and action plan table. Finally, the last section contains background information and references to online available documents in case the user requires more detailed explanation or more detailed information on selected topics (Farley et al., 2008; Kingdom et al., 2006).

3.3.3 Data Input

The user will indicate the specifications about the utility in this section. The input required includes numerical data on water quantities, costs and technical information on the distribution network. It also includes qualitative information optionally supported by a questionnaire for a self-assessment. The provided data are the initial source for the following assessment steps of the DSS.

3.3.3.1 Water utility data

The water utility data to be indicated are divided into 5 main categories:

- *General indications*: name of utility or area considered, reference period, duration (measurement period), country and country type (developing or developed country for benchmarking purposes);
- *System input volume and authorized consumption*: own sources, water imported, water exported—billed metered, billed unmetered, unbilled metered, unbilled unmetered consumptions;
- *Water losses*: total apparent losses if known or based on a calculation using unauthorized consumption, illegal connections, people per household, average consumption, meter tampering, bypasses at registered customer, average consumption, other illegal connections, customer meter inaccuracies, and data-handling errors;
- *Network*: length of mains, number of active and inactive customer service connections, average length of service connection, total pipeline length, number of fire hydrants, and their average length;
- *Management and monitoring*: average operating pressure, minimum supposed operating pressure, continuity of supply, pipe material, leaks on mains, leaks on service connections, average flow rate of the reported leaks, and average duration of the leaks; and
- *Financial data*: selected currency, water tariff (sales price) excluding value-added tax (VAT), direct water production and distribution costs including VAT, annual financial losses, and annual budget for water-loss reduction.

Most of those data are usually available in water utilities. Nevertheless, flexibility should be offered to the user, and mandatory data are indicated with an asterisk in the DSS. Furthermore, most components are linked to a corresponding entry in the glossary to explain what data should be considered for each component.

For several data, different input methods are possible for the user. As an example, unbilled unmetered consumption may be indicated in cubic meters or percentages of system input volume, depending on which unit is more familiar for the user. Another example is the calculation of apparent losses. The user can indicate total apparent losses directly in cubic meters of water or by inserting values for unauthorized consumption, meter inaccuracies, and data handling errors that are then automatically analyzed and calculated to obtain a value for total apparent losses. This choice of indications shall give the user more flexibility and increase the quality of the data acquired.

Another innovative feature included in the data input section is to consider data reliability and accuracy. For most of the data to be provided, the user should also specify the source of the data and if it is measured (2% default error margin), or estimated (50% default error margin), or if error margin can be specified (manual entry of error margin). Those error margins are considered for every calculation included in the DSS.

3.3.3.2 Self-assessment questionnaire

The self-assessment considers 14 main categories related to water-loss reduction (Table 3-16). Those categories are based on six years of work experience with the strategic alliance for water-loss reduction and many interactions with engineers and managers from water utilities around the world.

Table 3-16: Main water utility efficiency categories included in the decision-support system for water-loss reduction

Water Utility Efficiency Categories for Water-Loss Reduction	
1. Data & Metering	8. Operation & Maintenance
2. Network Documentation	9. Apparent Losses
3. Water Balance & Perf. Indic. (PI)	10. Human Resources
4. District Metered Areas (DMA)	11. Equipment and Budget
5. Active Leakage Control (ALC)	12. Organization
6. Pressure Management (PM)	13. Managerial Commitment
7. Infrastructure Management (IM)	14. Public Awareness

For each category, the user should define two scores between 1 and 5, from 1 (*very low*) to 5 (*very high*) in order to define the status and the goal to be achieved in a medium timeframe. This scoring allows further identification of the efficiency level and improvement potential for different categories.

The user (either water utility staff or an external consultant) has the option to indicate those qualitative scores in a subjective manner based on that user's knowledge and assessment of the water utility. In addition, a questionnaire is also available in order to provide guidance and support the self-assessment (see Appendix XI). This questionnaire is based on several references (AWWA, 2016; Charalambous, 2014; Malcolm Farley, Gary Wyeth, Zainuddin Bin Md. Ghazali, Arie Istandar, & Sher Singh, 2010) and provides a concrete framework to define what is level 1 and what is level 5. It also allows comparing several water utilities in terms of performance. For each category, a score is calculated by averaging the score of all questions answered in the given category. The use of the questionnaire is optional, and its results can be adjusted by the user.

3.3.4 Situation Analysis

The situation analysis section makes use of the data input to calculate useful information to analyze the current situation of the water utility and identify the potential for improvement. The section integrates main calculations usually integrated in other tools (e.g. WB-Easycalc, AWWA Free Audit Software, PIFastCalcs) and contains the IWA water balance, several charts for NRW (including the water utility efficiency compass), and performance indicators; it furthermore proposes a what-if analysis, letting the user analyze how changes in parameters could influence water losses, finances, and performance indicators.

3.3.4.1 International Water Association water balance and non-revenue water charts

Calculating the International Water Association (IWA) water balance is one of the first steps to analyze water losses. In the DSS, calculation is performed according to IWA standards, including the calculation of error using the 95% confidence limit approach (Lambert, 2003). It is possible for the user to visualize different types of water balances: water quantity with error margin, percentage of system input, error bounds (minimum and maximum value), and financial costs (production and selling costs).

The water balance is also represented in a graphical form, and several additional charts are included in the DSS that can be easily understood by managers and non-experts. For example, the maximal financial annual savings that can be attained with water-loss reduction are graphically represented.

Regarding the WU-efficiency based on the self-assessment presented in Section 3.3.3.2, the results are presented in the form of a spider diagram (Figure 3-7) that can easily be understood. The difference between status and goals represents the potential for improvement, and this graphic supports the identification of priorities for measures and strategy development.

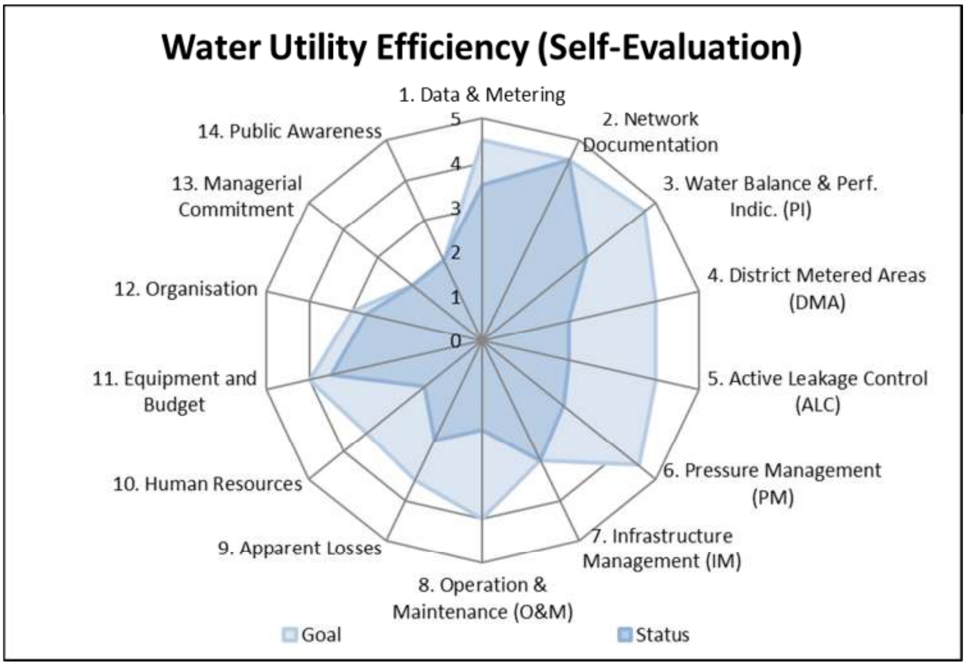


Figure 3-7: Water utility efficiency result for the fictive case of Neustadt.

3.3.4.2 Performance indicators

Performance indicators are calculated to assess water utilities present status, to analyze progress from years to year and to compare their performances with other water utilities (benchmarking with international performing classes). The calculation of performance indicators, together with the IWA water balance, supports the analysis of a water utility strengths, weaknesses and potentials for water-loss reduction in order to set targets. Most widespread performance indicators are included in the DSS (e.g. Infrastructure Leakage Index [ILI], Pressure Management Index [PMI], Apparent Leakage Index [ALI], etc.), and all include the calculation of the error using the 95% confidence limit method, something that has not been done before (Helena Alegre et al., 2016).

To compute the 95% confidence limits, two basic formulas are applied. If two values are added or subtracted (e.g. $V_{SystemInput} = V_{OwnSources} + V_{Import} - V_{Export}$ where V stands for Volume), the variances of the variables are added up ($Var_{SI} = Var_{OS} + Var_I - Var_E$), where $Var_X = (x * \varepsilon_X / 1.96)^2$, x is the actual value, and ε_X is the corresponding estimated error. In the case of the values being multiplied or divided (e.g. $ILI = CARL/UARL$), a slightly different formula is used: $\varepsilon_{ILI} = \sqrt{\varepsilon_{CARL}^2 + \varepsilon_{UARL}^2}$.

The list of performance indicators, their formula, description and values used for the benchmarking are presented in Appendix XIII. Figure 3-8 presents the DSS calculation of the ILI, one of the most robust indicators of real water losses: the resulting value is indicated, along with the error level and the grade performance according to international performance classes (in this case A–D). The user then has the possibility to enter a target value that could be a potential strategic objective, and a new calculation indicates the changes with this new value: the new performing grade and the potential water savings in quantity percentage and financial terms.

Performance indicator	Unit	Indicator value	Error [%]	Performing grade	Target value	Target performing grade	Water saving [m³*a⁻¹]	Water saving [%] of NRW	Water saving [€*a⁻¹]
ILI - Infrastructure Leakage Index	[-]	9.8	12.1	D	6	C	272,145.53	29.2	54,429.11

Figure 3-8: Decision-support system calculation of the Infrastructure Leakage Index (ILI) for the fictive case of Neustadt.

3.3.4.3 What-if analysis

The what-if analysis is a concept developed in the tool WB-EasyCalc (Liemberger, 2019) an understanding of the influence of several parameters on water losses, finances, and performance indicators. A similar approach has been included in Water Utility Compass, as shown in Figure 3-9. The parameters of real losses, apparent losses, unbilled authorized consumption, average supply time, and operating pressure can be varied, and the effects of these variations are automatically calculated.

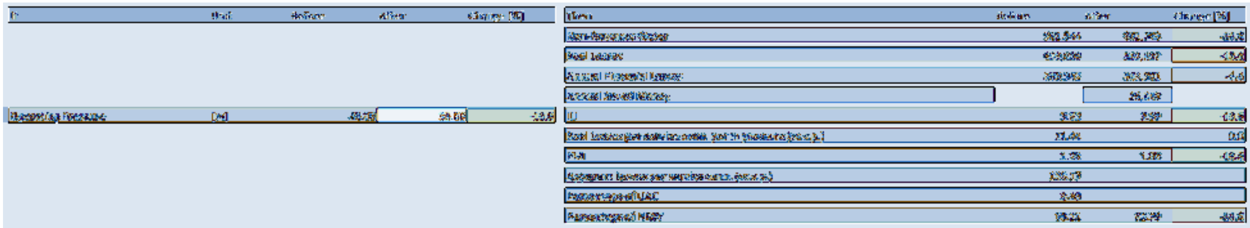


Figure 3-9: What-if analysis integrated in the decision-support system for the fictive case of Neustadt.

3.3.5 Suggested Priorities, Measures and Action Planning

Water-loss reduction is a complex topic involving many considerations. It is therefore important to define a vision and strategy that can be realistically implemented with the resources at disposition. In this section, the user can define a mission and select areas to focus on in priority.

After formulating a mission and identifying up to 10 strategic objectives, the user can assign measures to each objective. For this purpose, a database of more than 250 measures is included in the DSS; many measures are based on the tool from Waterloss project (Waterloss Project, 2012). This database, presented in Appendix XII, is linked with the answers from the self-assessment questionnaire, and based on the status and objectives, the most adequate measures are automatically proposed. Furthermore, the user also has the option to browse all included measures, perform a search, or to add a custom formulated measure.

Finally, the DSS includes a rough sketch of the elaboration of an action plan to achieve the formulated goals. This final output can easily be exported, together with other results of the assessment to be used in presentations or reports.

3.3.6 Chapter Summary

This chapter has presented the methodology applied for the development of an innovative DSS for water-loss reduction. The tool has an architecture that aims at supporting water utility engineers, managers and consultants to perform an assessment of the water utility situation, defining a strategy and elaborate an action plan with realistic objectives and measures. The tool includes data error calculation and a list of measures automatically suggested to the user based on the assessment and fixed objectives. The tool is embedded in a user-friendly interface based on Microsoft Excel, and the background information and calculation algorithms can be integrated in other programs and interfaces at a later stage.

CHAPTER 4 CASE STUDIES AND APPLICATIONS

4.1 Introduction

This chapter presents several applications and plausibility checks conducted with the two developed decision-support systems (DSSs). For water reuse with Poseidon, the resulting DSS is applied and compared with known case studies in order to assess the reliability and accuracy of the proposed treatment trains. It is also applied to Vietnamese case studies within the context of a study tour with local stakeholders. As the DSS had primarily been developed for four Latin American countries (Argentina, Brazil, Chile and Mexico), its application to different locations demonstrates the universality of the developed DSS stated in the hypothesis. For water-loss reduction, Water Utility Compass was applied to the case of Alytus water utility in Lithuania and within several capacity-building activities around the world (Figure 4-1). Both DSSs have also been applied to additional cases. For example, Poseidon is integrated within the Coroado project's online DSS, which is focused on Latin America, and Water Utility Compass has been applied to a major Swiss water utility, but the results cannot be published for reasons of confidentiality.

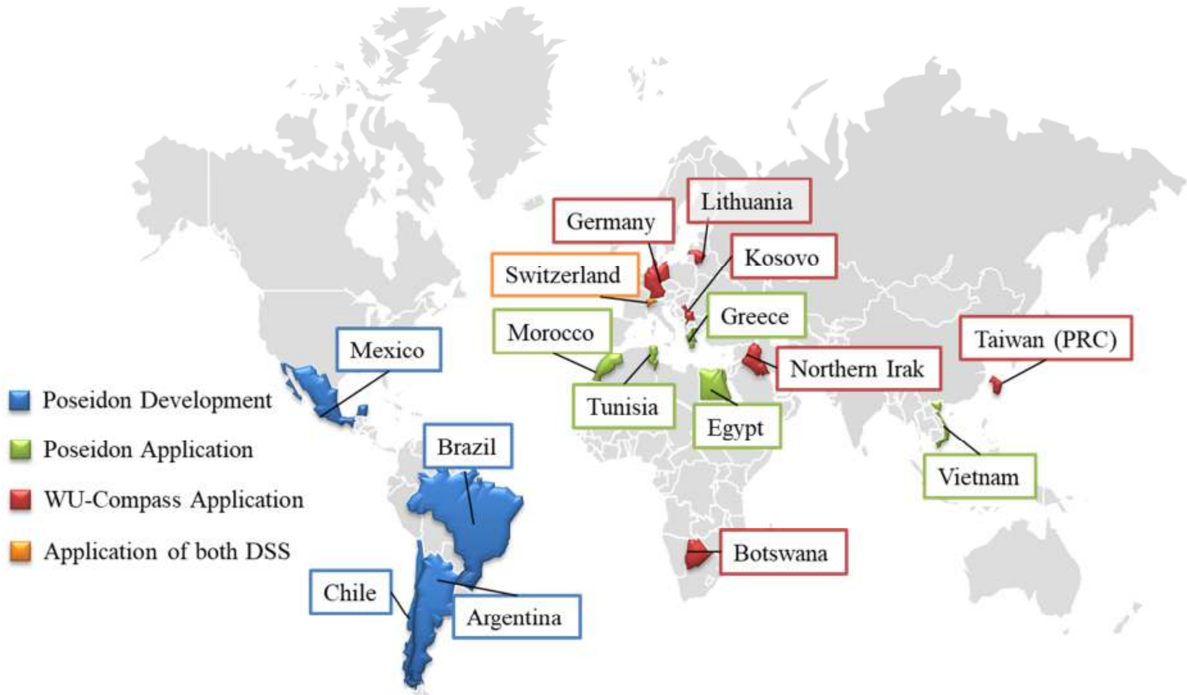


Figure 4-1: Different applications countries of the developed decision-support system.

4.2 Water Reuse – Accuracy and Reliability of Poseidon: Plausibility Check

To assess the plausibility of the calculated results with the DSS, in a first stage, 13 treatment trains were simulated based on literature review (Table 4-1) (Asano et al., 2007; US-EPA, 2004a). In a second stage, the resulting removal performance of pollutants included in the reference were compared under the same indicated wastewater quality (Figure 4-2).

Table 4-1: Treatment trains considered for the plausibility checks (Asano et al., 2007; US-EPA, 2004a)

Process type and location	**Unit processes used in the DSS**
P1 - Jamnagar Export Refinery Project	Equalization basin; low-loaded activated sludge with de-N + sec. sedimentation; dual-media filtration; activated carbon; chlorine dioxide
P2 - Water resource management V Valley	Chlorine gas; dual-media filter; ultrafiltration; activated carbon; chlorine gas
P3 - Recirculating vertical flow constructed wetland (RVFCW) Israel/Peru	Constructed wetland; dual-media filtration; UV-disinfection
P4 - Mexico-San Luis Potosi Agricultural reuse	Grit chamber; sedimentation with coagulant; constructed wetland
P5 - Mexico San Luis Potosi. Industrial reuse	Grit chamber; sedimentation with coagulant; low loaded activated sludge + secondary sedimentation; dual-media filtration; ion exchange
P6 - Beetham WWTP Trinidad and Tobago	Bar screen; grit chamber; extended aeration; sedimentation without coagulant; UV disinfection
P7 - Emergency potable reuse in Chanute Kansas	Bar screen; grit chamber; sedimentation with coagulation; trickling filter with secondary sedimentation; chlorine gas
P8 - Direct potable reuse treatment process Denver-Ultrafiltration	Sedimentation with coagulant; dual-media filtration; UV disinfection; activated carbon; ultrafiltration; ozonation; chlorine gas
P9 - Direct potable reuse treatment process Denver-Reverse osmosis	Sedimentation with coagulant; dual-media filtration; UV disinfection; activated carbon; reverse osmosis; ozonation; chlorine gas
P10 - Constructed wetlands Turkey	Anaerobic stabilization pond; constructed wetland
P11 - Title 22 Greece	Bar screen; grit chamber; sedimentation without coagulant; low loaded activated sludge with de-N + sec. sedimentation; dual-media filter; chlorine dioxide
P12 - Soil Aquifer Treatment Israel	Bar screen; grit chamber; low loaded activated sludge with de-N + sec. sedimentation; soil aquifer treatment; chlorine gas
P13 - Building MBR- Japan	Bar screen; grit chamber; MBR; activated carbon; chlorine dioxide

In Figure 4-2 the pollutant-removal efficiencies simulated are compared to the literature value for all included parameters. More than 70% of all considered parameters of removal efficiency have less than 20% difference between the literature value and the simulated results. Nevertheless, the relative error is smaller for seven parameters (BOD, COD, TSS, fecal coliform [FC], turbidity, total coliform [TC] and TOC), whereas four parameters show a higher relative error (total nitrogen [TN], total dissolved solids [TDS], total phosphorous [TP] and nitrates) (Figure 4-3). If only the removal efficiency of the first seven parameters is considered, around 90% of all parameters have less than 20% difference between the reported value in the literature value and the simulated results.

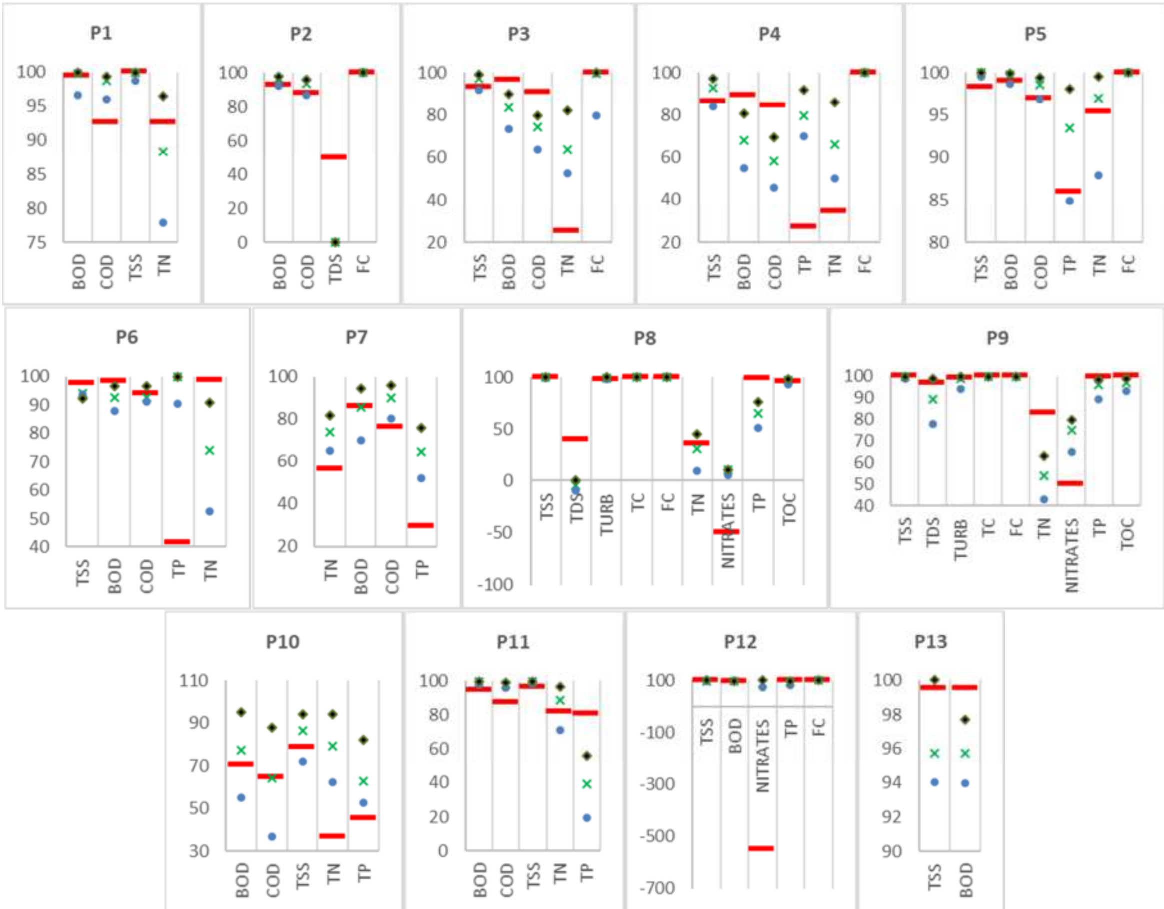


Figure 4-2: Plausibility check of the 13 simulations P1–13 results. The y-axis *shows pollutant-removal efficiencies [%] for the literature value (–) and for the decision-support system simulation operating under minimal (●), average (✕) and maximal (◆) unit processes efficiencies.*

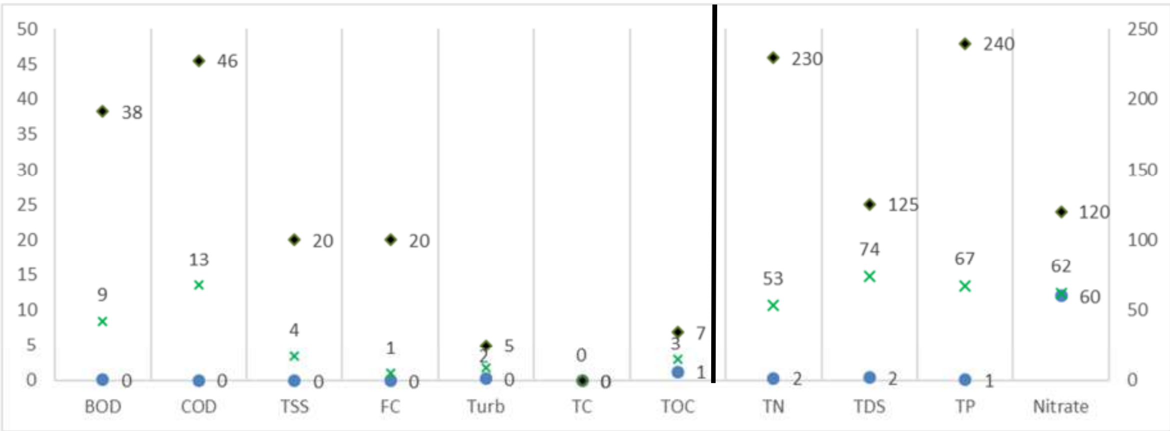


Figure 4-3: The y-axis presents the relative error for different water quality parameters in [%]. The first 7 parameters simulation operating under minimal (●), average (✕) and maximal (◆) unit processes efficiencies refer to the primary axis on the left, and the last 4 parameters, to the secondary axis on the right.

The higher relative error for TDS and nitrates occurs because in some unit processes, the TDS (and the conductivity) increases. This explanation applies for the nitrates as well, since their concentration increases after the nitrification processes. These concentration increases would require a more sophisticated model that is beyond the scope of the present DSS. The discrepancy of the TN and the TP results is due to simplifying the modelled process compared to the reference processes and probably some inaccuracies in the removal performances database for those two parameters.

As a result, those estimated removal performances provide a first estimate for the pre-feasibility stage intended by the DSS developed. While applying the DSS to a case study, the user should consider the results of the presented plausibility checks and consider the results for TN, TP, TDS and Nitrate only as suggestive.

The cost component described in the previous chapters offers an important piece of information for the assessment, comparison, and selection of the different treatment trains, as cost is often one of the key aspects considered. Using annualized costs per cubic meter enables easy comparison and understanding of the influence of different factors and whether required additional costs are also calculated (e.g. total capital expenditures [CAPEX]). If different treatment trains are more seriously considered, a deeper cost assessment should be conducted: “Therefore, despite a considerable body of literature reporting costs of unit processes and their combinations, planning level estimates of treatment options are not easily transferable from existing projects, and are generally produced with a wide margin of accuracy of −30% to +50% (Landon et al. 2003).”

4.3 Water Reuse - Application to Vietnam

This section applies Poseidon and demonstrates the main features and content of this innovative DSS. The DSS uses a new holistic approach through its application in the case of Vietnam. As the DSS had primarily been developed for four Latin American countries (Argentina, Brazil, Chile and Mexico), its application to a different country from another continent demonstrates its transferability across contexts (see universal aspect of the second main hypothesis). This application is published in the *Journal of Vietnamese Environment* (in press).

4.3.1 Introduction

While Southeast Asian countries, and Vietnam in particular, are facing challenges in sustaining water security, water reclamation has received increasing consideration as a favorable mitigating solution. Despite the availability of adequate technologies and constraints regarding economy, policy, legislation, society, and environment, stakeholders and decision makers often resist exploiting the potential to implement solutions. First, we present the results of an application of a decision-support system (DSS) for evaluating water reclamation, supporting pre-feasibility studies, and capacity building for water reclamation in Vietnam. The developed DSS and its data are open access and provide information for local and international water and wastewater quality standards. The DSS supports the promotion of water reclamation and the commissioning of more detailed feasibility studies. In this research, we identified case studies with high potential in the Vietnamese context, and the DSS was applied to identify adequate technologies that comply with local environment. Second, we conducted a systematic evaluation, the Political, institutional, social, technological, legal, and economic (PISTLE) analysis considering six dimensions (political, institutional, social, technical, legal, and economic) in the frame of a multiple local stakeholder workshop. The results identify key barriers and drivers of the implementation of several water reclamation measures to overcome the identified barriers. The results presented here can serve as a starting point for the development of water reclamation applications in Vietnam.

This research was carried out in relation to an initiative of the United Nations Industrial Development Organization (UNIDO) and an educational workshop of 17 local stakeholders to Switzerland on 10 May 2019. This workshop was part of an educational tour in Switzerland of eco-industrial parks, and it aimed to understand the potential for water reuse in Vietnam. The first objective of this workshop was to introduce the topic of water reclamation in a presentation, as it is currently not applied in Vietnam. The second objective was to demonstrate that water reclamation could have potential utility in selected exemplary case studies and to propose a preliminary ranking of technological options. The Vietnamese legal and regulatory context allows the reuse of treated wastewater (Government of Vietnam, 2012). As water reuse is not yet implemented in Vietnam, however, the third objective was to identify barriers and drivers for the implementation of water reuse and discuss necessary measures that could foster implementation during stakeholder dialogue.

In this section, the application of a decision-support system (DSS) for evaluating the potential for water reclamation in Vietnam is presented. The DSS's objective is to identify technological options that can treat wastewater to the desired quality for several representative case studies.

4.3.2 The Vietnamese Case Study

4.3.2.1 Water security and integrated water management in Vietnam

Water pollution is one of the most critical environmental issues in Vietnam. The Ministry of Natural Resources and Environment states that almost 80% of the diseases in Vietnam are caused by polluted water. Industrial zones discharge an estimated 1 million m^3 of untreated wastewater per day directly into receiving water bodies (Ministry of Foreign Affairs Netherlands, 2018). While domestic wastewater is mainly treated in household's septic tanks, only a small share of it is actually treated (10%). An even smaller share (4%) is safely disposed.

While many urban wastewater projects have been accepted, most of them are not part of a comprehensive integrated water management concept and are being implemented on a case-by-case basis. It seems that urban developers also often delay construction of their wastewater treatment components, in order to reduce capital and operation costs (World Bank, 2013).

Provincial or city budgets cover most of the costs related to operation and maintenance of drainage and wastewater treatment systems, but this budget meets only about 10–20% of costs for collection systems and excludes the operation and maintenance costs of WWTPs.

Income from wastewater operations is mostly generated through a wastewater surcharge on the water bills of customers (Ministry of Foreign Affairs Netherlands, 2018).

Without much investment, 30% of water could be saved in the sectors of textiles, food processing, and leather. Investment opportunities may exist through initiatives of the (donor-funded) development of "eco-industrial parks" to make existing industrial zones more sustainable—for example with the provision of techniques for wastewater treatment and the recovery of nutrients. In this direction, UNIDO has initiated projects in the catchment areas of the two largest rivers in Vietnam: the Mekong River and Red River (Ministry of Foreign Affairs Netherlands, 2018).

Since 1995, Vietnam has constantly adapted regulations and standards to meet wastewater challenges. While these adaptations have improved the legal framework and set the basis for eco-industrial parks through many changes, they also created uncertainty among local governments for designing and implementing wastewater projects (Ministry of Foreign Affairs Netherlands, 2018).

Vietnam has a comprehensive legal framework in environmental sanitation, including urban wastewater management, but with certain shortcomings. Overly ambitious and sometimes conflicting targets for environmental protection and wastewater collection and treatment are included in legal documents. There is a lack of synchronization as well as overlaps and gaps in the regulations prepared by various ministries. Additionally, few incentives are provided to encourage private-sector investment in the wastewater business (World Bank, 2013).

Deficiencies outside of the legal frameworks include limited personnel and funding for environmental monitoring, insufficient enforcement because of corruption and inadequate resources, low penalties for noncompliance, and little public disclosure of industrial pollution information (Ministry of Foreign Affairs Netherlands, 2018).

4.3.2.2 Typical wastewater quality in Vietnam, regulations and selected case studies

No official regulations for wastewater use exist in Vietnam, except for maximum TC for effluent discharge to surface water (US-EPA, 2012a). Regulations currently applied are for effluent standards and have undergone significant changes since the first standard was issued in 1995. Current effluent standards in Vietnam specify water quality parameters in terms of Class A and Class B depending on whether treated wastewater is discharged to water bodies with a function of drinking water supply (Class A) or not (Class B) (World Bank, 2013). For water use in agriculture, the national technical regulation on water quality for irrigation (QCVN 39: 2011/BTNMT) applies (Phuong & Nguyen, 2013).

In Appendix X, typical wastewater qualities from municipal wastewater for 12 water-quality parameters are compiled. Most effluent qualities (after treatment) meet the water quality standard class A (discharge with drinking water function), and all effluent qualities meet the parameters of class B (discharge without drinking water function). Regarding irrigation water quality, only two parameters from the regulation correspond to the selected set of 12 parameters: FC and TDS. However, no information was found on those parameters from typical wastewater.

To proceed with an exemplary assessment, it has been decided to make use of national and international guidelines for water quality requirements and typical wastewater quality profiles types that have been established based on Vietnamese data and complemented with international typical qualities for unknown parameters (Asano et al., 2007; World Bank, 2013). If available, the water quality parameters values from Hanoi have been considered (Kim Lien); otherwise, values based on typical international case studies have been considered (Appendix X). Based on this research, eight case studies for water reuse in Vietnam have been established (Table 4-2), and the corresponding water qualities considered are presented in Table 4-3.

Table 4-2. Selected case studies (wastewater type, quantity and intended reuse)

Case N°	Wastewater	Quantity [m^3/d]	Reuse
1 - A	Typical untreated municipal wastewater (MWW) Vietnam	10,000	Agricultural irrigation of non-food crops (ISO Guidelines, cat. C)
1 - B	Typical treated wastewater (WW) Vietnam		
2 - A	Typical untreated MWW Vietnam	10,000	Restricted urban irrigation and agricultural irrigation of processed food crops (ISO Guidelines, cat. B)
2 - B	Typical treated WW Vietnam		
3 - A	Typical untreated MWW Vietnam	10,000	Unrestricted urban irrigation and agricultural irrigation of food crops consumed raw (ISO

3 - B	Typical treated WW Vietnam		Guidelines, cat. A)
4 - A	Typical EIP Effluent – before treatment	1,000	Industrial Reuse- Recirculating Cooling Towers (Texas EPA):
4 - B	Typical EIP Effluent – after treatment		

Table 4-3: Selected wastewater and water quality requirements

Water quality classes	**Turb** NTU	**TSS** mg/L	**BOD** mg/L	**COD** mg/L	**TN** mg/L	**TP** mg/L	**FC** CFU/100 ml	**TC** CFU/100 ml	**TDS** mg/L	**Nitrate** mg N/L	**TOC** mg/L
ISO-Guidelines											
Cat. A: irrigation of food crops consumed raw	5	10	10	-	-	-	-	100	-	-	-
Cat. B: irrigation of processed food crops	-	25	20	-	-	-	-	1,000	-	-	-
Cat. C: irrigation of non-food crops	-	50	35	-	-	-	-	10,000	-	-	-
Texas Water reuse Standards											
Texas EPA: Industrial Reuse- Recirculating Cooling Towers	-	-	20.00	-	-	-	200.00	-	-	-	-
Typical MWW in Vietnam											
Typical untreated MWW Vietnam	100	86	94	189	44	-	10,000	1E+07	720	18	140
Typical treated WW Vietnam	2	6	11	22	16	-	-	10,000	500	3	10
Typical Industrial Park WW in Vietnam											
Typical IP Effluent – before treatment	-	200	200	400	60	8	-	3,000	-	-	-
Typical IP Effluent – after treatment	-	49.5	29.7	49.5	14.85	3.96	-	3,000	-	-	-
Typical River in Vietnam											
Typical River Vietnam	-	205	67	-	-	-	-	-	-	-	-

4.3.3 Materials and Methods

4.3.3.1 Decision-support system for water reuse (Poseidon)

To enable the assessment of the defined case studies, the Poseidon DSS has been used (Emmanuel Oertlé et al., 2019) and complemented with additional Vietnamese and international data. The wastewater quality data, as well as various regulations, have been included in the DSS. Furthermore, key data for national cost calculation have been included (Table 4-4). Poseidon DSS is available as open access at the Zenodo repository: http://doi.org/10.5281/zenodo.1971933 (Emmanuel Oertlé, 2018a).

Table 4-4. Parameters considered in the Vietnamese community profiles for the calculation of the cost component

Parameters	Unit	Default value	Reference	Comment
Currency	[VND]	Vietnamese Dong		The reference community is based on USD from 2006.
Exchange rate to USD2006	[VND / USD]	16,191 (2006) 20,418	(European Commission, 2019) (Coinnews Media Group LLC, 2018)	To define the exchange rate, it is recommended to use the exchange rate from 2006 and to include inflation rate or other evolution factors since 2006. (European Commission, 2018)
Land cost	[VND/m2]	2,500,000	(World Bank, 2015)	Acquisition costs and the unit costs for land have to be merged into this overall land cost factor.
Electricity cost 2018	[USD/kWh]	0.07	(GlobalPetrolPrices.com 2018)	Average electricity cost should be used.
Personal cost	[VND/per month]	37,500,000	(Arcadis Vietnam Co. Ltd, 2017)	Minimum wage for enterprises operating in region I (most expensive)
Discount rate (r) 7.10.2017	%/a	4.25%/a	(Central Intelligence Agency, 2019)	Discount rate r = nominal interest rate (i) – actual inflation rate (p)

The DSS was applied to every case study defined (Figure 4-4). The top-ranking options for treatment trains that shows the lowest lifecycle treatment cost (in USD per cubic meter) and based on the following weighting of assessment criteria (Figure 4-5) are presented as results.

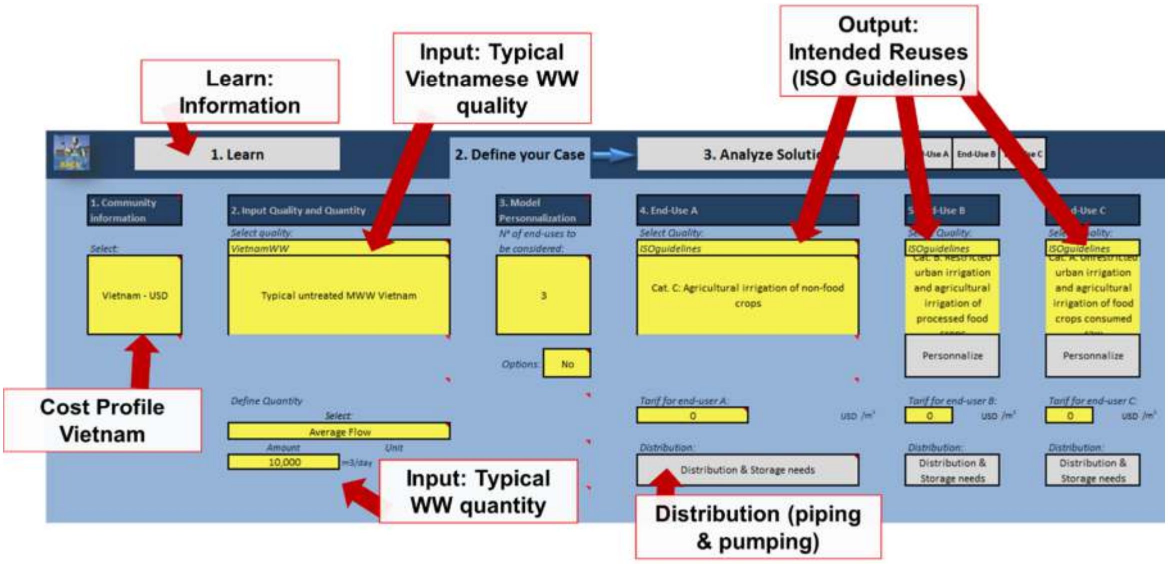


Figure 4-4: Application of Poseidon.

Technical evaluation		Requirements and impacts	
Reliability	Important	**Power demand**	Regular
Ease to upgrade	Not important (not considered)	**Chemical demand**	Not important (not considered)
Adaptability to varying flow	Not important (not considered)	**Odor generation**	Not important (not considered)
Adaptability to varying quality	Important	**Impact on ground water**	Not important (not considered)
Ease of O & M	Very Important	**Land requirment**	Not important (not considered)
Ease of construction	Not important (not considered)	**Cost of treatment**	Important
Ease of demonstration	Not important (not considered)	**Quantity of sludge production**	Not important (not considered)

Figure 4-5: Weighting profile applied with assessment criteria for multi criteria analysis with information on qualitative or semi-quantitative aspect.

4.3.3.2 Workshop and Vietnamese delegation

The stakeholders of the workshop were representatives from the Government of Vietnam and key experts from different ministries (Ministry of Planning and Investment, Ministry of Construction, Ministry of Finance, Ministry of Science and Technology, and Ministry of Natural Resources and Environment). Furthermore, the workshop was attended by park managers (Ninh Binh, Da Nang Hightech Park and Can Tho Processing Industrial Zones) and relevant stakeholders engaged in industrial park management and industrial production (representatives from the project implementation team for the eco-industrial park initiative for sustainable industrial zones and from the Vietnam Academy of Social Sciences). During the workshop, the stakeholders were trained to strengthen the Vietnamese national capacity towards the implementation of Decree 82, in particular its eco-industrial park elements. The objective was to support the key Vietnamese ministries and authorities in drafting and endorsing the ministerial circulars on eco-industrial park development. Wastewater management is a crucial aspect of industrial-park management, and as stakeholders are involved at various levels of influence in Vietnam, it was decided to include the topic of water reclamation in the workshop.

In preparation for the workshop in Switzerland, efforts were made to gather relevant data integrated into the current research. The DSS was applied with the stakeholders for the selected case studies. After the presentation of the results, a guided stakeholder dialogue was conducted that articulated by the following questions:

1. Potential for water reuse in Vietnam: how do you perceive the potential for water reuse in Vietnam? What type of reuse has the most potential?
2. What are the main barriers and drivers of water reuse in Vietnam?
3. What measures would be necessary to overcome the identified barriers?

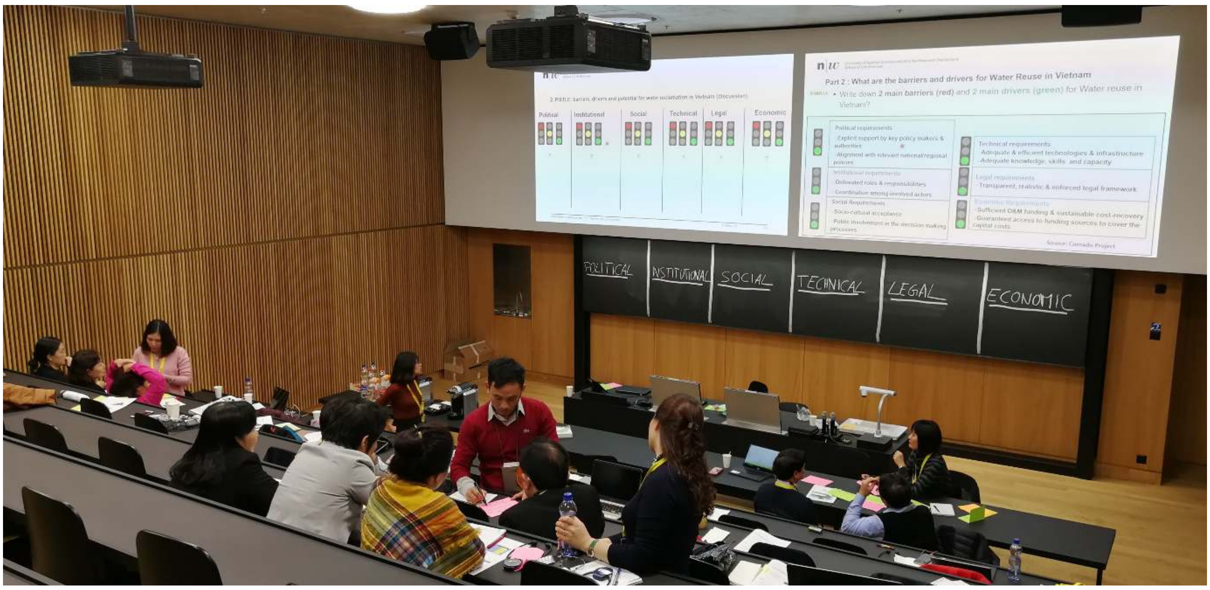


Figure 4-6: Workshop stakeholders during the dialogue identifying barriers and drivers for water reuse.

4.3.4 Results

4.3.4.1 Results from the Decision-Support System

The results show that for every case study considered, treatment trains (i.e., series of unit process technologies) complying with the water quality requirements were identified (Table 4-5). Figure 4-7 presents the detailed results for case study 1A. The results include the two top-ranking options based on cost and the top-ranking option based on weighted evaluation factors for all case studies considered. Those results are a good indication of the potential for water reuse and identified potential treatment trains, but this is a simplified assessment (pre-feasibility) that should be considered with limitations, as it is based only on the 12 parameters defined in the DSS. Additional parameters that are currently not considered but should be included in future feasibility studies. Industrial wastewater, especially, might contain specific contaminants, such as heavy metals, dyes, bleaches, or other chemicals.

Table 4-5. Two top-ranking options based on cost and top-ranking option based on weighted assessment factors for all case studies considered

Case N°	TT1 (cost)	Cost [USD/m^3]	TT2 (cost)	Cost [USD/m^3]	TT3 (weights)	Cost [USD/m^3]
1 - A	Lagooning: Australia I	0.22	Title 22: Spain	0.25	Wetlands: Spain	0.54
1 - B	No treatment	0	No treatment	0	No treatment	0
2- A	Lagooning: Australia I	0.22	Title 22: Spain	0.25	Only disinfection: Chile	0.51
2 - B	Lagooning: Australia I	0.22	Lagooning: Australia II	0.25	Wetlands: Spain	0.54
3 - A	Lagooning: Australia I	0.22	Title 22: Belgium	0.52	Lagooning: Australia I	0.22
3 - B	Lagooning: Australia I	0.22	Lagooning: Australia II	0.25	Wetlands: Spain	0.54
4 – A	Lagooning: Australia I	0.58	Lagooning: Argentina	0.64	Wetlands: Spain	1.01
4 - B	Wetlands: Nicaragua	0.37	Wetlands: Brazil	0.38	Wetlands: Spain	1.01

Note: "TT" stands for "Treatment train"

Nevertheless, the results demonstrate a potential for water reuse in Vietnam, and technologies are available that could treat typical Vietnamese wastewater to comply with international standards. For cases 1–3, many identified options have a cost ranging between 0.22–0.54 USD/m^3 for reclaimed water to comply with international standards (0.37–1 USD/m^3 for case 4 at a smaller scale).

Figure 4-7: Case 1A: Typical untreated municipal wastewater for agricultural irrigation of non-food crops (ISO Guidelines, cat. C): three top-ranking options based on cost.

4.3.4.2 Top-ranking treatment trains

Table 4-5 presents the identified treatment trains based on the list of 70 treatment trains included in the DSS. Those trains are mostly based on typical benchmark technologies and on case studies around the world. The results show that three treatment trains have a high potential for the defined case studies, which were highly ranked in the assessment: Lagooning Australia I, Title 22: Spain and Wetlands Spain. The identified treatment trains reference case studies have the following characteristics, and the cost factors are depicted in Table 4-6:

Lagooning Australia: Wastewater treatment plant effluents are reused for horticultural irrigation. The main crops irrigated are root and salad crops, brassicas, wine grapes, and olives (i.e., unrestricted irrigation). Sewage is treated in the WWTP by an activated sludge process. The effluents from secondary treatment are then held in shallow aeration lagoons for a minimum of six weeks, before passing through a dissolved air flotation and dual-media filtration process at the water reclamation plant. Here, the effluents discharge via a chlorinator in a balancing storage before being pumped in the pipeline for distribution for horticultural irrigation (AQUAREC, 2006).

Title 22 - Spain: The secondary effluent from a WWTP in Madrid is reclaimed in a tertiary treatment that includes sand filtration and disinfection. After UV disinfection, the reclaimed water is sent to the main reservoirs and then delivered for park irrigation. The main reservoirs receive chlorination (chlorine dioxide is used as the secondary disinfectant) (AQUAREC, 2006). Only the tertiary treatment step is displayed here.

Wetlands Spain: The WWTP is of the extended aeration type and currently consists of a mechanical pre-treatment step and two parallel treatment lines—each of which comprises a biological reactor, a clarifier, and three effluent polishing ponds. A chemical treatment for phosphorus removal exists as well. Further treatment is achieved by means of a wetland system (three parallel cells) (AQUAREC, 2006; Sala et al., 2004).

Table 4-6. Cost factors for three typical treatment trains that comply with several case studies

Cost factors	**Unit**	**Lagooning Australia I**	**Title 22: Spain**	**Wetlands Spain**
Capital Costs per year	[1,000 USD/year]	462	462	768
Capital Expenditure (CAPEX)	[1,000 USD]	7,750	7,750	12,882
Land Cost per year	[1,000 USD/year]	21	21	110
Energy cost per year	[1,000 USD/year]	36	36	93
Labor cost per year	[1,000 USD/year]	42	42	113
Other Operation and Maintenance costs per year	[1,000 USD/year]	227	227	879
Total costs per year	[1,000 USD/year]	787	787	1,962

End Flow per year	[1,000 m^3/year]	3,650	3,650	3,613
Cost/m^3	[USD/m^3]	0.22	0.22	0.54

4.3.4.3 Stakeholder workshop

The stakeholders were divided in three mixed groups that worked in parallel and treated the three main questions of the participatory workshop. The first question addressed the perceived potential for water reuse in Vietnam and the type of reuse that showed the most potential. All stakeholders specified a potential ranging between average and high for wastewater reuse in Vietnam (two groups out of three perceived a high potential) (Table 4-7). While all stakeholders saw opportunities in the industrial sector, two groups mentioned that water could potentially be reused for agriculture. Reuse of water for landscape irrigation or for ecological reasons was also mentioned by one group.

Table 4-7: Study group's perception of wastewater reuse potential and type of reuse

Group	Potential	Type of reuse
1	High	Agriculture irrigation, landscape irrigation, industrial reuse
2	High	Industrial reuse
3	Average	Industrial reuse, agriculture irrigation, ecological

The second question, regarding the main barriers and drivers, was carried out as a participatory stakeholder dialogue. This question was answered based on the PISTLE framework. A similar number of barriers and drivers resulted from the dialogue (Table 4-8). Regarding political and social dimensions, no significant barriers were identified, and the stakeholders evaluated those two categories as favorable to the implementation of water reclamation (green color). Regarding institutional, technical, and economic dimensions, both barriers and drivers were identified, but no clear trend could be established. This lack of a clear trend led to a neutral evaluation of those categories (yellow color). The legal dimension showed important barriers, especially due to the lack of regulations, and the stakeholders estimated that this category highly hampers the implementation of water reuse in Vietnam (red color).

In the stakeholder evaluation, the workshop was assessed as ”very good” to ”excellent.” In particular, the dialogue was perceived as excellent, and the stakeholders’ institutions requested to extend it with additional future workshops.

1 *Table 4-8: The defined barriers and drivers and their assessment*

	Political	Institutional	Social	Technical	Legal	Economic
Drivers	Clear direction	In process of improvement	1) High demand for using recycled water 2) Social requirements	1) Best available technology (BAT) available 2) Several good practices available	1) Green Growth Strategy 2) Decree 82	1) Economic requirements 2) Economic benefits 3) Protection of environment and public health 4) Private invest possible
Barriers	Lack of political regulations	1) Overlap and gaps in responsibility of stakeholders 2) Institutional requirement (coordination among actors)	No or little confidence in quality	1) Inadequate skills and knowledge 2) Old technology possible incompatible with modern technology	1) Legal requirements 2) Lack of instructions and standards for water reuse 3) Lack of perception and policy regulations	1) Small and medium size enterprises are financially weak 2) Preferential credit available, but with a strict and complicated procedure
Assessment	+	**0**	+	**0**	**-**	**0**

The third question aimed to identify measures necessary to overcome the identified barriers. Based on the answers of the previous questions, stakeholders selected the legal and economic dimensions to propose measures.

Regarding the economic dimension, all groups agreed that more financial incentives for economic actors are needed. These should support actors that intend to be involved with wastewater reuse. Regarding the legal dimension, the stakeholders agreed that the plethora of existing guiding documents would need to be integrated to establish a clear and unique guidance for all the ministries. One group mentioned that the regulations would also need to be extended in relation to water reuse. Even though in 2018, Decree 82 was implemented, allowing the reuse of treated wastewater in industrial parks, other regulations are lacking, as are standards for wastewater reuse in agriculture. The introduction of a bonus-malus system was another idea that could drive development in this sector.

Group	Economic Measures	Legal Measures
1	1) Private, public and third party (PPP) 2) Apply payback rewards to successful implementations	1) Develop a complete standard for wastewater reuse 2) Environmental technology must be prioritized legally
2	1) Financial incentives for investors 2) Tariff incentives for treated wastewater users	1) Completion of the existing legal framework 2) Sanctions for not using recycled or treat-

Table 4-9: The stakeholders proposed measures to improve wastewater reuse in Vietnam

		ed water
3	1) Incentives from government 2) Database of best available technologies (BATs)	1) Update regulations on reuse of wastewater 2) Coordination between different ministries or agencies 3) Implementation of existing regulations

4.3.5 Discussion on the Application

The present section 4.3 demonstrates the application of a decision-support system for water reuse to the Vietnamese case study. Preliminary research identified key data on typical wastewater quality in Vietnam and current water quality regulations for water reuse. Some gaps were identified, and missing parameters were complemented with values from international case studies to identify four typical cases showing a potential for water-reuse implementation in Vietnam.

For all defined case studies, adapted treatment trains that could treat wastewater to the desired quality at reasonable costs could be identified and are presented in this section 4.3. The results show that technological options are available for water reuse in Vietnam, but the concept has not yet been implemented in Vietnam.

The participatory workshop organized with 17 local stakeholders and key experts indicated that a high potential for water reuse exists in Vietnam and that the political and social contexts are favorable to the implementation of water reuse. The main barriers hampering the implementation of water reuse lay in the legal and economic dimensions, according to the stakeholders.

Several measures were identified in those categories with the aim of fostering the implementation of water reuse and enabling a favorable environment. It seems that the most important measures to be adopted are focusing on simplification and unification of water quality regulations, since those are currently complicated and not coordinated among ministries. Furthermore, financial incentives and diverse economic instruments were also suggested by the stakeholders, even though many funds are available from donor agencies to support such projects in Vietnam.

The material developed for and used during the workshop has been offered to Vietnamese stakeholders. The future will reveal whether this initiative will support changes and the implementation of water reclamation in Vietnam.

Future research on water reuse in Vietnam should focus on (i) specific case studies with a high potential for water reuse and (ii) exemplary cases to implement the demonstration sites for wastewater reclamation, maintaining both high quality and affordability.

4.4 Water Reuse – Additional Applications

Some years after the development of Poseidon, the experience showed that one of the key applications of the DSS is capacity building. This application has already been implemented in the master curriculum of the University of Applied Sciences and Arts Northwestern Switzerland (FHNW), the Agricultural University of Athens (AUA) and elsewhere internationally (e.g. Morocco, the Netherlands). The students can use the DSS to investigate different unit process characteristics and their interactions in treatment trains, and students can thus gain a systemic understanding of the complex topic of water reclamation. The tool can be used as a “sandbox” for several exercises and scenario comparisons.

Additionally, the DSS has been integrated into the COROADO online DSS. The technology selection is there applied to the Latin-American context and linked with other analysis regarding water vulnerability (Stathatou et al., 2015). This integrated online system will be subject to upcoming additional publications.

This DSS will be further developed in other projects. It is foreseen to broaden the DSS’s application field by adding more technologies and updating the underlying database. It is also important to develop additional training material to allow the tool’s application at a large scale. In this sense, the DSS presented in this paper is upgraded in the European project “MadforWater.” Thereby, integrated technological and managerial solutions for wastewater treatment and efficient reuse in agriculture tailored to the needs of Mediterranean African countries are being developed (Frascari et al., 2018).

4.5 Water-Loss Reduction – Application to the Case of Alytus Water Utility in Lithuania

This section applies Water Utility Compass and demonstrates the main features and content of this innovative DSS. The DSS uses a new holistic approach through its application of the case of Alytus water utility in Lithuania. Note that the application of Water Utility Compass to the Lithuanian case presented below was conducted together with Prof. Mindaugas Rimeika and Anželika Jurkienė, each of whom had long-time experience with the water utility. A joint paper was selected and presented at the Urban Water Conference in Venice, Italy, in June 2016 (E. Oertlé et al., 2016). The text of the publication with, minor edits, is presented in this section.

4.5.1 Description of the Area

Alytus is a city in southern part of Lithuania, about 105 km from its capital Vilnius. The population in 2013 was 57,281, and the city is the capital of the region. The local municipality owns the water utility. Alytus Water Utility is responsible for water and wastewater services for Alytus city. Groundwater is the only source for the city water supply, taken from two well fields, consisting of 19 wells, where depth varies from 40–130 m. Both well fields have water treatment facilities where iron and manganese are removed in open filters. Due to the hilly terrain, pressure in the distribution network is kept rather high at about 40–70 m, with certain pressure-reduction zones implemented where pressure was becoming unacceptably high. In the network, seven local booster pumps exist for high raised blockhouses.

The price for water and wastewater services was 2.13 EUR/m^3 in 2015, where drinking water comprises 34% of that cost. Direct costs for water extraction, treatment, and supply to the network is 0.14 [EUR/m^3]. Average water supply for the city was 8,200 m^3 per day in 2015. Citizens are the biggest water consumers, with a share of about 62% of total usage. The oldest part of water network was built in the 60s, but the majority was constructed from 1970–1985. The total length of water distribution and service lines is about 400 km, mainly consisting of cast iron and PE. The steel pipelines were greatly affected by corrosion and have therefore almost all been replaced.

For many years, the NRW level in the Alytus water supply network was more than 0.7 million m^3 per year. In 2012, the company therefore started an extensive project for water losses reduction, for which the developed DSS was applied; the results are presented in this paper.

4.5.2 Application to the Lithuanian Case

Water utilities in Lithuania lack sufficient practice of efficient water-loss reduction, information about practical measures, and capacities for the use of specialized equipment for the detection of leaks. Water losses in Lithuania’s water supply systems represent on average 30% of water input in the systems. Alytus Water Utility started its water-loss reduction project in 2012. During the project, main problems and weakest points were revised, and possible and applicable measures for water-losses reduction were proposed. The work was conducted together with consultants and company employers, leading to highly successful knowledge transfer. During project implementation, several methods were applied, such as water meter calibration, setting district metering areas (DMAs) as well as flow and noise measurements. The holistic DSS applied to the project aims to help the water company to calculate the key performance indicators and propose a list of measures for an adequate and realistic action plan for Alytus water utility in Lithuania.

As the water-loss reduction project started in 2012, the reference year of 2011 for data and calculation was used. Raw data were gathered from the company's accounting system. Water extracted from the ground is measured by mechanical meters, and water supplied to networks is measured by magnetic flow meters. According to the readings of water meters, 99.5% of water users pay for water, and water meters are installed in each private house or block flat. The rest of the customers (0.5%) are invoiced according to the water consumption rate set by the water utility. Every month, the users self-report their water consumption and pay according to the tariff.

Single-flow water meters of Class B are used in Lithuania for water accounting. The customer's water meters are replaced every 8–12 years, while bulk water meters are replaced only when they do not pass metrological verification, every 2 years.

4.5.3 Water Balance, Performance Indicators and Water Utility Efficiency 2011

The water balance was calculated based on data available and provided by the water utility. The resulting water balance (Table 4-10) includes the water volumes and evaluated error margin. The water balance system boundaries start at the meter after the water treatment plant, and for this reason, the water utility's own water usage before this point was not included in the water balance calculation (the utility's usage includes office use at the treatment plant, WWTPs, and water for filter backwashing, representing about 120,000 m^3 per year, about 4% of water supplied to the network). In addition, performance indicators included in the DSS and calculated for the water utility are presented in Table 4-11, including computation of the error.

Table 4-10: Water balance calculation for Alytus water utility in 2011 including all water volumes (m^3/year) and evaluated error margin

<table>
<tr><td rowspan="3">System Input Volume

3,074,753 ±5%</td><td rowspan="3">Authorized Consumption

2,371,034 ±5%</td><td rowspan="2">Billed Authorized Consumption
2,370,064 ±5%</td><td>Billed Metered Consumption
2,365,864 ±5%</td><td rowspan="2">Revenue Water
2,370,064 ±5%</td></tr>
<tr><td>Billed Unmetered Consumption
4,200 ±50%</td></tr>
<tr><td colspan="2">Unbilled Authorized Consumption</td><td>Non-Revenue</td></tr>
</table>

		970 ±50%	Water 704,689 ±29%
	Water Losses 703,713 ±28%	Apparent Losses 85,500 ±50%	
		Real Losses 618,219 ±32%	

Table 4-11: Performance indicators of Alytus Water Utility, 2011

Performance Indicator	Unit	Value	Error [%]	Grade
Infrastructure leakage index (ILI)	$[-]$	2.8	34.5	B
Pressure management index (PMI)	$[-]$	1.3	5.0	Average
Real losses per service connection	$\left[\frac{l}{N_{conn} * d}\right]$	435.3	32.9	C
Losses per main	$\left[\frac{l}{km * d}\right]$	6,529.5	32.9	Good
Percentage of non-revenue water	[%] of System Input Volume	22.9	29.3	D
Apparent losses per service connection	$\left[\frac{l}{N_{conn} * d}\right]$	60.2	50.5	B
Apparent leakage index (ALI)	$[-]$	0.7	50.2	A

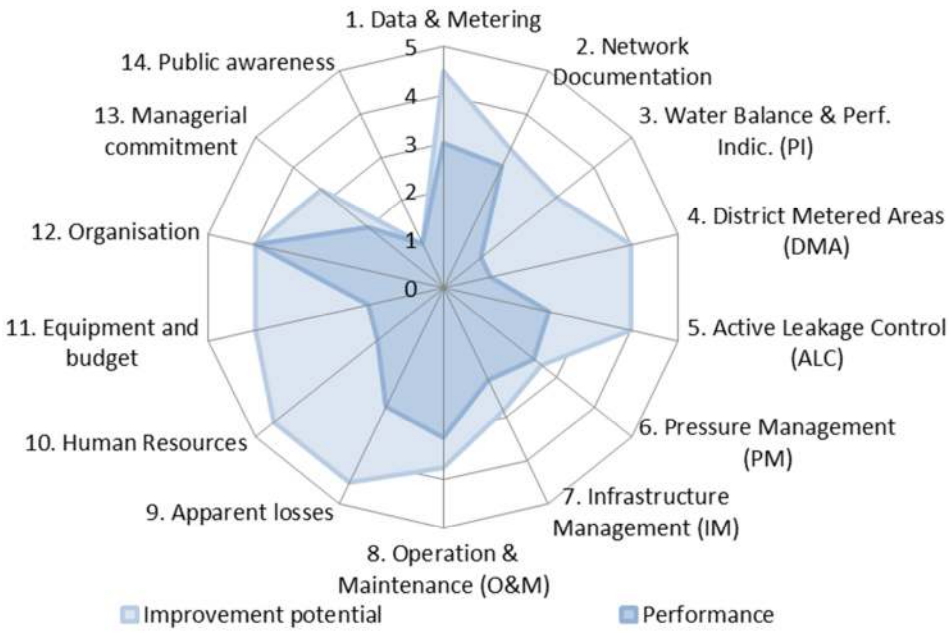


Figure 4-8: Water utility self-assessment assessment, 2011.

The water utility efficiency has also been self-evaluated by applying Water Utility Compass: the assessment conducted considers 14 different categories influencing water-loss reductions. Each topic consist of 4–6 questions and results in a spider diagram (Figure 4-8), showing for each category where the current status is and what is the potential for improvement.

4.5.4 Action Plan 2011–2015

The water balance, performance indicators, and the water utility efficiency assessment clearly indicate which categories shall be prioritized and where measures should be implemented. After the selection of most adequate measures and after complementing them with additional measures, an action plan for each selected category was prepared. The holistic DSS applied aims to help the water utility to prioritize and set up the action plan, considering the 14 categories. Five categories for water reduction were selected, where the water utility has the weakest efficiency and the highest potential for improvement:

- *Category 4*. DMAs,
- *Category 5*. Active leakage control (ALC);
- *Category 9*. Apparent losses;
- *Category 10*. Human resources; and
- *Category 11*. Equipment and budget.

4.5.5 District Metered Areas and Active Leakage Control

The next step was to analyze several measures for each category. For example, it was decided to create seven pilot DMAs in the city and to test all necessary steps to implement all applicable ALC measures. Those seven selected DMAs cover about one-quarter of the city area, and the DMAs were selected in different environments, such as industrial zones, blockhouses, or private housing areas, as well as mixed infrastructure. For the fourth category, district metered area, the DSS suggested the following measures, based on the data input and algorithm from the DSS:

- Install an appropriate size meter to measure the inflow to the DMA.
- Install logging equipment for continuous flow monitoring.
- Establish some DMAs and start analyzing the data.
- Check boundary valves. Try to adapt DMA borders to natural boundaries. Use suitable meters and PRV's.
- Keep track of the type of customers in the, DMAs and create requirement lists for each type of customer.
- Conduct nighttime step-testing (reducing the size of the area by closing valves).
- Assess DMAs with minimum night flow measurement and calculation.

4.5.6 Apparent Losses

Another output from the analysis is that apparent losses by volume calculated by the DSS do not seem so important (Figure 4-9a). However, apparent losses raised particular interest due to the fact that consumed water usually ended up in the wastewater system, leading to additional costs not charged for apparent losses. Reducing apparent losses therefore yields a double-benefit: customers pay for the water supply and for the associated wastewater costs (Mutikanga, Sharma, & Vairavamoorthy, 2009). Concerning the action plan, the utility requested special attention to apparent losses, and one accepted measure was to upgrade and change water meters to metrological Class C.

a. Annual water loss, m^3/yr. b. Annual saving potential EUR/y.

Figure 4-9: Data from Water Balance, 2011. Real losses in red and apparent losses in blue.

4.5.7 Human Resources and Equipment

A specialized NRW group formed in 2012, as foreseen in the human resources development plan. The group consists of five members: four employees and one head. Aside from active leakage control activities, which are the group's main task, it is responsible for inspecting all network manholes once each year. The team is equipped with intrusive flowmeters with data loggers, noise loggers, correlators, ground microphones, optical distance meters, data loggers for water meters, and other equipment.

4.5.8 Situation 2015

The specialized NRW group gained experience from the water leakage project and is now able to implement the ALC program independently. Members of the group became experts and could provide training for other water utilities. Water leakage management is now a continuous project, and after 3 years of work, the utility gained an understanding of how DMA and ALC shall be implemented and has everything in hand to further progress. The water utility Performance Indicators improved substantially during the project, as presented in Table 4-12.

Table 4-12: Performance indicators of Alytus Water Utility, 2015.

Performance Indicator	**Value 2011**	**Value 2015**	**Grade 2011**	**Grade 2015**
Infrastructure leakage index (ILI)	2.8	1.4	B	A
Pressure management index (PMI)	1.3	1.3	average	average
Real losses per service connection	435.3	208.4	C	B
Losses per main	6,529.5	3,214.1	good	good
Percentage of non-revenue water (NRW)	22.9	13.8	D	C
Apparent losses per service connection	60.2	35.8	B	A
Apparent leakage index (ALI)	0.7	0.5	A	A

Between 2012 and 2015, water meters of class C were installed for 35% of customers. According to research, the payback period of a Class C meter is shorter than one year. The use of Class C water meters for customers reduced apparent water loss by 40%, as the replacement of meters allowed the utility to increase measured water consumption by 10 L/day/flat.

Designing DMAs and verifying boundary valves took on average 2–3 months. A similar period was allocated for implementing ALC measures at each DMA. During the project, real water losses in the network were reduced by about 40%, but within limited area of network (Figure 4-10).

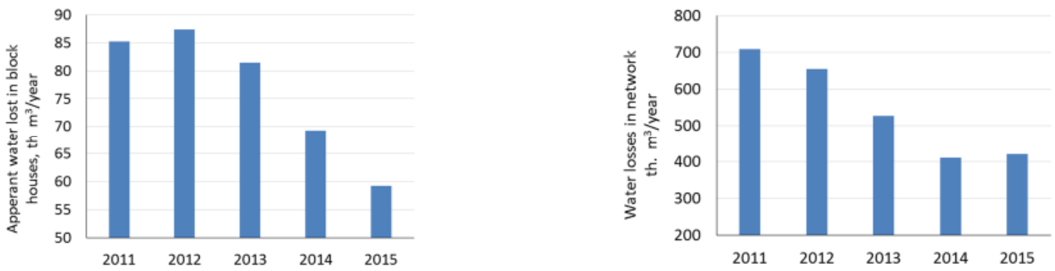


Figure 4-10: Water loss reduction during 2011–2015.

4.5.9 General Analysis and Discussion

Before a new project, it is of vital importance to assess the present situation and determine clear targets. Water utilities should identify the weakest points in the system and prepare plans on how to increase assets and knowledge. The developed DSS aims to apply a holistic approach to the topic of water-loss reduction, including the most relevant features, and to better analyze the state of the art. Based on that profile of strengths and weaknesses (Figure 4-8), an adequate and realistic action plan can be proposed, and the water utility can select measures to be implemented. In this case study, the action plan for water reduction was implemented during a three-year period, and targeted values were achieved. However, a three-year period is too short to implement all measures and create DMAs for the whole water network. Nevertheless, the knowledge and experience of water utility staff gained during the project allows continuing progress in the leakage-reduction program.

Real water loss slightly increased again in 2015, principally due several large breakdowns in pipelines involving long location time and due to the limited area of network sectored into DMAs, where active leakage control can be carried out. The assessment and analysis of previous years' experience clearly indicates the need for complete network zoning for the whole city, which would allow the identification of network areas with bursts or higher leakages. This zoning will require investment in flow measurement and data transmission equipment, and these investments would pay off. In the future, it is planned to link with the water distribution network DMAs with a hydraulic model, which would allow the utility to work with modern, fast, and adequate responses to changes in the network.

The tool was also applied to a Swiss water utility in the frame of consulting activities to improve the environmental performance of the utility. The results cannot be published, for reasons of confidentiality, but the work done was comprehensively and led to further consulting work with the company.

4.6 Water-Loss Reduction – Additional Applications

The development of the DSS has been done as part of the development and execution of a modular training concept for water-loss reduction. The trainings were conducted several times over the years, either in Germany for international participants (e.g. Botswana, Bosnia, Columbia, Egypt, Kosovo, France, Granada, Northern Iraq, Palestine, St. Lucia, St. Vincent, Taiwan, Turkey, Zambia) or in different countries around the world (Albania, Benin, Bolivia, Brazil, Burkina Faso, Germany, Jordan, Myanmar, Peru, Switzerland, Uganda).

The training of stakeholders in the water sector consists of two distinct sections, which can be conducted independently of each other and are addressed to different stakeholder groups. In order to prepare the ground and to create advantageous conditions and incentives for water utilities to better manage water losses in their systems, and to reduce the amount of NRW, a “preparatory” module for decision makers in the water sector has been developed in the format of a so-called information and motivation event.

An interactive technical training program can then support motivated water utilities in addressing the reduction of water losses within their systems. This training program consists of four one-day modules, which can be carried out as a four-to-five-day training session with side activities or can be split into modules according to the specific circumstances. This in-house training has to be completed by practical on-the-job trainings of the relevant staff, in particular with respect to data collection (e.g. for a reliable water balance), as well as for operation and maintenance of pressure-management equipment. The objectives of the technical training have been defined as follows:

- to understand the different types of water losses, their causes, impacts and, as such ,the importance of water-loss reduction;
- to be able to establish a water balance (according to IWA standards) and to calculate performance indicators;
- to learn about various appropriate information systems and to be able to apply them;
- to know about key intervention methods for WLR (DMAs design, pressure management, active leakage control, infrastructure management, and leak repair);
- to exchange experiences and to benefit from each other; and
- to implement an action plan for WRL in the respective water utilities of the participants.

The training approach is based on the idea of ”Experiential Learning,” which means that learning takes place by experiencing and critically reflecting upon it afterwards. Hence, training is a combination of transfer of theoretical knowledge, interactive exercises based on case studies, and practical experiences gathered through hands-on training with real equipment. The training equips all participants with theoretical, methodological, and practical expertise that they can use to improve their water utilities' management. The knowledge acquired throughout this training is then deepened and applied to the water utilities' specific situations by further on-the-job-training, comprising support on data collection and assessment, organizational development and management, and onsite training for operation and maintenance of the installed pressure management equipment.

In order to facilitate the work in specific water utilities and to complement the theoretical aspects of water-loss reduction, Water Utility Compass has been applied in the frame of two trainings conducted with the Strategic Alliance for Water Loss Reduction in Hamburg in March 2016 and April 2017. The participants were staff members of water utilities from Taiwan, Botswana, Iraq, and Kosovo and could all apply the tool with their own data, which they prepared before coming to the training week. The target groups for this training program were primarily executive staff of water utilities, as well as engineers, designers and planners, department heads(and other managers),and operators of the water distribution systems (technicians, "network masters", workers, etc.). Depending on the specific local conditions, more participants could be addressed, such as professionals of specialized training institutes, representatives of governmental agencies in the water sector, students of technical universities, members of associations, and civil society organizations.

Each group could reliably obtain results within one week, including the calculation of their IWA water balance and performance indicators. They could also select several measures and elaborate a first draft of an action plan. The participants came back to their water utility after one week of training with the tool, and they can initiate a process of continuous improvement in line with their daily work for water-loss reduction. Results showed that water utilities had a great interest in the training and found the tool useful and straightforward to understand and apply. The resulting action plans cannot be published for confidential reasons, however (Figure 4-11).

Figure 4-11: Training participants applying Water Utility-Compass and developing an action plan for their own water utility, Hamburg, April 2017.

4.7 Chapter Summary

This chapter has presented several applications and plausibility checks conducted with the two developed DSSs. For water reuse, Poseidon was applied and compared with reference case studies in order to assess the reliability and accuracy of the proposed treatment trains. This comparison showed that the results are within an acceptable range of error. While some limitations were identified, especially for certain specific water-quality parameters, those can be overcome by involving field experts during assessments. It was also applied to Vietnamese case studies within the execution of a study tour with local stakeholders, and the DSS proved to be very useful and provided sound results at a pre-feasibility stage. Furthermore, Poseidon is integrated within a broader online DSS from the Coroado project to be applied widely in Latin America in order to support and promote the concept of water reuse to enhance the resilience of water systems. For water-loss reduction, Water Utility Compass was applied to the case of Alytus water utility in Lithuania and within several capacity-building activities around the world. The application served its purpose, and the DSS supports the improvement of water utility management practices. The diverse applications showed that both DSSs provide relevant results valued by their users and target groups. Capacity building is a key aspect that should always be conducted in parallel with the implementation of these tools.

CHAPTER 5 RESULTS AND DISCUSSION

5.1 Water Reuse

5.1.1. Resulting Decision-Support System and Guidance for Use

The first version of the resulting DSS is open access and can be found on the Zenodo repository together with a handbook with guidance for use (Emmanuel Oertlé, 2018a). This handbook provides detailed instructions that are too extensive to be included in the main text of this thesis (Appendix III). Key features from the DSS are presented in Figure 5-1 and Figure 5-2. First, the user needs to become familiar with the informative sections describing the unit processes, treatment trains, and water quality classes included in the DSS. Secondly, the user needs to enter data for a first assessment on the starting tab (Figure 5-1).

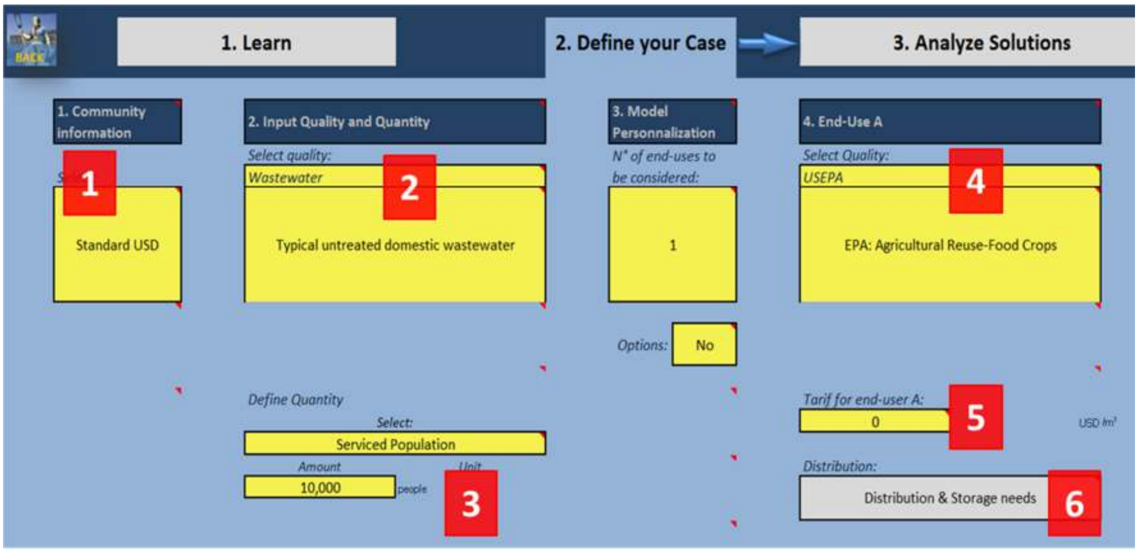


Figure 5-1: Data input in simple mode.

1. *Community information:* The user can either select a pre-defined profile or specify a national currency. The exchange rate is USD2006. Other information is related to labor, electricity, land costs, nominal interest, and inflation rates.
2. *Input quality:* The water or wastewater quality for treating can be specified here, either by selecting from a list of pre-defined types of wastewater or by specifying up to 12 quality parameters manually.
3. *Input quantity:* The quantity of water or wastewater for reuse can be specified.

4. *End-use quality:* The water quality required for the intended end-use after treatment can be specified by choosing from a list of pre-defined quality classes or by indicating the water quality parameters manually.
5. *Price of reclaimed water:* Input of the selling price to the intended end-user can be specified.
6. *Distribution and storage needs:* The user can indicate the required length of the pipes, the elevation differences, and the land type to calculate the piping and pumping costs for both the input wastewater and output reclaimed water. The need for a storage facility can also be specified, and corresponding costs are calculated.

Furthermore, it is possible for the user to manually define three specific treatment trains comprised of up to 10 unit processes. Additionally, it is possible to add unit processes. Based on those input data, the Excel tool calculates the performance, cost, and other assessment criteria for all the treatment trains included in the system. On this basis, it proposes a ranking for valid options. A screenshot of the results is presented in Figure 5-2. The detailed results are also available in a tabular representation in the DSS. In the screenshot of graphical results, a range of information is displayed and can be numbered into the following eight features (highlighted in red):

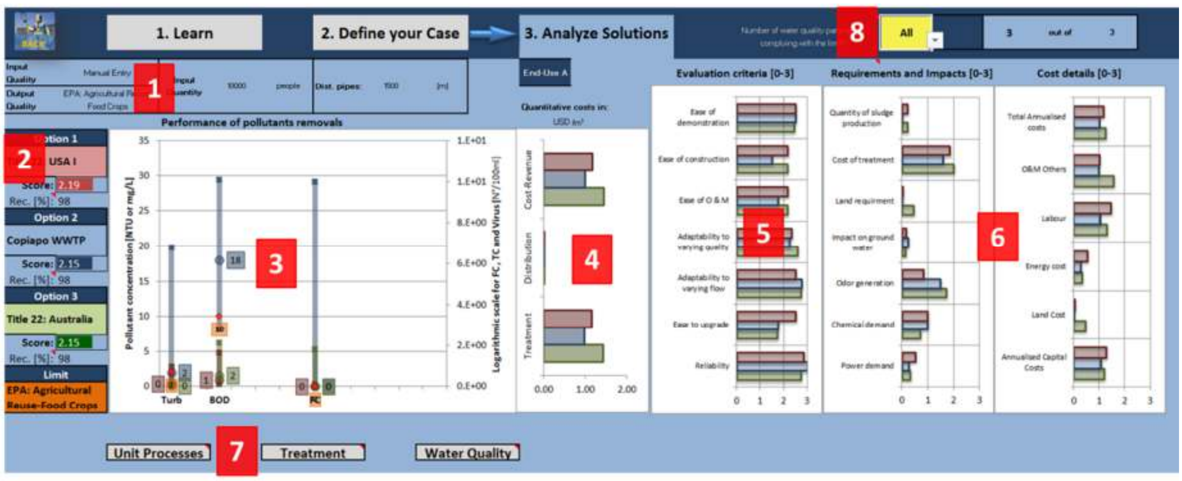


Figure 5-2: Example results sheet.

1. The data input (input quality and quantity, output quality, and distribution) is recapitulated.
2. The three best options are displayed in the colors (red, blue, and green). For each option, the name of the treatment train is displayed with the overall treatment train score.

This score is based on the assigned weights and the recovery percentage. The chosen limit for the output quality required is indicated in orange.

3. The chart displays the pollutant removal performances under minimum, average, and maximal performance. The limit is shown in orange. The user can see how well the three options perform. There are two scales: on the right, for most quality parameters in NTU (turbidity) or mg/L and, on the left, for logarithmic scale for FC, TC, and virus (in n°/100 mL).
4. The specific costs are presented in the selected currency per cubic meter. Cost − revenue is the cost of treatment and distribution minus the foreseen selling price to the end-user. If this value is negative, the selected option would produce monetary profits. The specific costs are calculated with the lifecycle cost methodology (OPEX, CAPEX, cost of capital through interest rate, electricity costs, labor costs useful life, etc.).
5. The assessment of the criteria results is displayed. The values are between 0 and 3, where 0 = nil, 1 = low, 2 = medium, and 3 = high. For the criteria, a high value is considered positive for the calculation of the overall treatment train score. This score is based on the weights, which are displayed under the option name (point 2).
6. The results for requirements, impacts, and costs are displayed. The values are between 0 and 3: 0 = nil, 1 = low, 2 = medium, and 3 = high. For those criteria, a high value is considered as negative for the calculation of the overall treatment train score. This score is based on the weights, which are displayed under the option name (point 2).
7. The three buttons are links to the "Learn" component. Depending on the option selected, the user can look in the database to understand the details of each treatment train, unit process, and water quality class.
8. If no treatment train complies with the required water quality, the user can choose how many water quality parameters should comply with the requirements (e.g., 2 out of 3).

5.1.2. Screening of Water-Reuse Options: Ranking, Filtering, and Comparison

The chosen approach for sequential decision optimization is a screening approach. On this approach, information provided by the user concerning water quality and local parameters ruled out options that did not meet the minimal requirement. The minimal requirements were determined before running an assessment and ranking algorithm for the remaining options for water reuse. In short, the DSS includes a set of unit processes and treatment trains, and the user can specify certain parameters. The DSS calculates the performance of every unit process and treatment train included in the database for the provided parameters, and it then applies an assessment algorithm to present a ranking of options. These options comply with the minimal requirements and result in the highest overall score.

To analyze each scenario based on the input data provided (available wastewater to be reused, intended reuse, and several locally specific characteristics required for the calculation), the system will calculate the following parameters:

- pollutant-removal performance of every treatment train included in the system,
- specific lifecycle treatment costs, and
- overall score of multi-criteria analysis based on normalization and local weighting.

On this basis, the DSS proposes an assessment algorithm that provides a ranking of options while meeting the minimal requirements (Figure 3-6). The algorithm proposes three different assessment methodologies that derive a ranking from the list. The first method (1) eliminates all treatment trains that do not comply with the quality requirements (based on the maximal removal performance of each unit process). Rankings are then given based on the weights for each single indicator, as previously defined by the user. The second method (2) first eliminates all treatment trains that do not comply with the required quality and then ranks only the three options with the lowest lifecycle treatment costs. The user can then evaluate the three options by analyzing the calculated set of assessment criteria. The third method (3) is primarily intended for experts, and it enables a targeted selection of the top-ranking options, based on a manual or subjective assessment of all presented assessment criteria.

5.1.3. Discussion

The main result is the development of a DSS for water reuse (Poseidon) addressed to a wide range of users at the stage of a pre-feasibility study in order to select and propose feasible treatment trains for water reuse and foster more detailed feasibility studies. The DSS was the subject of a peer-reviewed publication, and all underlying datasets have been uploaded on an open-access repository as supplementary material to the publication (Emmanuel Oertlé et al., 2019). The DSS has also been applied to Vietnamese case studies presented in this thesis and in the process of publication.

The developed DSS enables a quick screening of options. It can perform a pre-feasibility study and supports the promotion of water reuse in regions, where it remains an emerging concept. The DSS enables the identification and comparison of possible treatment trains meeting the local requirements. If a case study shows a potential for water reuse, reuse implementation can be fostered. The DSS covers a broad range of scenarios for water reuse, and diverse stakeholders can understand the results. However, an actual implementation of a water-reuse scheme implies additional local conditions and technical details, which are not covered in the DSS. These results enable an identification of potential options that should be considered in a more detailed study.

The created underlying datasets are additional central outputs of this research, aside from the DSS itself. The data aggregation, published in an open-access format, allows the estimation of the removal performances, the lifecycle capital, operational costs, and additional assessment indications for most unit processes. This aggregation was implemented for wastewater treatment and water reclamation in a simple manner. The cost component is an important piece of information for the viability, comparison, and selection of the different treatment trains, since the cost is often the key aspect. Using costs per cubic meter makes these key aspects easily comparable and understandable in terms of the influence of different factors. Additionally, if required further costs can be calculated (e.g. total CAPEX). The equipment costs and therefore the total capital cost for every unit process can be calculated independently for every possible flow between 10 and 20,000 [m^3/day]. Similarly, by combining different water quality guidelines together and by proposing a holistic approach to water reuse, possibilities for future interdisciplinary research can emerge. Such research could include the use of another support (e.g. an online tool), the inclusion of additional technologies, combination with complementary solutions (e.g. irrigation technologies), or the internationalization of the DSS concept.

If the developed DSS takes an approach similar to that of existing software cited in this thesis, it presents several unique features that contribute to progress in the field of management systems for water reuse:

- The general approach and uncomplicated user interface targets a wide range of potential users and is to be used for pre-feasibility studies and capacity learning. As presented in the literature review, the majority of other existing approaches focus on technical aspects and are mostly design tools for engineers. With Poseidon, a full assessment can be made by specifying only three pieces input information (wastewater to be reused quantity and quality, and intended reuse), leading to the identification of top-ranking options and the calculation of the results of all relevant parameters, such as lifecycle costs, pollutant-removal efficiencies and diverse assessment criteria. It is a universal tool that can be applied anywhere and takes into account local specificities.

- Poseidon includes a pre-selection of treatment trains. The approach of including a set of exemplary treatment trains in the DSS makes it accessible to non-expert users, as there is no need to design treatment trains. The results obtained refer to existing treatment trains and corresponding case studies. Nevertheless, the possible option for the user to create its own treatment train offers full flexibility for anyone, and the DSS can be applied in several different manners and for different purposes.
- The DSS includes several dimensions and information beyond technical aspects. The inclusion of information such as unit process description, water quality classes and the multi-criteria analysis for assessment of options also offers unique features to the field.
- Several published databases included in the DSS (unit processes, treatment trains, pollutant-removal efficiencies, coefficients for cost calculation, water quality guidelines) have been updated several times, streamlined, and simplified. Those databases allow simple calculation of different cost components and other data such as pollutant removals (with certain limitations) for all technologies included in the DSS. These exhaustive databases are key results of this thesis and represent resources that could be used, improved, or updated by other experts in the field.
- Finally, Poseidon is open access and is based on Excel, so that anybody can make use of it. As presented in the literature review, most of the other tools following a similar approach are not to be found anywhere.

Some years after the development of Poseidon, the experience showed that one of the key applications of the DSS is capacity building. This application has already been implemented in the master curriculum of the University of Applied Sciences and Arts Northwestern Switzerland (FHNW), the Agricultural University of Athens (AUA) and elsewhere internationally (e.g. Morocco, the Netherlands). The students can use the DSS to investigate different unit process characteristics and their interactions in treatment trains, and students can thus gain a systemic understanding of the complex topic of water reclamation. The tool can be used as a “sandbox” for several exercises and scenario comparisons.

Additionally, the DSS has been integrated into the COROADO online DSS. The technology selection is there applied to the Latin-American context and linked with other analysis regarding water vulnerability (Stathatou et al., 2015). This integrated online system will be subject to upcoming additional publications.

As demonstrated in previous paragraphs, the developed DSS reached the objectives defined in this thesis. Nevertheless, certain limitations should always be considered when applying the DSS:

- The field of water reuse is dynamic, and several aspects are changing. For example, the different regulations are regularly updated, and for this reason, the user should always be aware of the situation for real implementation; the data should always be double-checked with an expert from the field. Furthermore, water quality guidelines are sometimes only recommendations and several countries have their own regulations. It is always critical to know what quality is required for the end-user, and some regions do not always offer a clear answer to this question. For example, some application scenarios show a mismatch between available quality parameters from the wastewater to be reused and the quality parameters specified by a specific water-quality guideline for a given type of reuse.
- The pollutant-removal efficiencies are simplified, and the results should be considered with care. The user should keep in mind that for a given unit process, the real market normally proposes a wide range of suppliers and technologies that all perform differently. Furthermore, the operation of a given technology and its location normally also play a role in the performance. For this reason, the values obtained from the DSS are a good indication at pre-feasibility stage, but should go through an in-depth assessment for specific feasibility studies or design of water-reuse schemes.
- The choice of parameters to be considered both for the required quality for the end user and for the pollutant-removal efficiencies is not always straightforward. The DSS considers only 12 key parameters, but certain specific industrial pollutants (e.g. dyes from the textile industry, fungicide from the fruit packaging industry, microplastics or heavy metals) are not considered in the tool. The user should therefore always have general awareness and be certain that the relevant pollutants are considered before making recommendations. The DSS is principally designed to be applied for more classical types of wastewaters.
- As demonstrated in the plausibility check, the calculation of pollutant-removal efficiencies shows good results for seven parameters (BOD, COD, TSS, FC, turbidity, TC

and TOC), whereas four parameters show a higher relative error (TN, TDS, TP and nitrates). These limitations should be considered by users of Poseidon.
- The cost simulation calculation is in an acceptable range and provides a useful cost indication, but it is only indicative, and it should be assessed more specifically for more in-depth studies.

This DSS will be further developed in other projects. It is foreseen to broaden the DSS's application field by adding more technologies and updating the underlying database. It is also important to develop additional training material to allow the tool's application at a large scale. In this sense, the DSS presented in this paper is upgraded in the European project "MadforWater." Thereby, integrated technological and managerial solutions for wastewater treatment and efficient reuse in agriculture tailored to the needs of Mediterranean African countries are being developed (Frascari et al., 2018).

5.2 Water-Loss Reduction

The main result is the development of a DSS for Water-Loss Reduction (i.e., Water Utility Compass) addressed to water utilities and consultants in order to support the assessment, strategic planning, and continuous-action planning and implementation of water-loss reduction measures. The DSS was the subject of a peer-reviewed publication including its application to the Lithuanian case study and is available on the website of the strategic alliance for water-loss reduction (E. Oertlé et al., 2016; Strategic Alliance for Water Loss Reduction, 2016). The tool has also been successfully applied to a major Swiss water utility within consulting work, but the results cannot be published for reasons of confidentiality.

The developed DSS allows one to obtain a clear assessment of a water utility's efficiency in regard to its management and especially to water-loss reduction. In addition, a water balance and several performance indicators are calculated, considering data uncertainty with a 95% confidence limit. This systemic situation analysis can be done only by entering a limited amount of data and is the basis for the definition of strategies, measures, and the establishment of an action plan. The DSS can also be used for monitoring through its reapplication at different times.

The application of the DSS Water Utility Compass based on input data specific to a water utility helps analyze strengths and weaknesses of the utility and develop an action plan that will help to reduce water loss. The tool can assist the user better to understand water losses and find appropriate measures to save water. The Water Utility Compass DSS was tested on Alytus Water Utility (Lithuania). The developed and implemented three-year action plan allowed a reduction of NRW by 40%. Based on the results achieved and the experience gained, the DSS has been used to develop the new action plan for five years.

The tool not only helps the user to find appropriate measures. It also enables the user to learn more about the relationship and interplay of water-loss components, and to understand better the individual situation. The results show that the water utility had a great interest and found the tool especially valuable.

If the developed DSS takes a similar approach to the existing software cited in this thesis, it has several unique features that contribute to progress in the field of management systems for water-loss reduction:

- Water Utility Compass is the only solution offering the applied holistic approach considering baseline data, situation analysis, and action planning in a single open-access DSS. It is flexible and can be applied for any water utility in the world. It is also holistic in the sense that many important dimensions of water utility management are considered, not only the technical considerations.
- The representation of the water utility's efficiency in one single spider diagram, based on a self-assessment and specific questionnaire, is a new approach and was valued by users in the field.
- The inclusion of the error calculation with the 95% confidence limit for data input, for the water balance and for the calculation of performance indicators is unique, and the DSS performs all the error calculations automatically, normally a complex undertaking for users mainly working on practical issues.
- The list of measures automatically selected based on priority areas from the potential analysis brings a novel feature that supports the establishment of tailor-made action plans. The measures proposed also present new ideas to the users.
- Embedding a DSS within a one-week technical training course offers added value as well, as it allows participants to work with their own data and not focus only on theoretical and fictive practical exercises.
- The user interface is simple and can be understood by anyone. The elaboration of the assessment requires some work from field experts, but the results are presented in a way that can be understood by the top management of the water utility.

The DSS is the culmination of years of experience and practical knowledge gained through the varied training around the world and the different materials developed with the Strategic Alliance for Water Loss Reduction. The application of the DSS to the Lithuanian case and its use during capacity-building activities showed that participant can quickly obtain results for their own water utilities anywhere in the world and use the DSS to support the establishment of action plans to foster the improvement of water-loss management. Nevertheless, the DSS also has some limitations, as it cannot verify the source of the data provided. Furthermore, some data input, especially for the self-assessment questionnaire, are qualitative and therefore subjective. It is the responsibility of the user to judge whether the provided data are correct, relevant, and complete. In order to improve the quality of provided data, it is suggested that several employees of a given water utility be involved during the assessment.

Water Utility Compass is a first version of a new WLR-tool and will be updated regularly. Feedback and improvement suggestions from users are welcome to make the tool more user-friendly. The Water Utility Compass tool is available at www.waterloss-reduction.com and can be accessed freely by anyone interested (Strategic Alliance for Water Loss Reduction, 2016).

5.3 Chapter Summary

The main results of this thesis are two DSSs developed for water-reuse pre-feasibility studies and for management support of water-loss reduction at water utilities. Both DSS are embedded within capacity building, and participatory workshop activities and have been applied in different manners. They contribute to their corresponding fields of applied research through several key novel features, such as their holistic approaches, a straightforward user interface that can be applied by a wide range of users, and other specific features addressed in this thesis. While some limitations have been identified, both DSSs contribute to improving resilient water management practices worldwide. All research objectives have been achieved and the results presented validate the two main hypothesis.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary

Globally, many water systems experience water stress due to a range of influences, leading to potential adverse effects if no adequate response is implemented. The complexity involved, not only regarding the technologies, but in a broader environment considering political, social, economic, legal, and environmental constraints, often makes it complicated for stakeholders to work together towards resilient systems and water basins. Water is a vital resource, and a real need for action exists for many regions that might face a water deficit between demand and supply as well as water quality issues, as stated in the United Nations' Sustainable Development Goals (United Nations, 2017). Even if many solutions with a potentially positive impact are available to decision makers and other stakeholder involved, there is a need for decision-support, especially in developing countries and emerging economies.

This thesis investigates two primary hypotheses. The first main hypothesis is that there exists a lack of managerial tools to assist and support the decision-making processes involved in the selection and planning of water-reuse systems and water-loss reduction systems. The second main hypothesis posits that the complexity involved in such decisions may be streamlined with the development of universal and comprehensive DSSs understandable by a wide range of potential users in order to support the selection of options and promote their implementation.

This thesis aims to identify the gaps of available managerial tools and to facilitate decision making with the development of two DSSs for water reuse and water-loss reduction in order to facilitate and promote the implementation of sound measures to improve water systems. Two main approaches are presented in this thesis, embedded within the water resilience framework, in order to facilitate and promote implementation:

- development of a DSS for water reuse (Poseidon) addressed to a wide range of users at the stage of a pre-feasibility study in order to select and propose feasible treatment trains for water reuse and to foster more detailed feasibility studies; and
- development of a DSS for water-loss reduction (i.e., Water Utility Compass) addressed to water utilities and consultants in order to support the assessment, strategic

planning and continuous-action planning and implementation of water-loss reduction measures.

Based on the literature review of the context, vulnerability, and responses for sustainable water management, the analysis of water reuse and water-loss reduction needs and DSSs available, the state of the art and progress so far have been assessed. This chapter reviewed key aspects involved with sustainable water management in order to foster the implementation of solutions for water reuse and water-loss reduction in water distribution networks. It satisfied the first main hypothesis by investigating the lack of managerial tools and gathered the main information required for the development of two innovative DSSs. Based on the gaps identified, several main objectives and key directions for the development of Poseidon and Water Utility Compass were defined. Those key aspects listed in section 2.5 address the main areas where the two DSSs developed will show novel features and progress beyond the state of the art.

1. *Straightforward solutions with clear representation of results*.
2. *Simple user interface, flexibility and expert mode*.
3. *Systemic and holistic approach*.
4. *Data transparency, local conditions, and universality*.
5. *Capacity building*.
6. *Foster implementation*.
7. *Availability and future development*.

The methodology chapter has presented the development of both DSSs and described in detail the functioning and the underlying data and calculations of both systems. For water reuse, the development process resulted in a database of unit processes and treatment trains with corresponding parameters. This database allows one to calculate and present pollutant-removal efficiencies; quantitative lifecycle treatment and distribution costs; assessment scores based on a range of criteria, factsheets, and information on technologies; typical treatment trains; quality classes; and additional general topics. The algorithm applied calculates everything for any case to be assessed and then proposes a screening-ranking methodology in order to present the three most adequate solutions based on the results and the applied weighting. Furthermore, some further assessment is offered to expert users, for example the possibility to add additional treatment trains, add more unit processes, define the water quality of the influent and requirements for effluent, customize the distribution design, or make a personalized assessment of results. The whole tool is embedded in a user-friendly interface based on Microsoft Excel, and the background information and calculation algorithms can be potentially integrated into other programs and interfaces.

Regarding the development of an innovative DSS for water-loss reduction, the tool has an architecture that aims to support water utility engineers, managers, and consultants to perform an assessment of the water utility situation, define a strategy, and elaborate an action plan with realistic objectives and measures. The tool includes data error calculation and a list of measures automatically suggested to the user based on the assessment and on fixed objectives. The tool is embedded in a user-friendly interface based on Microsoft Excel, and the background information and calculation algorithms can be potentially integrated in other programs and interfaces at a later stage.

This case studies and the DSS applications chapter presented several applications and plausibility checks conducted with the two developed DSSs. For water reuse, Poseidon was applied and compared with reference case studies in order to assess the reliability and accuracy of the proposed treatment trains. This assessment showed that results are relevant and within an acceptable range of error. While some limitations were identified, especially for some specific water quality parameters, those can be overcome by involving field experts during assessments. Poseidon was also applied to Vietnamese case studies within the conduction of a study tour with local stakeholders, and the DSS proved to be very useful and provided sound results at the pre-feasibility stage. Furthermore, it is integrated within a broader online DSS from the Coroado project to be applied widely in Latin America in order to support and promote the concept of water reuse as a response to enhance the resilience of water systems. For water-loss reduction, Water Utility Compass was applied to the case of Alytus water utility in Lithuania and within several capacity-building activities around the world. The application served its purpose, and the DSS supports the improvement of water utility management practices. The diverse applications showed that both DSSs are providing relevant results valued by their users and target groups. Capacity building is a key aspect that should always be conducted in parallel.

The main results of this thesis are two DSSs developed for water-reuse pre-feasibility studies and for management support of water-loss reduction at water utilities. Both DSSs are embedded within the capacity building and participatory workshop activities and have been applied in different manners. They contribute to their corresponding fields of applied research through several key novel features, such as their holistic approaches, straightforward user interfaces that can be applied by a wide range of users, and other specific features addressed in this thesis. While some limitations have been identified, both DSSs contribute to improving resilient water management practices worldwide.

6.2 Conclusions

In an article focusing on drought management, Karavitis et al. states: “The common thread in any discussion of sustainable water development and integrated water resources management emphasizes how new strategies are needed because water resources problems and their impacts are becoming more and more multifaceted and large-scale” (Karavitis et al., 2014). This statement is completely true and was a corner stone that led to the formulation of the current thesis hypothesis. The hypothesis stated that the complexity involved could be streamlined with the development of universal and comprehensive DSSs understandable by a wide range of potential users in order to support the selection of options and promote their implementation. Those DSSs should serve for the development of measures and strategies to cope with the complex and multifaceted challenges of integrated water resources management. In can be stated that the two main hypothesis have been proven in all its six main aspects for both DSSs developed in this research (Figure 6-1).

	Hypothesis	Poseidon	WU-Compass	Notes
1	Lack of managerial tools	√	√	Both DSS unique, published and open access
2	Universal	√	√	Successfully applied in different countries
3	Comprehensive	√	√	Plausibility check, unlimited personalization options
4	Accessible	√	√	Successfully applied for different target groups
5	Options selection	√	√	Demonstrated within DSS applications
6	Promote implementation	√	√	Lithuanian action plan and Vietnamese case study

Figure 6-1: The six main aspects of the hypothesis have been proven for both decision-support systems.

This thesis could identify the gaps of available managerial tools and could successfully develop of two DSSs for water reuse and water-loss reduction in order to facilitate and promote the implementation of sound measures to improve water systems and facilitate decision-making.

Their ongoing application and continuous development contribute to some extent to the improvement of water management practices and to the development of new strategies around the globe. Both DSSs developed help to move from a conceptual idea towards realistic options and can demonstrate that selected approaches are feasible.

As demonstrated in the results chapter, the specific objectives of this thesis were also achieved, and the main contributions to the field have been listed. Both DSSs exhibit unique and innovative features. For water reuse, it is possible to proceed to a complex assessment by specifying only three information inputs (wastewater to be reused, including both quantity and quality, plus intended reuse) leading to the identification of top-ranking options and the calculation results of all relevant parameters. Furthermore, the approach of including a set of exemplary treatment trains in the DSS makes it accessible to non-expert users, as there is no need to design treatment trains. Water Utility Compass is the only solution offering the applied holistic approach considering baseline data, situation analysis, and action planning in a single open-access DSS. The representation of the water utility efficiency in a spider diagram and the inclusion of the error calculation with the 95% confidence limit for data input, for the water balance and for the calculation of performance indicators, is unique. Both DSSs are open access, as is the whole dataset used, and these tools can therefore be further applied and updated by other researchers and practitioners from the field. They are both simple to understand and apply for a wide range of users, even without a technical background. The DSSs includes several dimensions and information beyond technical aspects. The inclusion of information such as unit process description, water quality classes, and the multi-criteria analysis for assessment of options also brings a unique feature to the field.

If one considers the water resilience framework introduced in Section 1.2, it is clear that a DSS is not a standalone solution but only a supporting tool that should be accompanied by a range of other measures. For example, the experience showed that the application of the DSSs presents the best results when embedded in capacity-building activities or participatory workshops. Even if an independent user can make use of the DSSs, the involvement of some field experts during a specific application normally maximizes its impact. The varied applications of the DSSs show that associated capacity building, consulting, and facilitation activities are crucial to obtain results. One should keep in mind that a problem is solved only when suggested measures are implemented, and several measures are necessary to foster top-ranking options. Those measures can be of different natures (e.g., political, institutional, social, technical, legal or economic). These aspects have been addressed to some extent during the application of the case studies (i.e., in the Vietnamese case), but their comprehensive assessment is beyond the scope of this thesis and must always be case specific. The path from DSS results to implementation involves several additional actions, and for the case of Poseidon, more detailed feasibility studies and process schemes designed for specific cases. While successful implementation depends on many external factors, the tools developed in this thesis should contribute to the promotion, capacity development, and implementation of solutions for water-loss reduction and water reuse.

Finally, this thesis demonstrates that for any water system, technical and managerial solutions are available to make it more resilient, even if it might not always be economically, socially or environmentally sound. Decision-support systems can be tools to promote water reuse and water-loss reduction, but they are not alone sufficient to ensure successful implementation; the willingness of local stakeholders is a prerequisite for sustainable water resources management and to move from vicious to virtuous cycles.

6.3 Recommendations for Future Research and Exploitation

While these conclusions close a chapter, it appears that those years of work in the field of water management, the conceptual approach and the lines of thoughts applied along this thesis open up new ideas and potential future research. In other words, the conclusions of this thesis are actually only a prompt for further research, continuous development of the developed DSSs, and their application to a wide range of case studies and capacity-building opportunities.

It turns out that the field of integrated water management is vast and that the situation will encounter more challenges in the future, requiring endeavors and management solutions such as those presented in this thesis. For example, some ideas for future research or exploitation channels related to this thesis are as follows:

- Future studies could develop an extended version of Poseidon or an online version of the tool with the inclusion of additional features: for example,
    - resource recovery for water reuse (e.g., phosphorous recovery);
    - specific technologies and pollutant parameters for microplastics or industrial wastewater pollution;
    - agricultural irrigation models;

    - integration of a PISTLE analysis, such as the one presented for the Vietnamese case study;
    - the possibility for a community of experts to continuously complement the list of treatment trains, unit processes, or water quality guidelines and regulations;
    - integration of local vulnerability assessment as proposed in the online Coroado DSS; and
    - translation into different languages.
- Researchers could develop an online version of Water Utility Compass that could be linked with online data monitoring and could be integrated in the digitalization strategies of water utilities. For example, Water Utility Compass could be tailor made to a specific water utility and used as a cornerstone for strategic planning and monitoring purposes.
- Future study could make use of the tools as central points of capacity-building events, in summer schools, or within diverse curricula for engineers or water professionals. Future study could be linked with the development of a complete eLearning concept that could be applied everywhere around the world.
- Integration and further development of those tools within future projects could be investigated, as initiated in the Mad4Water project that implements pilot plants for water reuse in Mediterranean and North African countries and aims at developing strategies for water reuse and efficient irrigation practices in those countries.
- Development of commercial tools including commercial products suppliers and continuous up-to-date information could be pursued. Such a product could be integrated within a consulting-offer package and presented to companies alongside the feasibility and process design studies for project implementations.

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CHAPTER 8 APPENDIXES

APPENDIX I PUBLICATION – POSEIDON

Oertlé, E.; Hugi, C.; Wintgens, T.; Karavitis, C.A. Poseidon—Decision Support Tool for Water Reuse. Water 2019, 11, 153.

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Article

Poseidon—Decision Support Tool for Water Reuse

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Abstract: In an era when many water systems worldwide are experiencing water stress regarding water quantity and quality, water reuse has received growing attention as one of the most promising integrated mitigating solutions. Nevertheless, the plethora of technologies and their combinations available, as well as social, economic, and environmental constraints, often make it complex for stakeholders and especially decision makers to elicit relevant information. The scope of the current study is to develop a decision support tool that supports pre-feasibility studies and aims at promoting water reuse and building capacities in the field. The tool developed currently encompasses 37 unit processes combined into 70 benchmark treatment trains. It also contains information on water quality standards and typical wastewater qualities. It estimates the removal performances for 12 parameters and the lifecycle costs including distribution. The tool and all underlying data are open access and under continuous development. The underlying systemic approach of the tool makes it intuitive also for users with limited prior knowledge in the field to identify most adequate solutions based on a multi-criteria assessment. This should help to promote water reuse and spearhead initiates for more detailed feasibility and design commissioning for implementation of water reuse schemes.

Keywords: water reuse (WR); decision support tool (DST); option selection; wastewater recycling; water reclamation; integrated water resources management (IWRM); unit processes (UP); treatment trains (TT); multi-criteria analysis (MCA)

1. Introduction

1.1. Water Reuse and Decision Support Tools (DSTs)

Water reuse (also called water reclamation or water recycling) has received growing attention as one of the most promising integrated solutions to mitigate water stress by improving access to good quality water. It can be an alternative to tapping new water sources (e.g., through seawater desalination), as it performs two fundamental functions that appear to be the primary incentives for implementing water reuse schemes. Treated wastewater can be reused as a water resource for beneficial purposes, and wastewater is kept out of receiving environments and, thus, pollution is reduced [1]. The objective of water reuse is the treatment of wastewater to a stage of purity that can directly be used for specific purposes, such as agriculture, industry, urban, domestic, potable reuse, and surface or groundwater recharge. Producing high purity effluents that are suitable for local reuse applications can be achieved by upgrading existing treatment plants or by designing new treatment plants for this purpose. In this way, the effluents comply with quality requirements for the intended reuse. The first step in the selection and design of the most appropriate treatment option is the investigation of techno-economic feasibility of treatment options for a reuse scheme [2].

The presented research focuses on the pre-feasibility stage and considers potential water reuse schemes in a systemic approach schematically (Figure 1). This allows determining if an identified area with potential for water reuse could lead to a feasible reclamation scheme with the current resources, technologies, and available information.

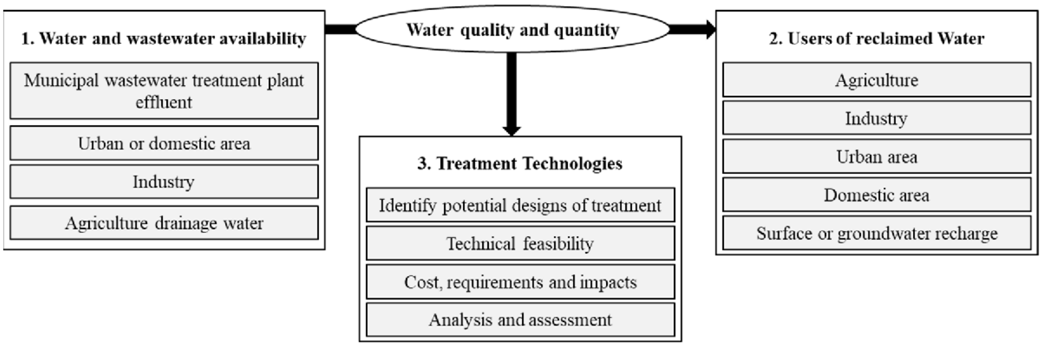

Figure 1. Water reuse for pre-feasibility in a systemic approach: (1) wastewater for reuse, (2) type of intended reuse, and (3) identification and assessment of technology.

A typical pre-feasibility assessment starts with the identification of potential reclaimable water or wastewater (1) and evaluates if this water could be treated and reused for different purposes (2). Depending on quality and quantity of available and required water, adequate treatment technologies can be identified and assessed (3). This can include assessing costs, requirements, and impacts, pollutant removal performance as well as additional technical criteria such as reliability, ease of operation, and maintenance to propose the most promising solutions and support the decision to proceed or abandon reuse options.

There are several decision support tools (DSTs) available for water and wastewater treatment selection and design that have been reviewed by Hamouna et al. [3] (Table 1). Most DSTs usually address planners and designers with a strong focus on technical aspects, usually dominating the logic of the developed systems reviewed [3]. Hamouna et al. [3] also mention that there is a need for integrated decision support tools that are generic, usable, and that consider a system analysis approach. The present paper aims to address this need for a user friendly and comprehensive interface with solid background calculations. A broad range of stakeholders can then apply the DST to facilitate the implementation of water reuse solutions, by applying a multi-criteria assessment. The DST differs from existing tools by proposing a different scope of application, rather than a comprehensive technical design. The different scope consists of the pre-feasibility, capacity building, and promoting the concept of water reuse. The DST's underlying data and pre-selected information are open access and transparent.

Table 1. Selected list of main decision support systems reported in literature ([3]).

Name of Tool or Authors	Reference	Scope		Key Methods	Open Source
		Technical & Economic	System Analysis		
Krovvidy et al.	[4]	X		Rule-based, heuristic search, neural networks, certainty factors for the developed rules	-
Kao et al.	[5]	X		Process modeling, mathematical programming, solves mass balance on a treatment train, graphical display of designs	-
Krovvidy et al.	[6]	X		Case-based reasoning, heuristic search, define cost per unit removal of contaminant	-
SOWAT	[7]	X		Rule-based, heuristic search, fuzzy logic, fuzzy functions for technology performance, ability to check a user-defined train	-
Yang et al.	[8]	X		Expert system, fuzzy logic, certainty factor for technology treatability, user-defined fuzzy preference of technologies	-
MEMFES	[9]		X	Industrial wastewater, expert system, simulation, analytical hierarchy process, a tutor provides justification for outcome. Surveyed the system's user-friendliness	-
Rodriguez-Roda et al.	[10]	X		Simulation, issue-based information systems, reports describe the deliberation over a decision, searching design records using keywords	-
SANEX	[11]		X	Conjunctive elimination, multi-attribute utility technique, multi-disciplinary set of sustainability indicators, multi-level amalgamation used for rating	-
Wukovits et al.	[12]	X		Knowledge-based system, heuristic search, easy update of process database, possible communication with other programs	-
WAWTTAR	[13]		X	Modeling and simulation, screening, multi-criteria decision analysis, output: least cost alternative, assesses risk, and more, community specific data considered in the decision	X
WASDA	[14]	X		Technical design, rule-based, design equations, friendly user interface, process design calculation module	-

Table 1. *Cont.*

Name of Tool or Authors	Reference	Scope		Key Methods	Open Source
		Technical & Economic	System Analysis		
WADO	[15]	X		Industrial wastewater, rule-based, mixed integer non-linear programming, investigates regeneration opportunities from water used in industrial processes	-
WTRNet	[16]	X		Modeling & simulation, linear & NL programming, genetic algorithm, provides user guidance for treatment train selection through either an expert or a stepwise approach	-
Zeng et al.	[17]		X	Analytical hierarchy process, grey relational analysis, allows comparison between alternatives considering the entire criteria	-
Zhu et al.	[18]		X	Drinking water, Bayesian probability networks, considers performance uncertainty, variables measuring impact on public health	-
MOSTWATAR	[2]	X		Genetic algorithms, fitness score, techno-economic feasibility investigation	-
MEDAWARE	[19]	X		Existing wastewater facilities, online tool, multi-criteria analysis	-
WASWARPLAMO	[20]	X		Modeling & simulation, linear & NL programming, genetic algorithm, provides user guidance for treatment train selection through either an expert or a stepwise approach	-
Chamberlain et al.	[21]		X	Integrated model, logic programming, explicit ontology, selection based on stated values and priorities	-
NOVEDAR_EDSS	[22]		X	Intelligent/expert screening of process technologies	X for academic purposes
Huang et al.	[23]	X		Integrated model, urban wastewater, genetic algorithm, multi-objective optimization, non-dominated sorting	-

1.2. Objective and Task

The main objective of this study is to develop a DST for pre-feasibility studies to promote water reuse in regions where it is still an emerging concept. The aspiration is that for the every case study, at least one potential for water reuse option with an adequate treatment train that meets the local requirements can be identified. As the number of possible technologies and treatment trains is important and requires expertise, a simplification is needed to offer a clear user interface. In this way, even non-expert users can participate in the assessment and understand the results, while pertinent calculations are being performed in the background. The proposed concept is that the user should only provide data on the quantity and quality of the foreseen input (wastewater to be treated), the foreseen type of reuse, and limited information on the local specificities. Based on this input, the DST should provide options of treatment trains that can meet the local requirements and specificities (Figure 2). As any first application, the DST should be very simple and user-friendly also for non-experts. It should also encompass more advanced application possibilities for experts requiring more detailed analysis. The scope of applying this DST begins with awareness raising and identification of the potential for water reuse. The scope ends before carrying out a detailed feasibility study and design of water reuse schemes. To promote the concept of water reuse and serve training purposes, the DST also includes capacity-building components for users that are not familiar with water reuse technologies. The developed DST composes of several elements in a transparent, widely used spreadsheet software (Microsoft Excel).

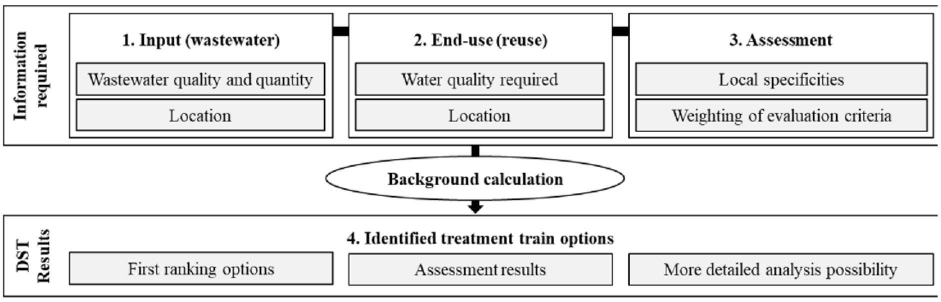

Figure 2. The architecture of the decision support tool (DST) Poseidon requires limited information from the user to calculate and present most adequate treatment trains according to local conditions.

In Section 2, materials and methods are presented, which depict the core concepts of the developed DST. Different technologies that are included, water quality parameters, water quality classes, pollutant removal efficiencies, and assessment criteria are listed and presented. The underlying cost curves are presented for every unit process and the calculation of annualized treatment and distribution costs, as well as the screening and assessment algorithms for the options' identification. In Section 3, the final DST user interface results are presented. This includes a plausibility check as a proof of concept to evaluate the reliability of the results. This is compared with examples from the literature. Finally, guidance is provided on how the DST can be applied to case studies, and how to consider results and their limitations. In Section 4, the findings, applications, and limitations of the DST, as well as future research directions, are discussed in a broader context.

2. Materials and Methods

2.1. Water Reuse Options: Unit Processes and Treatment Trains

To proceed to the intended type of water reuse, a myriad of widespread technology options is available. Usually only experts from the field of wastewater treatment and sanitary engineering can resort upon a wide knowledge and understanding of the whole set of technologies and their combinations. Water reclamation technologies can be classified into primary, secondary, and tertiary treatments, as well as for disinfection. Individual technologies are called unit processes (UP). The 37 selected unit processes in the system are shown in Table 2 (the selection bases on [20,24] and personal communications with water reuse experts).

Table 2. List of unit processes considered in the DST.

Primary Treatment	Disinfection
Bar screen Coarse screen Equalization basin Grit chamber Sedimentation without coagulant Sedimentation with coagulant	Chlorine gas Chlorine dioxide Ozonation Ultraviolet disinfection
Secondary Treatment	**Tertiary Treatment**
Anaerobic stabilization ponds Activated sludge (high loaded with secondary sedimentation) Activated sludge (low loaded with denitrification and with secondary sedimentation) Activated sludge (low loaded without denitrification but with secondary sedimentation) Extended aeration Membrane bioreactor (MBR) Rotating biological contactor (RBC) Stabilization ponds: aerobic Stabilization ponds: facultative Trickling filter with secondary sedimentation	Constructed wetland Activated carbon Advanced oxidation process Dual media filter Electrodialysis Enhanced biological phosphorus removal (EBPR) Flocculation Ion exchange Maturation pond Microfiltration Nanofiltration Post-denitrification P-precipitation Reverse osmosis Soil-aquifer treatment (SAT) Ultrafiltration

Often, these unit processes will also be combined commonly referred to as treatment trains (TTs). For each identified case study with a potential for water reuse, plenty of feasible combinations of technologies that can meet the required pollutant removal target at the desired treatment cost might be available. Under the applied concept, a water reuse option has to be composed of a feasible treatment train that fulfills the water quality requirements of the intended uses.

In the implemented DST, the combination of those 37 unit processes can lead to series of maximum 10 unit processes per treatment train. If one considers that every single unit process can be a starting point and that every unit process could be used several times, this statistically leads to about 10^{16} possibilities. Chen & Beck [25] have noted that if one compiles all possible treatment trains, as many as 50,000 options should be considered as possible trains to identify promising options. Indeed, most of those possibilities are not relevant, and many can be directly eliminated. However, this shows the complexity of the process to establish the ideal treatment train given the local situation.

As the developed DST addresses a broader range of users and aims at promoting water reuse, the approach chosen in the present DST is to propose a list of the most representative treatment trains. This is based on best-practice examples and case studies from the literature, as well as from expert interviews. Local water reuse schemes from Latin America are also included in the DST, due to the geographical focus of the European project COROADO, that partially funded the current research [26]. At the time of writing, the list is composed of almost 70 treatment trains. With this approach, the user does not need to be an expert in wastewater treatment technologies to proceed with an analysis, as the non-exhaustive list already provides an overview of most common possibilities. The system also provides some features for experts, where it is possible to create up to three user-specific treatment trains and assess the calculated results. A review of benchmarks treatment trains led to a list of treatment trains that are examples from global water reuse and reclamation practices presented in detailed tables provided in Supplementary Materials [27]. This includes a list of all treatment trains with the unit processes and the corresponding reference. All treatment trains are categorized in typical basic treatment schemes categories according to van der Graaf, 2005 [28] (Table 3).

Table 3. Treatment train (TT) categories, description, and list of treatment trains included in the DST [28].

Category	Processes	Possible Applications	Treatment Trains Included in the DST (from Literature and Case Studies) [28]
1—Title 22 [1]	Influent → P- and N-removal → Dual media filtration → Coagulation / flocculation → Disinfection by UV or chlorine → Reclaimed water	The reuse varies from urban applications and green landscaping to industrial usage.	Benchmark Technology, Italy, Australia, Cyprus, Greece, Spain, USA I, Brazil I, Belgium, Brazil II, Mexico, South Africa
2—Soil aquifer treatment (SAT)	Influent → P- and N-removal → Infiltration through large ground areas → Reclaimed water	The final water can be reused for unrestricted irrigation.	Benchmark Technology, Israel, USA
3—Wetlands	Influent → P- and N-removal → Constructed wetlands as a natural polishing step → Reclaimed water	Reuse can be done in nature conservation or agriculture.	Benchmark Technology, Nicaragua, Peru, Brazil, USA, Spain, Mexico, Senegal
4—Lagooning	Influent → Lagooning (several types in series) → Occasionally followed by chlorination → Reclaimed water	Reuse of the effluent by (very) restricted irrigation.	Benchmark Technology, Israel, France, Australia I, Australia II, South Africa, Argentina, United Arab Emirates
5—Disinfection only	Influent → Conventional wastewater treatment → Chlorination → Reclaimed water	Treated water can be reused for irrigation under restricted conditions.	Benchmark Technology, USA, Chile, Brazil
6—Direct membrane filtration	Influent → Micro- or Ultrafiltration (new concept) → Reclaimed water	Treated water can be reused for agricultural applications.	Benchmark Technology, USA, Australia
7—Local membrane bioreactor (MBR)	Influent → Package MBR system (package MBR system) → Reclaimed water	Reuse of the water in the direct neighborhood (e.g., as toilet flush water).	Benchmark Technology, USA, Brazil, China, Japan
8—High wastewater quality	Influent → P- and N-removal → Double membrane filtration (MF/UF followed by RO) → Possible extension with other processes → Reclaimed water	The treated water is of so high quality that many applications (industrial, households, etc.) are possible.	Benchmark Technology, Belgium, Singapore, Namibia, The Netherlands, United Kingdom, USA I, USA II

[1] The name of this benchmark technology originates from the homonymous Californian regulation.

2.2. *Water Quality Parameters, Water Quality Classes, and Pollutant Removal*

2.2.1. Water Quality Parameters

Water quality can be defined by an almost indefinite number of parameters: the topic is immense and the purpose of many books [29–31]. The concentration of any substance or constituent potentially present in wastewater could be a parameter to be analyzed, in addition to all physical, chemical, and biological parameters that can be measured. This requires a selection of the most relevant parameters based on the relevance of several parameters, namely, different intended reuse, data availability of removal performance of the different technologies, and the technology's inclusion in most prominent guidelines for quality standards, recommendations by water reuse experts, as well as the ease to measure and monitor the parameters. After several organized workshops with experts in the field of water reuse [32], 12 key water quality parameters were considered as most appropriate for the identification and initial assessment of the potential of water reuse options, and were integrated in the DST (Table 4). Future versions of the tool might address more specific types of contaminants, such as microplastics, organic contaminants, emerging pollutants, or specific pollutants of industrial wastewater (e.g., dyes and bleach from textile industry, fungicides and pesticides from agricultural food processing)

Table 4. Water quality parameters included in the DST.

Parameter	Unit	Parameter	Unit
Biological Oxygen Demand BOD	mg/L	Total Nitrogen, TN	mg/L
Chemical Oxygen Demand COD	mg/L	Total Organic Carbon, TOC	mg/L
Fecal Coliforms, FC	cfu/100 mL	Total Phosphorous, TP	mg/L
Nitrate	mg NO_3–N/L	Total Suspended Solids TSS	mg/L
Total Coliforms, TC	cfu/100 mL	Turbidity	NTU
Total Dissolved Solids, TDS	mg/L	Virus (nonspecific)	PFU/100 mL

2.2.2. Water Quality Classes

The user of the DST can specify the values of each parameter for the reclaimable wastewater and the requirements for the intended reuse independently, but if the user is not a specialist or needs support, descriptive water quality classes have been established for the DST. Supplementary Materials [33] include the quality classes with the corresponding parameters (Table 4). Please note that some references do not provide limits of constituents for each of the 12 considered parameters. If no value is specified or if no data could be found, a dummy value of "−1" is set in the tables. Three types of water quality classes are considered (Table 5):

1. Typical wastewater quality that is intended for reuse (e.g., effluent from a waste water treatment plant (WWTP))
2. Recommended water quality for and intended use based on international guidelines, such as WHO or ISO [34,35].
3. Additional guidelines and regulations, such as local legislation from different countries, considered for the water quality required for different types of intended reuse, such as EPA guidelines [36].

Table 5. Overview of most prominent international guidelines and standards for treated WW reuse.

Guidelines with Reference	Description
US-EPA, Guidelines for water reuse 2012 [36]	This update from the 2004 US-EPA guidelines [37] is an exhaustive reference report considering all types of water reuse.
WHO, Guidelines for the safe use of wastewater, excreta and greywater 2006 [34,38–41]	In 2006, WHO published four volumes of a third edition of its Guidelines for the safe use of wastewater, excreta, and greywater in agriculture and aquaculture. The revised Guidelines reflect a strong focus on disease prevention and public health principles.
WHO, Guidelines for drinking-water quality: Fourth edition [41]	The fourth edition of the World Health Organization's (WHO) Guidelines for drinking-water quality (GDWQ) builds on over 50 years of guidance by WHO on drinking-water quality, which has formed an authoritative basis for the setting of national regulations and standards for water safety in support of public health.
ISO Guidelines for treated wastewater use for irrigation projects 2015 [35]	ISO 16075-3:2015 covers the system's components needed for the use of treated wastewater for irrigation.
FAO Water quality for agriculture 1994 [42]	The FAO suggests various water quality criteria for general irrigation. The guidelines are practical and have been used successfully in general irrigated agriculture.
Proposal by the Aquarec project, 2006 [30,43]	The Aquarec project proposes seven quality categories for different types of reuses and compiled microbial and chemical limits for each category.
California code of regulation title 22 [44]	California Department of Health Services (DHS) establishes water quality standards and treatment reliability criteria for water recycling under Title 22 and establishes requirements for the use of recycled water not addressed by the uniform statewide [43]. These quality standards are often used as reference or used as a model to establish national water standards in other states or countries.

2.2.3. Pollutant Removal Efficiencies

Characteristic removal efficiencies (in %) of each unit process (Table 2) for the considered parameters (Table 4) are presented in Supplementary Materials [45]. For each parameter, the minimum removal, average removal, and maximum removal efficiencies (R_i) for the unit processes are provided. The different used percentages are based on literature [20,24] and several meetings that have been conducted with experts in the field of water reuse [32]. Equation (1) can then be used for the calculation of the expected effluent concentrations [20,24]:

$$C_{eff} = C_{inf} \times (1 - R_i), \quad (1)$$

where

C_{eff}: effluent concentration (water quality parameter unit, see Table 4)
C_{inf}: influent concentration (water quality parameter unit, see Table 4)
R_i: removal efficiency (%)

These input data are used in the DST to calculate the expected water quality after treatment (under minimum, average, and maximal removal efficiencies). Thereby, a unit process is a simplified concept with characteristic average performance values, as many different types of technologies fit in the same unit process, and each technology will all have different performances depending on each supplier and spatial application.

2.3. *Cost Estimation*

To assess and identify promising options, a typical user initially wants to know if the proposed technology will meet the technical requirements and achieve the required water quality. If the treatment train achieves the water quality, the next piece of information is the costs of treatment and distribution. It is important to include the costs of distribution from the beginning, as these costs are often significantly larger than the treatment costs [46].

For this purpose, a cost component has been developed and results in quantitative figures for the total cost of treatment in local currency per cubic meter of reclaimed water, as well as the distribution costs expressed in the same unit. The user can select or define several local parameters, such as the local currency, electricity costs, land costs, labor costs, and reclaimed water-selling price. On this basis, the DST will estimate overall specific costs automatically.

As costs are sometimes difficult to estimate for such a wide range of technologies considering local specificities and market prices, the uncertainty of the estimation is evidently high (a similar study estimates reasonable accuracy between −30% and +50% of actual costs [47]). Nevertheless, the range of calculated values with the DST already provides first figure approximations, allowing for making comparisons between different options at the pre-feasibility stage.

2.3.1. Elaboration of Cost Curves

In Supplementary Materials [45], the database of the regression coefficients, C and B, for every unit process (Table 2) and every cost component (Table 6) as a function of the average treated flow rate is presented. The cost components are calculated with Equation (2):

$$y = C \times Q^B, \tag{2}$$

where

Q: average flow [m^3/day]
y: any cost component calculated
C, B: regression coefficients

Table 6. Cost components included in the DST.

Cost Components	Unit	Comment
Construction cost	1000 USD 2006	Capital expenditure (CAPEX) calculation and annualization are described in Section 2.4.
Land requirements	ha	Default period of 30 years and same calculation for the annualization as of CAPEX is applied. Residual value after 30 years not considered.These values have to be multiplied by corresponding parameters from Table 7 provided in (CUR/ha) to obtain local costs.
Energy requirements	kWh/y	Both values have to be multiplied by corresponding parameters from Table 7 to obtain local costs.
Labor requirements	person-hour/month	
Other operation & maintenance	1000 USD 2006/y	As energy and labor are considered separately, this category considers additional operations & maintenance (O&M) costs consisting of [17] maintenance (usually assumed to 4% of total capital costs), and taxes and insurance (usually assumed to 2% of total capital cost). Furthermore, additional costs are individually added to different unit processes: chemicals (lime/calcium hydroxide, polymer, sodium hydroxide, sodium hypochlorite, sulfuric acid, cationic polymer, ferrous sulfate, hydrated lime, sodium sulfide), residual management (technology-specific costs), sludge disposal and concentrate disposal.

The coefficients for the cost component are based on the program WTRNet, developed within the Aquarec Project [24]. The project Aquarec has been funded by the European Commission and many of the project results are publicly available, such as the manual for water reuse [30]. In total, 336 simulations have been conducted (8 different flows ranging from 10 to 20,000 m^3/day and 42 unit processes with standard pollutant classes). Data have been collected from the different simulations, classified, and converted to USD from 2006. Power regressions have been applied, as this is justified from an economic perspective (economy of scale). Finally, the overall database has been reviewed and inconsistencies have been removed. Some data have been complemented by additional references, for example, for electro-dialysis, data from ion exchange have been used and electricity requirements of 2.9 kWh/m^3 (seawater desalination) have been applied [48]. It has to be noted that the DST calculations take into account the recovery percentage of each unit process.

2.3.2. Community Profiles for Cost Analysis

The developed cost component allows adapting the results to the local conditions by adapting several parameters in so-called "community profiles". Those parameters are used in the cost calculation to obtain locally specific results. By assembling results obtained with Equation (2) and parameters from Table 7, every cost component for any location can be calculated. For each community, or study site, the following criteria can be specified.

Table 7. Parameters considered in the community profiles for the calculation of the cost component.

Parameters	Unit	Default Value	Comment
Currency	CUR	USD	The reference community is based on USD from 2006.
Exchange rate to USD 2006	CUR/USD2006	1	To define the exchange rate, it is recommended to use the exchange rate from 2006 and to include inflation rate or other evolution factors since 2006 [49].
Land cost	CUR/ha	10,000 USD	Acquisition costs and the unit costs for land have to be merged into this overall land cost factor.
Electricity cost	CUR/kWh	0.05 USD	Average electricity cost should be used.
Personal cost	CUR/person-hour	20 USD	Average labor cost should be used, covering a mix of different types of personnel (blue and white collar).
Price of reclaimed water	CUR/m^3	2 USD	Selling price of the reclaimed water
Discount rate (r)	%/a	8%/a	Real interest rate r = nominal interest rate (i) − actual inflation rate (p)

2.4. *Calculation of Annualized Treatment Costs*

For comparable and easily understandable results, we calculated every cost in the local currency per m^3 (CUR/m^3) of reclaimed water based on the annual lifecycle costs. For this, we calculated every cost component independently as annual costs, and then summed them to determine the total lifecycle costs for the whole treatment train (TT). The different cost components are calculated for each unit process independently. Then, dividing the "total lifecycle costs for the whole treatment" by the annual volume of reclaimed water, we obtained the annualized treatment costs in (CUR/m^3) of reclaimed water (Equation (3)):

$$Treatment\ Cost_{Ann} = \sum_{i=1}^{N} (CAPEX_{Ann} + O\&M_{Ann} + Land_{Ann} + Energy_{Ann} + Labour_{Ann})/V_{Ann}, \quad (3)$$

where

$Treatment\ Cost_{Ann}$ = annualized unit cost of treatment per m^3 of reclaimed water (CUR/y/m^3)

N = number of unit processes i in the treatment train (TT) considered (-)
$CAPEX_{Ann}$ = annualized capital cost of unit process i (CUR/y)
$O\&M_{Ann}$ = annualized operation and maintenance cost of unit process i (CUR/y)
$Land_{Ann}$ = annualized land cost of unit process i (CUR/y)
$Energy_{Ann}$ = yearly energy cost of unit process i (CUR/y)
$Labour_{Ann}$ = yearly labor cost of unit process i (CUR/y)
V_{Ann} = volume of reclaimed water produced annually (m^3/y)

To calculate the total capital expenditure (CAPEX) for every unit process, the standard capital cost algorithm presented in Table 8 was used.

Table 8. Standard capital cost algorithm applied (adapted from [24,46,50]).

Factor	Used in the System	Default Value
Equipment cost (EC)	Technology-specific cost from the regressions defined as construction cost (Equation (2))	EC
Construction cost (CC)	Equipment installation (site development), piping, instrumentation, and controls	39% of EC
Indirect cost	Engineering + contingency	27% of CC
Total capital expenditure (CAPEX)	Total construction cost + total indirect cost	CAPEX = EC + 0.39 EC + 0.27 (EC + 0.39 EC) = (1.39 EC) 1.27 = 1.77 EC

The resulting total capital costs were annualized based on the expected life span of every considered unit process. The total capital cost multiplied by CRF results in annualized capital costs. For the annual values, the capital recovery factor (CRF) from Equation (4) was used. The same cost recovery factor was applied to annualize the land costs.

$$CRF = \frac{r \times (1+r)^n}{(1+r)^n - 1} = \frac{r}{1-(1+r)^{-n}}, \quad (4)$$

where

CRF = capital recovery factor (y^{-1})
r = discount rate (-) $\approx i - p$ (Fischer equation); i = nominal interest rate (-), p = actual inflation rate (-)
n = expected life span of the unit process (y)

2.5. Distribution Component

For comparable and easily understandable results, the distribution costs were also calculated in costs per m^3 of reclaimed water based on the annual lifecycle costs. The calculation of the total annual distribution of lifecycle costs allows the consideration of one transport pipe from the wastewater source to the treatment scheme, a storage tank, and another transport pipe to the end-use location (Figure 3). The detailed calculation procedure for the different distribution cost components are depicted in Appendix A and requires the different elevations, the flow rate, and the volume for the storage tank. Equation (5) is applied for the calculation of the annualized distribution costs per m^3 of reclaimed water.

Figure 3. Schematic representation for the distribution components and information required for the cost calculation (grey).

$$Distribution\ Cost_{Ann} = (Pump1_{Ann} + Pipe1_{Ann} + Storage_{Ann} + Pump2_{Ann} + Pipe2_{Ann})/V_{Ann}, \quad (5)$$

where

$Distribution\ Cost_{Ann}$ = annualized unit cost of distribution per m^3 of reclaimed water ($CUR/y/m^3$)
$Pump1_{Ann}$, $Pump2_{Ann}$ = annualized pumping costs (CUR/y)
$Pipe1_{Ann}$, $Pipe2_{Ann}$ = annualized piping costs (CUR/y)
$Storage_{Ann}$ = annualized storage costs (CUR/y)
V_{Ann} = volume of reclaimed water distributed annually (m^3/y)

2.6. Assessment Criteria

Valid options of treatment trains cannot alone be identified only based on meeting quality requirements of available reuse applications. To propose options adapted to local environmental, economic, and social conditions, different trains should be compared based on a broader scope of criteria. This is important since the pre-feasibility stage normally involves a consultation process between stakeholders.

The database of the technical assessment, requirements, impacts, and cost assessment criteria listed in Table 9, for all the unit processes included in the DST (Table 2), is provided in Supplementary Materials [45]. The qualitative criteria are fixed per unit process based on work by [1], and reviewed in expert workshops. Whereas the semi-quantitative criteria are based on quantitative estimations described in Section 2.3 and therefore depend on the local conditions specified by the user (e.g., volume of water treated, cost of electricity, etc.). Those quantitative values are then normalized to a value between 0 and 3 (to remain consistent with a range of other criteria) within the considered set of treatment trains. Consequently, they result in being semi-quantitative.

Important factors include the following aspects, namely, reliability of the process, ease of upgrading if the wastewater stream increases (e.g., due to population growth), adaptability to varying wastewater flows and qualities (e.g., seasonal differences), ease of construction, operation, management, and demonstration. Significant operational requirements and environmental impacts are evaluated for each unit process. This includes energy demand (which is often the most important operational cost), chemical demand (e.g., chloride, coagulants), land requirement (area needed to install a certain unit process), impact on groundwater, odor generation, and quantity of sludge production (depending on available area and transport infrastructure, generated sludge can lead to significant cost for transport and disposal). The third category considers the costs through annual lifecycle capital costs, land costs, energy costs, labor costs, other operational and maintenance costs (e.g., sludge disposal, chemicals required for operation), and total annualized lifecycle costs (Table 6).

Table 9. Overview of selected assessment criteria for multi-criteria analysis with information on qualitative or semi-quantitative aspects. The values are normalized between 0 and 3: (0 = nil, 1 = low, 2 = medium, and 3 = high).

Technical Assessment Criteria (TE)	Requirements and Impacts (RI)	Costs (C)
Reliability (Qualitative)	Power demand (Semi-quantitative)	Annualized capital costs (Semi-quantitative)
Ease to upgrade (Qualitative)	Chemical demand (Qualitative)	Land cost (Semi-quantitative)
Adaptability to varying flow (Qualitative)	Odor generation (Qualitative)	Energy cost (Semi-quantitative)
Adaptability to varying quality (Qualitative)	Impact on groundwater (Qualitative)	Labor (Semi-quantitative)
Ease of operation & maintenance (Qualitative)	Land requirement (Semi-quantitative)	Other operation and maintenance cost (Semi-quantitative)
Ease of construction (Qualitative)	Quantity of sludge production(Semi-quantitative)	Total annual costs of treatment (Semi-quantitative)
Ease of demonstration (Qualitative)		

Treatment Train Overall Assessment Score

The calculation of an overall assessment score for different treatment trains was determined by Equation (6). The user can assign different weights W_i to different assessment criteria depending on the local situation. For the calculation of the overall assessment score, all criteria were recalculated to a range between 0 and 1 and the semi-quantitative indicators were normalized. The criteria defined in Table 9 between 0 and 3 were divided by 3, and the semi-quantitative criteria divided by the highest value of the list of treatment trains considered in the DST. For the requirement, impact, and cost (RIC) criteria, for which a higher score was a negative characteristic, the formula $1 - RIC/3$ was applied to obtain a final overall assessment score (high score is positive).

$$OE^{TT} = 3 \cdot \left\langle \frac{\left[\sum_{i=1}^{N} W_i \times \left(\frac{TE_i^{Qual}}{3}\right)\right] + \left[\sum_{i=1}^{N} W_i \times \left(1 - \frac{RIC_i^{Qual}}{3}\right)\right] + \left[\sum_{i=1}^{N} W_i \times \left(1 - \frac{RIC_i^{Semi-Q.}/3}{MAX\overbrace{\left\{RIC_{i,j}^{Semi-Q.}\right\}}^{j}/3}\right)\right]}{\sum W_i} \right\rangle, \quad (6)$$

where

OE^{TT} = treatment train overall assessment score (-) (range 0–3)
W_i = weight of criteria i (-) (range 0–4, user-defined)
N = number of assessment criteria (-)
TE_i^{Qual} = Technical assessment qualitative criteria i score (-) (range 0–3)
RIC_i^{Qual} = requirement, impact, and cost qualitative criteria i score (-) (range 0–3)
RIC_i^{Semi-Q} = requirement, impact, and cost semi-quantitative criteria i score (-) (range 0–3)
$MAX\overbrace{\left\{RIC_{ij}^{UP}\right\}}^{j}$ = maximal value of requirement, impact, and cost semi-quantitative criteria i within the j amount of treatment trains included in the DST (-) (range 0–3)

2.7. Screening of Water Reuse Options: Ranking, Filtering, and Comparison

The chosen approach for the sequential decision optimization is a screening approach. In this approach, information provided by the user on water quality and local parameters did rule out options that did not meet the minimal requirement. The minimal requirements were determined before running an assessment and ranking algorithm for the water reuse remaining options. In short, the DST includes a set of unit processes and treatment trains, and the user can specify certain parameters. The DST does calculate the performance of every unit process and treatment train included in the database for the provided parameters, and does then apply an assessment algorithm to present a ranking of options. These options comply with the minimal requirements and result in the highest overall score.

To analyze each scenario based on the input data provided (available wastewater to be reused, intended reuse, and several locally specific characteristics required for the calculation), the system will calculate the following parameters:

- Pollutant removal performance of every treatment train included in the system
- Specific lifecycle treatment costs
- Overall score of multi-criteria analysis based on normalization and local weighting (OE^{TT})

On this basis, the DST proposes an assessment algorithm that provides a ranking of options while meeting the minimal requirements (Figure 4). The algorithm proposes three different assessment methodologies that derive a ranking from the list. The first method (1) eliminates all treatment trains that do not comply with the quality requirements (based on the maximal removal performance of each unit process). Then, a ranking is made based on the weights for each single indicator, which was defined by the user. The second method (2) first eliminates all treatment trains that do not comply with the required quality, and then ranks only the three options with the lowest lifecycle treatment costs. The user can then evaluate the three options by analyzing the calculated set of assessment criteria. The third method (3) is primarily intended for experts, and enables a targeted selection of the best options. These best options base on a manual or subjective assessment of all presented assessment criteria.

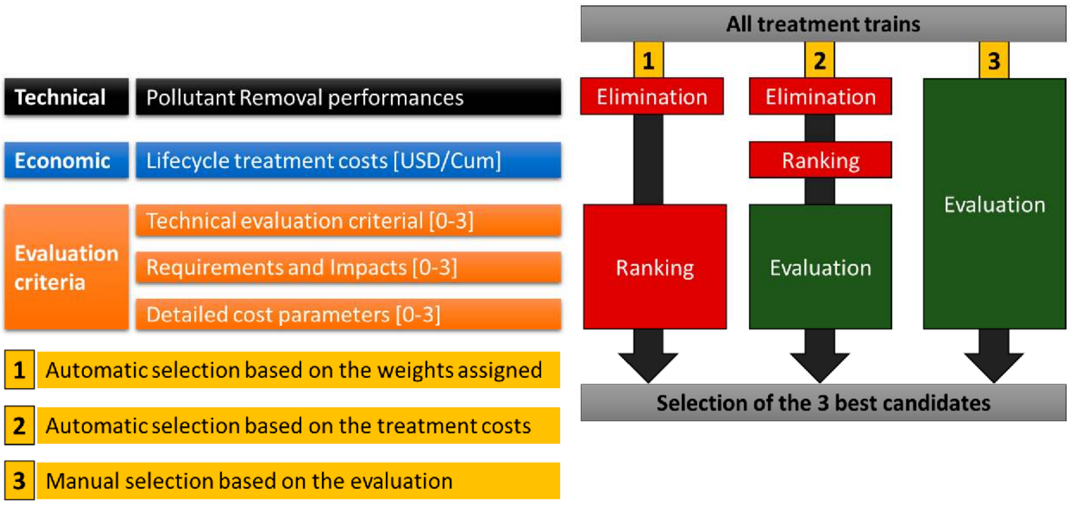

Figure 4. Assessment algorithm proposed by the stage II assessment.

3. Results

3.1. Main Novelties and Approaches in the Resulting DST

From the list of existing DSTs presented in the introduction, WTRNet [16], WAWTTAR, [13] and WASWARPLAMO [20] are the three main tools that inspired this research. Several data and approaches have been adapted from those tools, and they are transparently cited. The main advances of the DST presented in this paper, compared to those existing tools, include:

- Different scope of application. This means the main target of the DST is capacity-building and promoting the concept of water reuse at the pre-feasibility stage, whereas the other tools focus more on technical design. These tools support the creation of treatment trains for engineers and planners.

- Universal approach and user interface. The DST is generic, usable, and considers a system analysis approach for a broad target group. With the current DST, an analysis can be made by specifying three inputs, i.e., quantity and quality of reusable wastewater, and intended reuse.
- Pre-selected information is included in the tool, and the calculations are performed in the background. Benchmark treatment trains, unit process descriptions and specifications, water quality classes, lifecycle cost calculation algorithm, and several data—presented in Supplementary Materials—are included in the tool.
- A multi-criteria assessment is included to compare different options based on different weighting factors that can be defined by the end-user (Table 9).
- The DST and all underlying data are open-access and used by everyone, as the DST is based on Microsoft Excel. Several other tools are not publicly available or use outdated software. The database references are transparently cited, up-to-date, and complete. With the open-access publishing of the outcome, we allow future research to improve and complement both the data and the DST.

3.2. Resulting DST and Guidance for Use

The first version of the resulting DST is open access, and can be found on the Zenodo repository together with a handbook with guidance for use [51]. This handbook provides detailed instructions that are too extensive to be included in this paper. Key features from the DST are presented in Figures 5 and 6. First, the user needs to become familiar with the informative sections describing the unit processes, treatment trains, and water quality classes included in the DST. Secondly, the user needs to enter data for a first assessment, on the starting tab (Figure 5).

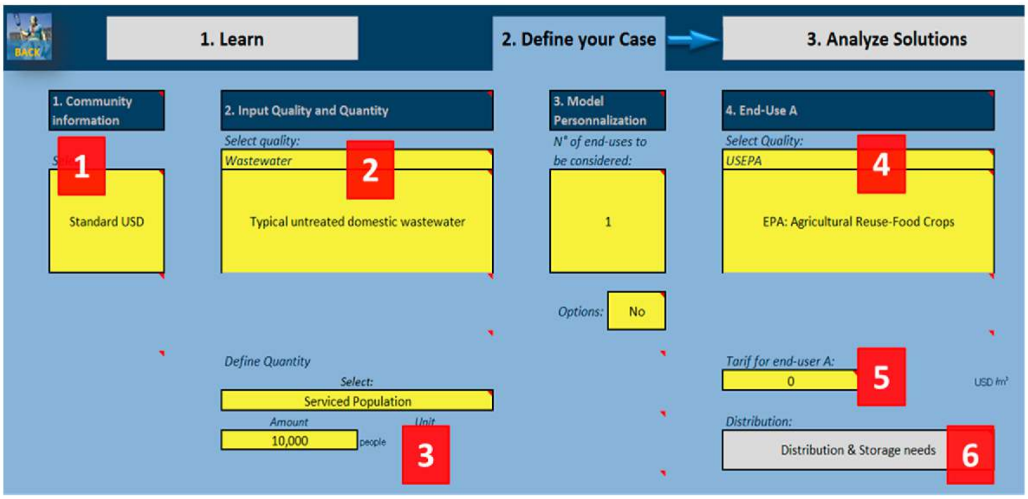

Figure 5. Data input in simple mode.

1. Community information: the user can either select a pre-defined profile or specify a national currency. The exchange rate is USD-2006. There is other information related to labor, electricity, land costs, nominal interest, and inflation rates.
2. Input quality: the water or wastewater quality for treating can be specified here, either by selecting from a list of pre-defined types of wastewater or by specifying up to 12 quality parameters manually.
3. Input quantity: the quantity of water or wastewater for reuse can be specified.

4. End-use quality: The water quality required for the intended end-use after treatment can be specified by choosing from a list of pre-defined quality classes or by indicating the water quality parameters manually.
5. Price of reclaimed water: input of the selling price to the intended end-user.
6. Distribution and storage needs: the user can indicate the required pipes length, the elevation differences, and the land type to calculate the piping and pumping costs for both the input wastewater and output reclaimed water. The need for storage facility can also be specified and corresponding costs are calculated.

Furthermore, it is possible for the user to manually define three specific treatment trains that are composed of up to 10 unit processes. Additionally, it is possible to add additional unit processes. Based on those input data, the Excel tool calculates the performance, cost, and other assessment criteria for all the treatment trains included in the system (Figure 4). On this basis, it proposes a ranking for valid options. A screenshot of the results is presented in Figure 6. The detailed results are also available in a tabular representation in the DST. In the screenshot of graphical results, a range of information is displayed and can be numbered into the following 8 features (highlighted in red):

1. Recapitulation of the data input (input quality and quantity, output quality, and distribution)
2. The three best options are displayed in the colors (red, blue, and green). For each option, the name of the treatment train is displayed with the overall treatment train score. This score bases on the assigned weights and the recovery percentage. The chosen limit for the output quality required is indicated in orange.
3. The chart displays the pollutant removal performances under minimum, average, and maximal performance. The limit is shown in orange. The user can see how well the three options perform. There are two scales, namely, on the right for most quality parameters in NTU (turbidity) or mg/L, and on the left for logarithmic for fecal coliform, total coliform, and virus (in n°/100 mL).
4. The specific costs are presented in the selected currency per cubic meter. Cost − revenue is the cost of treatment and distribution minus the foreseen selling price to the end-user. If this value is negative, the selected option would produce monetary profits. The specific costs are calculated with the lifecycle cost methodology (OPEX, CAPEX, cost of capital through interest rate, electricity costs, labor costs useful life, etc.).
5. The assessment of the criteria results is displayed. The values are between 0 and 3: 0 = nil, 1 = low, 2 = medium, and 3 = high. For the criteria, a high value is considered as positive for the calculation of the overall treatment train score. This score bases on the weights, which are displayed under the option name (point 2).
6. The results for requirements, impacts, and costs are displayed. The values are between 0 and 3: 0 = nil, 1 = low, 2 = medium, and 3 = high. For those criteria, a high value is considered as negative for the calculation of the overall treatment train score. This score is based on the weights, which are displayed under the option name (point 2).
7. The three buttons are links to the "Learn" component. Depending on the option selected, the user can look in the database to understand the details of each treatment train, unit process, and water quality class.
8. If no treatment train complies with the required water quality, the user can choose how many water quality parameters should comply with the requirements (e.g., 2 out of 3).

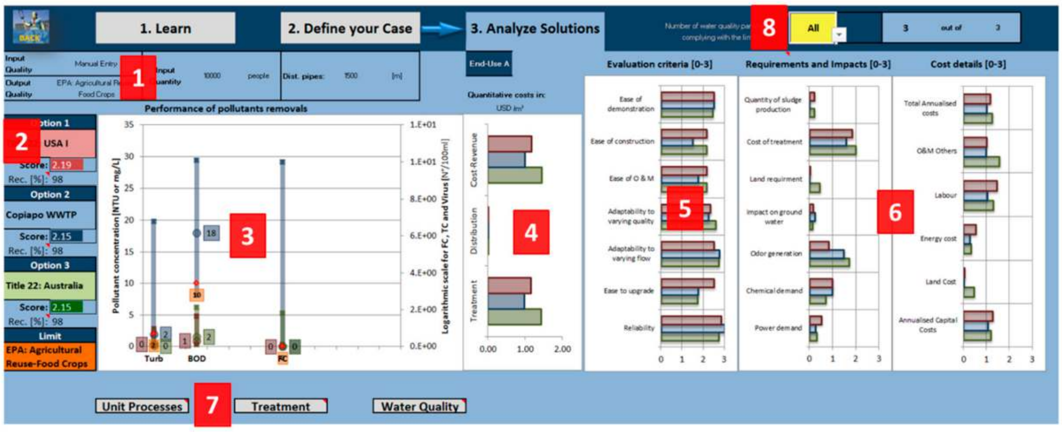

Figure 6. Example results sheet.

3.3. Plausibility Checks and Proof of Concept

To assess the plausibility of the calculated results with the DST, in the first stage, 13 treatment trains were simulated based on literature information (Table 10) [29,35]. In the second stage, the resulting removal performance of pollutants included in the reference were compared under the same indicated wastewater quality (Figure 7).

Table 10. Treatment trains considered for the plausibility checks ([29,35]).

Process Type and Location	Unit Processes Used in the DST
P1—Jamnagar Export Refinery Project	Equalization basin; low-loaded activated sludge with de-N + seccondary sedimentation; dual media filtration; activated carbon; chlorine dioxide
P2—Water resource management V Valley	Chlorine gas; dual media filter; ultrafiltration; activated carbon; chlorine gas
P3—Recirculating vertical flow constructed wetland (RVFCW) Israel/Peru	Constructed wetland; dual media filtration; UV-disinfection
P4—Mexico San Luis Potosi Agricultural reuse	Grit chamber; sedimentation with coagulant; constructed wetland
P5—Mexico San Luis Potosi. Industrial reuse	Grit chamber; sedimentation with coagulant; low loaded activated sludge + secondary sedimentation; dual media filtration; ion exchange
P6—Beetham WWTP Trinidad and Tobago	Bar screen; grit chamber; extended aeration; sedimentation without coagulant; UV disinfection
P7—Emergency potable reuse in Chanute Kansas	Bar screen; grit chamber; sedimentation with coagulation; trickling filter with secondary sedimentation; chlorine gas
P8—Direct potable reuse treatment process Denver: Ultrafiltration	Sedimentation with coagulant; dual media filtration; ultraviolet disinfection; activated carbon; ultrafiltration; ozonation; chlorine gas
P9—Direct potable reuse treatment process Denver: Reverse osmosis	Sedimentation with coagulant; dual media filtration; ultraviolet disinfection; activated carbon; reverse osmosis; ozonation; chlorine gas
P10—Constructed wetlands Turkey	Anaerobic stabilization pond; constructed wetland
P11—Title 22 Greece	Bar screen; grit chamber; sedimentation without coagulant; low loaded activated sludge with de-N + secondary sedimentation; dual media filter; chlorine dioxide
P12—Soil Aquifer Treatment Israel	Bar screen; grit chamber; low loaded activated sludge with de-N + secondary. sedimentation; soil aquifer treatment; chlorine gas
P13—Building MBR: Japan	Bar screen; grit chamber; MBR; activated carbon; chlorine dioxide

In Figure 7, the simulated pollutant removal efficiencies are compared to the literature values for all included parameters. More than 70% of all considered parameters of removal efficiency have less than 20% difference between the literature value and the simulated results. Nevertheless, the relative error is smaller for seven parameters (BOD, COD, TSS, FC, Turbidity, TC, and TOC), whereas four parameters show a higher relative error (TN, TDS, TP, and Nitrates) (Figure 8). If only the removal efficiency of the first seven parameters are considered, around 90% of all parameters have less than 20% difference between the literature value and the simulated results.

The higher relative error for TDS and Nitrates is because of that in some unit processes, the total dissolved solids (and the conductivity) increases. This applies for the nitrates as well, since their concentration increase after the nitrification processes. These concentrations increase would require a more sophisticated model that is beyond the scope of the present DST. The discrepancy of the TN and the TP results is due to simplifying the modeled process compared to the reference processes, and probably some inaccuracies on the removal performances database for those two parameters.

As a result, those estimated removal performances provide a first estimate for the pre-feasibility stage intended by the DST developed. While applying the DST to a case study, the user should consider the results of the presented plausibility checks and consider the results on TN, TP, TDS, and Nitrate as indicative only. A note is included in the DST and it is advised not to use those four parameters as elimination criteria.

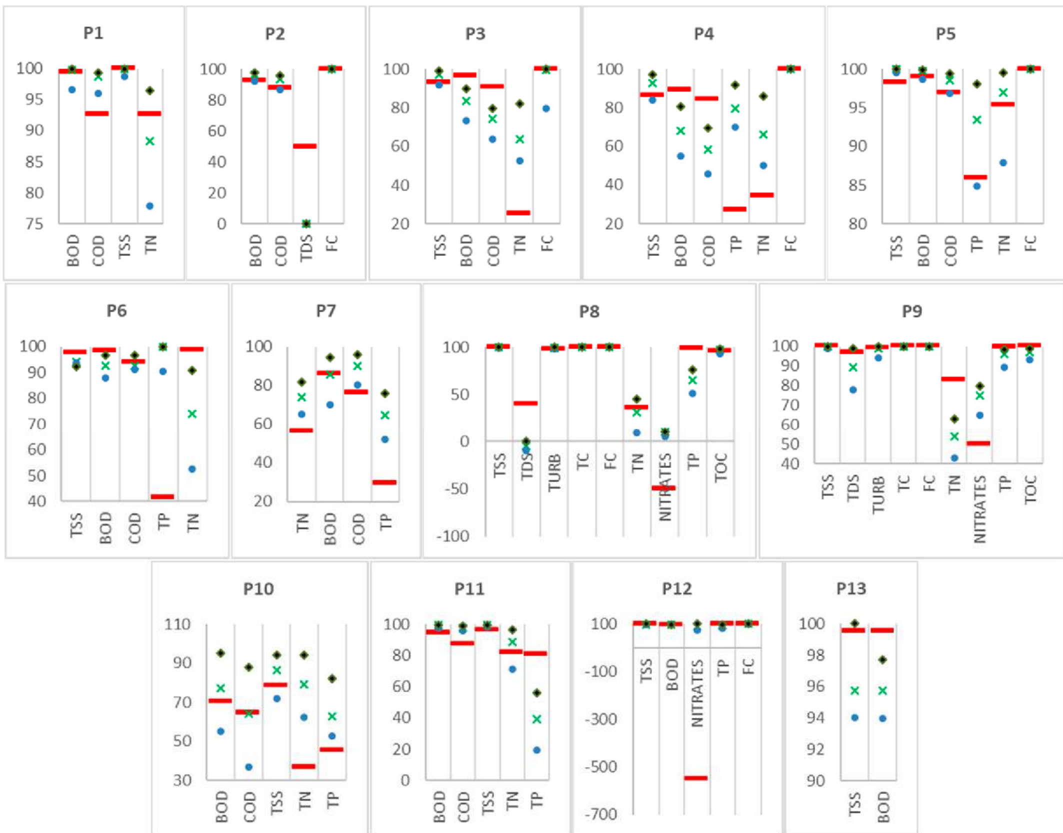

Figure 7. Plausibility check of the 13 simulations P1–13 results. The *y*-axis shows pollutant removal efficiencies (%) for the literature value (–) and for the DST simulation operating under minimal (●), average (×) and maximal (◆) unit processes efficiencies.

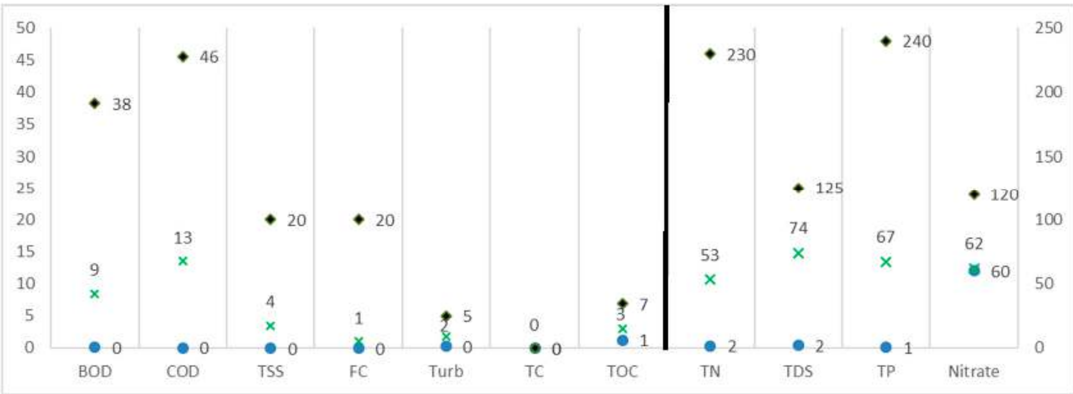

Figure 8. The *y*-axis presents the relative error for different water quality parameters in (%). The first 7 parameters simulation operating under minimal (●), average (×) and maximal (♦) unit processes efficiencies refer to the primary axis on the left and the last 4 parameters to the secondary axis on the right.

4. Discussion

The developed DST enables a quick screening of options. It can perform a pre-feasibility study and supports the promotion of water reuse in regions, where it is still an emerging concept. The DST enables identifying and comparing possible treatment trains that met the local requirements. If a case study shows a potential for water reuse, the reuse implementation can be fostered. The DST covers a broad range of scenarios for water reuse and diverse stakeholders can understand the results. However, an actual implementation of a water reuse scheme implies additional local specificities and technical information details, which are not covered in the DST. These results enable an identification of potential options that should be considered in a more detailed study.

The key application of the DST is capacity building. This is already implemented in the master curriculum of the University of Applied Sciences and Arts Northwestern Switzerland (FHNW), the Agricultural University of Athens (AUA), and elsewhere internationally (e.g., Morocco, Netherlands). The students can use the DST to investigate different unit process characteristics, their interactions in treatment trains, and gain a systemic understanding of the complex topic of water reclamation. The tool can be used as a "sandbox" for several exercises and scenario comparisons.

Additionally, the DST has been integrated into the COROADO online decision support system. There the technology selection is applied to the Latin American context, and linked with other analyses regarding water vulnerability [52]. This integrated online system will be subject to other publications.

The created underlying datasets are additional central outputs of this research besides the DST itself. The data aggregation, published in open access, allows the estimation of the removal performances, the lifecycle capital, operational costs, and additional assessment indications for most unit processes. This was implemented for wastewater treatment and water reclamation in a simple manner. The cost component is an important piece of information for the viability, comparison, and selection of the different treatment trains, since the cost is often the key aspects. By using costs per cubic meter makes, it them easily comparable and understandable of the influence of different factors. Additionally, the required further costs can be calculated, e.g., the total CAPEX. The equipment costs and, therefore, the total capital cost for every unit process can be calculated independently for every possible flow between 10 and 20,000 m^3/day. Similarly, by combining different water quality guidelines together, and by proposing a holistic approach to water reuse, possibilities for future interdisciplinary research can emerge. This could include the use of another support (e.g., online-based tool), the inclusion of additional technologies, the combination with complementary solutions (e.g., irrigation technologies) or the internationalization of concepts.

This DST will be further developed in other projects. It is foreseen to broaden the DST's application field by adding more technologies and updating the underlying database. It is also important to develop additional training material to allow tool application at a large scale. In this sense, the DST presented in this paper is being upgraded in the European project "MadforWater". Thereby, integrated technological and managerial solutions for wastewater treatment and efficient reuse in agriculture tailored to the needs of Mediterranean African Countries are being developed [53].

Supplementary Materials: The following are available online on the Zenodo open access repository:

1. Poseidon—Decision Support Tool for Water Reuse (Microsoft Excel) and Handbook, doi:10.5281/zenodo.1971933 [51]
2. Wastewater Treatment Unit Processes Datasets: Pollutant removal efficiencies, evaluation criteria and cost estimations, doi:10.5281/zenodo.1247434 [45]
3. Treatment Trains for Water Reclamation (Dataset), doi: 10.5281/zenodo.1972627 [27]
4. Water Quality Classes - Recommended Water Quality Based on Guideline and Typical Wastewater Qualities, doi:10.5281/zenodo.1252341 [33]

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Appendix A. Distribution Costs Calculation

This appendix describes the calculation procedure applied to calculate annualized distribution costs.

Appendix A.1. Pumps

The calculation for the distribution component has been taken from [24] that is based on [54,55]. The following two main equations are used for the pumping costs calculation:

Pumping capital costs:

$$\text{CAPEX} = (21{,}715 \times \text{H} \times \text{Q}^{0.52}) \quad \text{(A1)}$$

where:

CAPEX = pumping station capital cost [CUR]

H = required pumping head [m]

Q = design flow rate [L/s]

Note: Additionally, 5% of the capital cost is used for annual maintenance. For the annualisation of the capital costs, a life span of 15 years is used and the same procedure with the Capital Recovery Factor is applied.

Pumping costs required:

$$CE = \theta_{hp} \times C_e \times \frac{V_{ann} \times H}{2.7 \times \eta} \quad \text{(A2)}$$

where:

CE = Annual cost of energy required for pumping [CUR/a]
θ_{hp} = conversion factor to kWh (θ_{hp} = 0.746)
C_e = unit cost of energy [CUR/kWh]
V_{ann} = volume of water pumped annually [m^3/a]
H = pressure head required at the pump [m]
η = pump efficiency [%], (default value of 0.65)

Appendix A.2. Storage Facilities

Four different types of storage are considered: reservoir, concrete tank, covered concrete tank and earthen basin. The following equation is applied for the costs calculation:

$$UCS = C_1 \times V^{C_2} \quad \text{(A3)}$$

where:

UCS = Unit cost of storage facility [CUR]
C_i = Cost coefficients from Table A1
V = Storage volume [m^3]

Note: Additionally, 0.5% of the capital cost is used for annual maintenance. For the annualisation of the capital costs, a useful life of 30 years is used and the same procedure with the Capital Recovery Factor is applied.

Table A1. Storage facilities cost coefficients.

Storage Type	C_1	C_2
Reservoir	15,093	−0.60
Concrete tank	1238	−0.19
Covered concrete tank	5575	−0.39
Earthen basin	128	−0.24

Appendix A.3. Pipe

The cost curves for the pipe cost also come from [24] that derived the equations from data on the costs of installed pipes provided by UK water companies, reported in [56]. The model proposes pipe costs coefficient for three different types of land use: grassland, rural/suburban and urban. The following equation is applied:

$$CP = C_1 \times e^{C_2 \cdot D} \quad \text{(A4)}$$

where:

CP = Pipe unit cost [CUR/m]
C_i = Cost coefficients from Table A2
D = Pipe diameter [m]

Note: Additionally, 3% of the capital cost is used for annual maintenance. For the annualisation of the capital costs, a useful life of 50 years is used and the same procedure with the Capital Recovery Factor is applied.

Table A2. Pipe unit cost coefficients.

Land Use	C_1	C_2
Grassland	47.47	3.51
Rural/suburban	96.19	3.07
Urban	129.42	2.72

Appendix A.4. Required Parameters

Based on the cost curves equations described in previous chapters, the following parameters (Table A3) are required to calculate all incurring distribution costs:

Table A3. Input parameters required for the calculation of the distribution costs.

Parameter	Unit	Note
Length of pipe	m	Defined by the user
Pipe Diameter (D)	mm	Calculated by the simple design model presented in Section A7.
Total elevation difference (+uphill, −downhill)	m	Defined by the user. Please note that a negative elevation will not bring revenue to the model but will only annihilate the head due to friction and result in costs of zero for pumping. If the user plans to recover the energy, it has to be calculated independently by introduction of a turbine.
Volume of pumped water (Vann)	m^3/a	Calculated by the system based on the flow (if the distribution is before the treatment, the inflow is used; if it is after the treatment, the flow calculated with the treatment train recovery is used)
Pressure head required at the pump (H)	m	Calculated with the Hazen-Williams equation as described in Section A6.
Design flow rate (Q)	L/s	Calculated by the system based on the flow (if the distribution is before the treatment, the inflow is used; if it is after the treatment, the flow calculated with the treatment train recovery is used)
Storage volume (V)	m^3	Defined by the user

The biggest challenge in estimating costs for distribution is to estimate the appropriate design, namely the diameter of the pipes that will influence the velocity, pumping costs and piping costs. Once the design is fixed, the head loss can be calculated and added to the elevation to calculate the pressure head required for pumping.

Appendix A.5. Calculation of the Frictional Head Loss

To calculate the pressure head required for pumping, the Hazen-Williams equation is used. Note that the Hazen-Williams formula is empirical and lacks a theoretical basis. Be aware that the roughness coefficient are based on "normal" condition with approximately 1 m/s.

$$h_f = L \times \left(\frac{10.67 \times Q^{1.85}}{C^{1.85} \times d^{4.87}} \right) \tag{A5}$$

where:

h_f = head loss over the length of pipe [m]
L = length of pipe [m]
Q = volumetric flow rate [m^3/s]
C = pipe roughness coefficient (default value of 140)
d = inside pipe diameter [m]
Note: in the DST the equation with imperial units is used and converted.

Appendix A.6. Calculation of the Pressure Head Required for Pumping

$$H = h_f + Elevation \tag{A6}$$

where:

H = pressure head required at the pump [m]

h_f = head loss over the length of pipe [m]

Elevation = altitude difference between the beginning and end of the pipe, positive or negative. [m]

Appendix A.7. Simple Design Model for the Definition of the Pipe Diameter

The only unknown parameter is the inside pipe diameter. To determine this parameter, the assumption has been made that the velocity of the fluid should be 1 m/s. If the water velocity is fixed, the internal diameter can be obtained by using the following equation:

$$d = 2000 \times \sqrt{\frac{Q}{v \times \pi}} \tag{A7}$$

where:

d = Inside pipe diameter [m]

Q = Volumetric flow rate [m^3/s]

v = Flow velocity [m/s] (default value of 1)

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APPENDIX II PUBLICATION – WATER UTILITY COMPASS

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Application of a Decision-support System for Water Loss Reduction to the Case of a Water Supply System in Lithuania

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Abstract

For many water utilities worldwide, tackling the topic of water loss reduction is an event-driven strategy and a long term planning involving strategic approach is hardly applied. The water loss levels are very different between European countries as water losses vary from 7% to 50%. Lithuanian water utilities average water loss level of about 30% of total water supply.
Efficient water loss reduction requires a good understanding of the water utility and often involves actions related to different categories such as data and metering, network documentation, water balance and performance indicators, district metered areas, active leakage control, pressure management, infrastructure management, operation and maintenance, apparent losses, human resources, equipment and budget, organization, managerial commitment and public awareness. The complexity and abundance of parameters to be considered require the use of supporting tools and methods in order to work in a systematic way and propose most adequate measures.
This paper presents a unique decision-support system (DSS) that aims to help engineers and manager approach their water utilities in a holistic way by first evaluating the baseline and analysing the current situation by identifying where are priority areas with most potential in order to finally support the action planning of most appropriate measures.
The DSS has been applied to the case of a Lithuanian water utility with a 400 km water supply network connected to 57,000 water users. The system operates with an average pressure of 60 m and the current level of Non-Revenue Water in the

system was 704,000 cubic meter per year in 2011. The application of the DSS to this case study allowed to process to a full evaluation of a typical Lithuanian water supply network by supporting the establishment and implementation of a tailor-made three-year action plan and reducing Non-Revenue Water by 40%.

Keywords: water loss reduction; decision support system; water utility; performance indicators; water balance; assessment; strategy; action plan.

1 Introduction

1.1 The challenge of water loss reduction

In the field of drinking water supply and efficient water management, the topic of water loss reduction is crucial for a sustainable management of water resources. For many water utilities, tackling water losses is still part of an event-driven strategy and the long term planning and implementation of a strategic approach is challenging. The topic of water loss reduction being very complex, it is often complicated to have the big picture and to really make sound and efficient decisions. In effect, analysing the non-revenue water of a water utility and its causes quickly undercovers further underlying aspects, such as organisation, data, metering and knowledge of the network, human resources, equipment, water tariff, budget as well as managerial commitment and public awareness. Developing a sound strategy for water loss reduction often involves actions and measures involving cross-cutting issues that should be implemented in a coordinated manner.

The International Water Association (IWA) developed a wide range of guidance notes and technical documents presented and discussed during international conferences. However, most of the recommendations take time to be applied as habit changes are difficult. For example, the use of percentage of non-revenue water is still widely used to set targets rather than the Infrastructure Leakage Index (ILI) or other more appropriate indicators. Also, the IWA only provides its recommendations in English language and there is no official terminology involved for other languages [1]. In this regard, the Strategic Alliance for Water Loss Reduction developed a handbook translated into several languages that supports water utilities around the world to apply the IWA best practices [2, 3].

1.2 Need for a holistic decision support system

In order to support water utility managers to analyse their present situation of non-revenue water and to develop an adequate strategy, several decision-support systems (DSS) and help for calculation have been developed (table 1). Many DSS support the calculation of a water balance and main performance indicators based on IWA or other recommendations (EU, national regulations), sometimes including the error calculation according to the 95% confidence limit method. Some DSS focus on some water loss reduction measures, such as pressure management or active leakage control or a more exhaustive list of measures [4, 5]. Other DSS provide support for auditing water utilities and supporting the management and the development of a strategy (e.g. defining the economic level of leakage). If most listed DSS (table 1) have useful features for different purposes, there is no DSS that takes a holistic approach and include everything in a simple way in a single tool that can be applied worldwide and many of the existing tools require expert knowledge to be correctly applied and analysed or require the involvement of a consultant.

Table 1: Most prominent Decision Support Systems.

Name (with hyperlink)	**Main features**
ALCCalcs	Active Leakage Control
AWWA Free Audit Software	This spreadsheet-based water audit tool designed to help quantify and track water losses associated with water distribution systems and identify areas for improved efficiency and cost recovery. The tool is still founded upon the principles of the M36 Water Audit [6] methodology.
AZPandNDFCalcs	This free software explains how to identify and record the location of the Average Zone Point, and how to calculate the Night Day Factor by analysing pressure measurements taken at the Average Zone Point.
CalcuLEAKator	Water Balance and Performance Indicators calculation in accordance with IWA methodology using " bottom - up" approach.
Checkcalcs	Leakage and Pressure Management Opportunities.
ELLCalcs	Economic Leakage Levels.
EurWB&PICalcs	Software is designed to be used in the ‘Getting Started’ methodology to provide a quick assessment of current leakage management and ‘fit for purpose’ leakage performance indicators for any Utility system or sub-system, with quick simple sensitivity testing. Calculation based on EU Reference document [4].
PIFastCalcs	Water Balance & Performance Indicators.
PressCalcs	Pressure Management.
Waterloss DSS	Decision support tool and a prioritized list of measures for controlling water losses, adapted to regional conditions.
WB-Easycalc	Multi-lingual water balance and water loss performance indicator software.

1.3 Task and structure of the paper

This paper presents the development of a DSS aiming to apply a holistic approach for water loss reduction and includes most relevant features in one single Excel File, which results can be easily understood by non-experts and managers of the water utility. As the topic of water loss reduction involves more considerations than only isolated and uncoordinated measures, this innovative approach is considering main business areas of water utilities influencing water losses in a systemic way in order to identify priority areas and the DSS should also support the calculation of key performance indicators including the error calculation and propose a list of measures in order to support the elaboration of an adequate and realistic action plan. This paper presents the main features and content of this innovative DSS using a new holistic approach through its application of the case of Alytus water utility in Lithuania.

1.4 Description of the area

Alytus is a city in southern part of Lithuania, about 105 km from its capital Vilnius. The population in 2013 was 57,281 and the city is the capital of the region. The local municipality owns the Water Utility. Alytus Water Utility is responsible for water and wastewater services for Alytus city. Groundwater is the only source for the city water supply, taken from two well fields, consisting of 19 wells, where depth varies from 40 to 130 m. Both well fields have water treatment facilities where iron and manganese is removed in open filters. Due to hilly terrain, pressure in the distribution network is kept rather high at about 40-70 m with a few pressure reduction zones implemented where pressure was becoming unacceptable high. In the network, seven local booster pumps exist for high raised blockhouses.

Price for water and wastewater services was 2.13 Eur/m^3 in 2015, where drinking water part consists of 34%. Direct cost for water extraction, treatment and supply to the network is 0.14 Eur/m^3. Average water supply for the city was 8,200 m^3 per day in 2015. Citizens are the biggest water consumer with a share of about 62% of total usage. The oldest part of water network is coming from the sixties, but the major part was constructed during 1970-1985. Total length of water distribution and service lines is about 400 km, mainly consisting of cast iron and PE. Steel pipelines were hardly affected by corrosion and have therefore almost all been replaced.

For many years, the Non-Revenue Water level in the Alytus water supply network was more than 700 thousand m^3 per year. In 2012, the company therefore started an extensive project for water losses reduction, for which the developed DSS was applied and results are presented in this paper.

2 Material and Methods

2.1 Architecture of the DSS

The DSS called Water Utility Compass (WU-Compass) is split into four sections, each with a different focus (fig. 1).

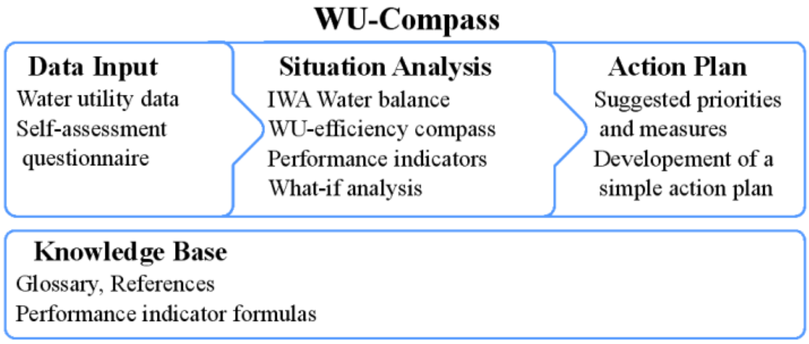

Figure 1: Structure and components of the WU-Compass.

The first section (Data Input) contains most of the forms for the user input including a tab which collects the most important statistics about the water supply company and a self-assessment questionnaire composed of 14 main categories influencing the efficiency of a water utility and its non-revenue water. The second section (Situation Analysis) presents some analytical results based on the data from the first section. The computation of the water balance included is based on the IWA standard as well as several performance indicators, and the error is calculated with the 95% confidence limit method [7] for every value and performance indicators. The second section also includes the possibility to vary the value of several performance indicators and some of the input values to analyse potential changes, identify potential for improvement and set targets. Those two sections together allow the user to analyse his current status in the area of water loss reduction as well as identify the remaining potential for improvement and priority areas (fig. 2).

The third section guides the user into the right direction regarding possible actions to take in the future. First, the user has to choose several areas to focus on and then the program lists suitable measures to tackle each of those areas based on the filled self-assessment questionnaire. This allows the user to create a simple tailor-made action plan. In addition, commonly used and more detailed measures are also included, which can support the user to gather supplementary ideas. The last tab creates and compiles a simple action plan for the user containing the selected measures as well as measures entered manually by the user. All output from the DSS can be copied and exported to either create a presentation or a report using the generated data, calculation, analysis, charts and action plan table. Finally, the last section contains background information and references to online available documents in case the user requires more detailed explanation or requires more detailed information on selected topics [8, 9].

2.2 Performance indicators and 95% confidence limit

Most widespread performance indicators are included in the DSS (e.g. ILI, PMI, ALI, etc.) and all include the calculation of the error using the 95% confidence limit method [7]. The calculation of performance indicators, together with the IWA water balance allows the user to analyse its present status and perform

benchmarking according to international performing classes. This supports the analysis of the water utility strengths, weaknesses and potential for water loss reduction in order to set targets.
To compute the 95% confidence limits, two basic formulas are applied. If two values are added or subtracted (e.g. $V_{SystemInput} = V_{OwnSources} + V_{Import} - V_{Export}$ where V stands for Volume), the variances of the variables are added up ($Var_{SI} = Var_{OS} + Var_I - Var_E$), where $Var_X = (x * \varepsilon_X/1.96)^2$, x being the actual value and ε_X being the corresponding estimated error. In the case of the values being multiplied or divided (e.g. $ILI = CARL/UARL$) a slightly different formula is used: $\varepsilon_{ILI} = \sqrt{\varepsilon_{CARL}^2 + \varepsilon_{UARL}^2}$.

2.3 Application to the Lithuanian case

Water utilities in Lithuania do not have sufficient practice of efficient water loss reduction, lack information about practical measures and lack capacities for the use of specialised equipment for the detection of leaks. Water losses in Lithuania's water supply systems represent on average 30%. Alytus Water Utility started its water loss reduction project in 2012. During the project, main problems and weakest points were revised and possible and applicable measures for water losses reduction were proposed. The work was conducted together with consultants and company employers, which led to a very successful knowledge transfer. During project implementation, several methods were applied, such as water meter calibration, setting District Metering Areas (DMAs) as well as flow and noise measurements. The holistic decision support system applied to the project aims to help the water company to calculate the key performance indicators and propose a list of measures for an adequate and realistic action plan for Alytus water utility in Lithuania.
As the water loss reduction project started in 2012, the reference year of 2011 for data and calculation was used. Raw data were gathered from the company accounting system. Water extracted from the ground is measured by mechanical meters and water supplied to network is measured by magnetic flow meters. According to the readings of water meters, 99.5% of water users pay for water and water meters are installed in each private house or block flat. The rest of the customers (0.5%) are invoiced according to the water consumption rate set by the water utility. Every month, the users indicate themselves their water consumption and pay according to the tariff.
Single-flow water meters of Class B are used in Lithuania for water accounting. The customer water meters are replaced every 8-12 years, while bulk water meters are only replaced when they do not pass metrological verification, occurring every 2 years.

3 Results

3.1 Water balance, performance indicators and water utility efficiency 2011

The water balance was calculated based on data available and provided by the water utility. The resulting water balance (table 1) includes the water volumes and evaluated error margin. The water balance system boundaries start at the meter after the water treatment plant and for this reason, the water utility's own water usage before this point was not included in the water balance calculation (This includes office use at the treatment plant, wastewater treatment plants and water for filter backwashing and represents about 120,000 m^3 per year or about 4% of supplied water to network). In addition, performance indicators included in the DSS and calculated for water utility are presented in table 2, also include the computation of the error.

Table 2: Water balance calculation for Alytus water utility in 2011 including all water volumes (m^3/year) and evaluated error margin.

<table>
<tr><td rowspan="5">System Input Volume

3,074,753
±5%</td><td rowspan="3">Authorized Consumption

2,371,034
±5%</td><td rowspan="2">Billed Authorized Consumption
2,370,064
±5%</td><td>Billed Metered Consumption
2,365,864 ±5%</td><td rowspan="2">Revenue Water
2,370,064
±5%</td></tr>
<tr><td>Billed Unmetered Consumption
4,200 ±50%</td></tr>
<tr><td colspan="2">Unbilled Authorized Consumption
970 ±50%</td><td rowspan="3">Non-Revenue Water
704,689
±29%</td></tr>
<tr><td rowspan="2">Water Losses
703,713
±28%</td><td colspan="2">Apparent Losses 85,500 ±50%</td></tr>
<tr><td colspan="2">Real Losses 618,219 ±32%</td></tr>
</table>

Table 3: Performance indicators of Alytus Water Utility, 2011.

Performance Indicator	**Unit**	**Value**	**Error [%]**	**Grade**
ILI	$[-]$	2.8	34.5	B
PMI	$[-]$	1.3	5.0	Average
Real Losses per service connection	$\left[\frac{l}{N_{conn} * d}\right]$	435.3	32.9	C
Losses per main	$\left[\frac{l}{km * d}\right]$	6529.5	32.9	good
Percentage of Non-Revenue Water	[%] of System Input Volume	22.9	29.3	D
Apparent Losses per service connection	$\left[\frac{l}{N_{conn} * d}\right]$	60.2	50.5	B
ALI	$[-]$	0.7	50.2	A

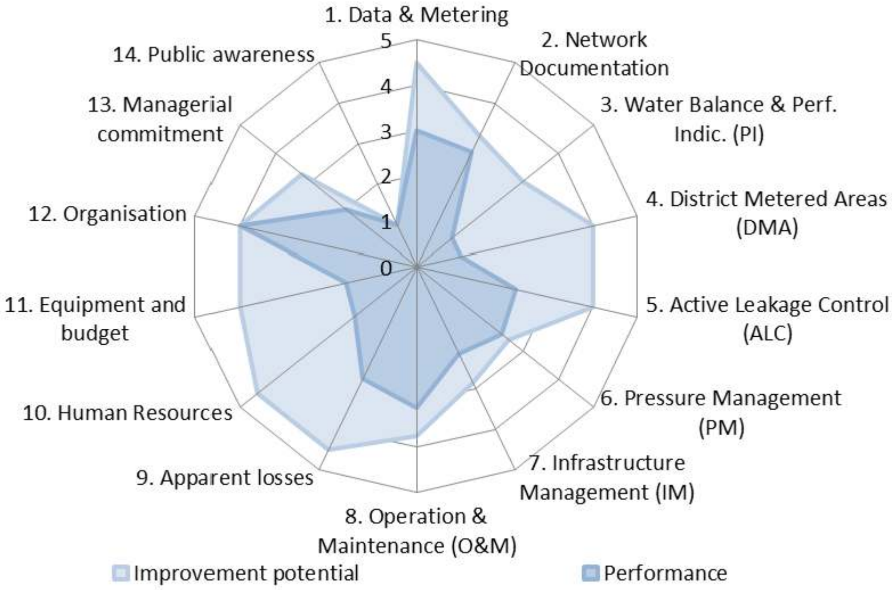

Figure 2: Water utility self-evaluation assessment, 2011.

The water utility efficiency has also been self-evaluated by applying WU-compass: the evaluation conducted considers 14 different categories influencing water losses reductions. Each topic consist of 4-6 questions and results in a spider diagram (fig. 2) showing for each category where is the current status and what is the potential for improvement.

3.2 Action plan 2011-2015

The water balance, performance indicators and the water utility efficiency evaluation clearly indicates which categories shall be prioritised and where measures should be implemented. After the selection of most adequate measures and complementing them with additional ones, an action plan for each selected category was prepared. The holistic decision support system applied aims to help the water utility to prioritise and set up the action plan considering the 14 categories. Five categories for water reduction were selected, where the water utility has the weakest efficiency and the highest potential for improvement:

- Category 4. District Metered Areas (DMA);
- Category 5. Active Leakage Control (ALC);
- Category 9. Apparent losses;
- Category 10. Human Resources;
- Category 11. Equipment and budget.

3.2.1 District Metered Areas and Active Leakage Control

The next step was to analyse several measures for each category. For example, it was decided to create seven pilot DMAs in the city and to test all necessary steps to implement all applicable ALC measures. Those seven selected DMAs cover about the quarter of the city area and the DMAs were selected in different environment, such as industrial zone, blockhouses or private houses area as well as mixed infrastructure. For the fourth category District Metered Area, the DSS suggested following measures, based on the data input and algorithm from the DSS:

- Install appropriate size meter to measure the inflow to the DMA;
- Install logging equipment for continuous flow monitoring;
- Establish some DMAs and start analysing the data;
- Check boundary valves. Try to adapt DMA borders to natural boundaries. Use suitable meters and PRV's;
- Keep track of the type of customers in the DMAs and create requirement lists for each type of customer;
- Night step-testing (reducing the size of the area by closing valves);
- DMAs with minimum night flow measurement and calculation.

3.2.2 Apparent Losses

Another output from the analysis is that apparent losses by volume calculated by the DSS do not seem so important (fig. 3a). However, apparent losses raised a particular interest due to the fact that consumed water usually end up into the wastewater system, leading to additional costs not charged for apparent losses. Reducing apparent losses therefore brings a double benefit: customers pay for the water supply and for the associated wastewater costs [10]. Concerning the action plan, the utility requested special interest on apparent losses and an accepted measure was to upgrade and change water meters to metrological Class C.

a. Annual water losses, m^3/yr. b. Annual saving potential Eur/yr.

Figure 3: Data from Water Balance, 2011. Real losses in red and apparent losses in blue.

3.2.3 Human Resources and Equipment

A specialised NRW group was gathered in 2012, as foreseen in human resources development plan. The group consists of 5 members: 4 employees and 1 head. Beside to active leakage control activities, which are their main task, the group is responsible to inspect all network manholes once a year. The team is equipped with intrusive flowmeters with data logger, noise logger, correlators, ground microphone, optical distance meters, data loggers for water meters and other equipment.

3.3 Situation 2015

The specialized NRW group grained experience from water leakage project and is now able to implement ALC program independently. Members of the group became experts and could provide training for other water utilities. Water leakage management is now a continuous project and after 3 years' work, the utility gained an understanding on how DMA and ALC shall be implemented and has everything in hand to further progress. Water utility PI improved substantially during the project, as presented in table 4.

Table 4: Performance indicators of Alytus Water Utility, 2015.

Performance Indicator	Value 2011	Value 2015	Grade 2011	Grade 2015
ILI	2.8	1.4	B	A
PMI	1.3	1.3	average	average
Real Losses per service connection	435.3	208.4	C	B
Losses per main	6529.5	3214.1	good	good
Percentage of Non-Revenue Water	22.9	13.8	D	C
Apparent Losses per service connection	60.2	35.8	B	A
ALI	0.7	0.5	A	A

Between years 2012 and 2015, water meters of class C were installed for 35% of customers. According to research, the payback period of a Class C meter is shorter than one year. The use of class C customer water meters reduced apparent water losses by 40% as the replacement of meters allowed to increase measured water consumption by 10 liters/day/flat.
Designing DMAs and checking boundary valves took on average 2-3 months. The similar period was allocated for implementing ALC measures at each DMA. During the project, real water losses in the network were reduced by about 40%, but within limited area of network, fig. 4.

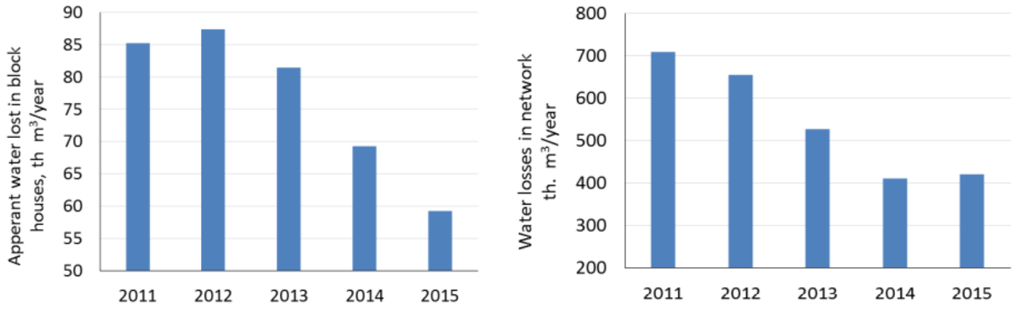

Figure 4: Water losses reduction during 2011-2015.

3.4 General Analysis and discussion

Before starting a new project, it is of vital importance to assess the present situation and determine clear targets. Water utilities shall identify weakest points in the system and prepare plans on how to increase assets and knowledge. The developed DSS is aiming to apply a holistic approach at the topic of water loss reduction, including most relevant features and to better analyse the state of the art. Based on that strength/weakness profile, fig. 2, an adequate and realistic action plan can be proposed and the water utility can selected measures that will be implemented. In this case study, the action plan for water reduction was implemented during a three-year period and targeted values were achieved. However, a three-year period is not enough to implement all measures and create DMAs for the whole water network. Nevertheless, knowledge and experience of water utility staff gained during the project allows continuing progress in the leakage reduction program.

Real water losses slightly increased again in 2015, principally due several large breakdowns on pipelines involving long location time and also to the limited area of network sectored into DMAs, where active leakage control can be carried out. The evaluation and analysis of last years' experience clearly indicates the need for a complete network zoning for the whole city, which would allow identifying network areas with bursts or higher leakages. This will require investment in flow measurement and data transmission equipment, and these investments would pay off. In the future, it is planned to link with the water distribution network DMAs with a hydraulic model, which would allow the utility to work with modern, fast and adequate responses to changes in the network.

4 Conclusions and outlook

The application of the DSS WU-Compass based on a water utility specific input data helps analyse strength and weakness and develop an action plan that will help to reduce water losses. The tool can assist the user to understand water losses better and find appropriate measures to save water. WU-Compass decision support system was tested on Alytus Water Utility (Lithuania). Developed and

implemented three-year action plan allowed reducing NRW by 40%. Based on achieved results and grained experience, the decision support system has been used to develop the new action plan for five years.
The tool not only helps the user to find appropriate measures. It also enables to learn more about the relationship and interplay of water loss components, and to understand better the individual situation. Results show that water utility had a great interest and found the tool really useful.
WU-Compass is a first version of a new WLR-tool and will be updated regularly. Feedbacks and improvement suggestions from the users are welcome to make the tool more user-friendly. The WU-Compass tool is available at www.waterloss-reduction.com and can be accessed freely by anyone interested.

5 References

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Acknowledgment

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APPENDIX III POSEIDON – HANDBOOK

The content of this appendix has been published as supplementary material to the publication presented in Appendix I (Emmanuel Oertlé et al., 2019), publicly available on the Zenodo repository: Oertlé, Emmanuel. (2018, December 5). Poseidon – Decision Support Tool for Water Reuse (Microsoft Excel) and Handbook (Version 1.0.0). Zenodo. http://doi.org/10.5281/zenodo.1971933.

Poseidon is a user-oriented, simple and fast Excel tool that aims to compare different wastewater treatment techniques based on their pollutant-removal efficiencies, their costs, and additional assessment criteria. Poseidon can be applied for pre-feasibility studies in order to assess possible water-reuse options and can show decision makers and other stakeholders that implementable solutions are available to comply with local requirements. This set of files consists of the following:

- a Poseidon Excel file that can be used with Microsoft Excel (as an XLSX file), and
- a handbook presenting the main features of the decision-support system (in PDF format).

Note: This handbook uses a personal tone, as it is addressed to a broad target group, and the writing style applied is purposefully more conversational than academic.

Handbook

Poseidon – A tool to Promote and Assess Water Reuse

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Basel, 05.12.2018

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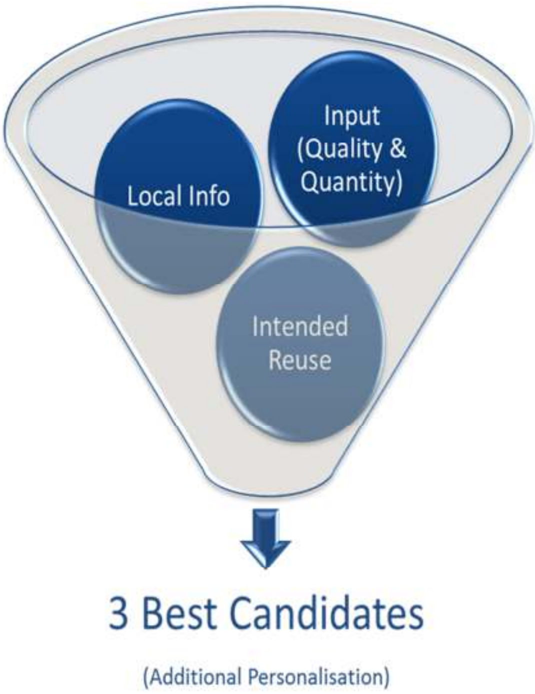
1. Introduction

Poseidon has been developed in the frame of the EU-project Coroado[7], which aims to develop and diffuse technologies for water recycling and reuse in Latin America by means of assessments, decision tools and implementable strategies. Coroado aimed at developing new concepts and adapting existing ones for water reuse. It produced a web-based toolbox for reuse and recycling technologies in the context of integrated water-resources management. The challenge of reuse and recycling technologies projects is not the lack of treatment techniques and technologies but rather lies in how such schemes may be implemented in the local context.

Poseidon itself is a user-oriented, simple, and efficient Excel-Tool, which aims to compare different wastewater treatment techniques based on their removal efficiencies, their costs, and additional assessment criteria. Furthermore, the background of the different technologies related to water reuse and the underlying theory are explained. Poseidon can be applied prior to a more detailed feasibility study in order to assess possible water-reuse options and can show decision makers and other stakeholders that implementable solutions are available to comply with local requirements, as shown in Figure 8-1.



Principle of Poseidon:

If you fill in some local information, data on the input (quality and quantity of wastewater to be treated) and the intended reuse, the tool will automatically propose the 3 best treatment trains candidates complying with your case study requirements.

Figure 8-1: Principle of Poseidon.

[7] www.coroado-project.eu This project has received funding from the European Union's Seventh Programme for research, technological development and demonstration under grant agreement No 2830.

2. Basic mode

Typical users: Users not used to this tool and non-experts of wastewater treatment technologies and their assessment and comparison.

Typical use: The typical intended use of this basic mode is to learn about water-reuse treatment technologies and to analyze which treatment trains would comply with your own situation, as shown in Figure 8-2.

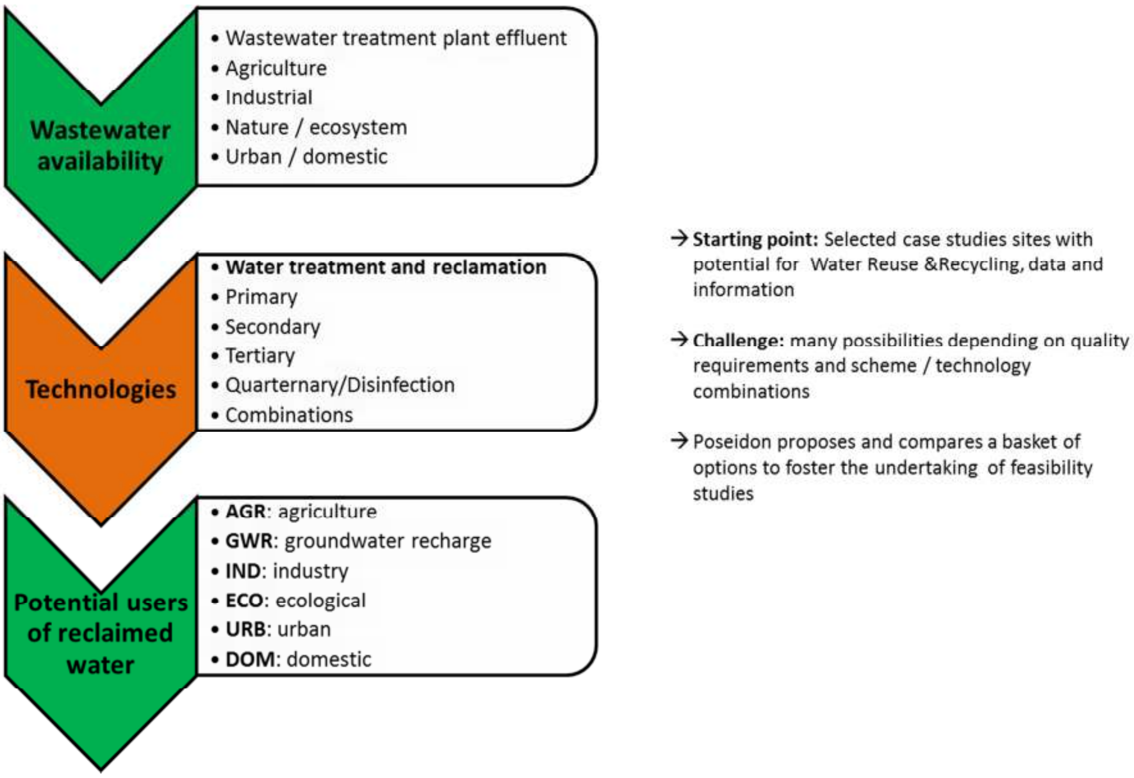


Figure 8-2: Main objectives.

2.1. Learn

Learn about Poseidon by clicking on the button "*1. Learn.*" There are possibilities to learn more about the tool, the individual unit processes or treatment trains, and the water quality classes and the limitations of Poseidon (see also Chapter 4).

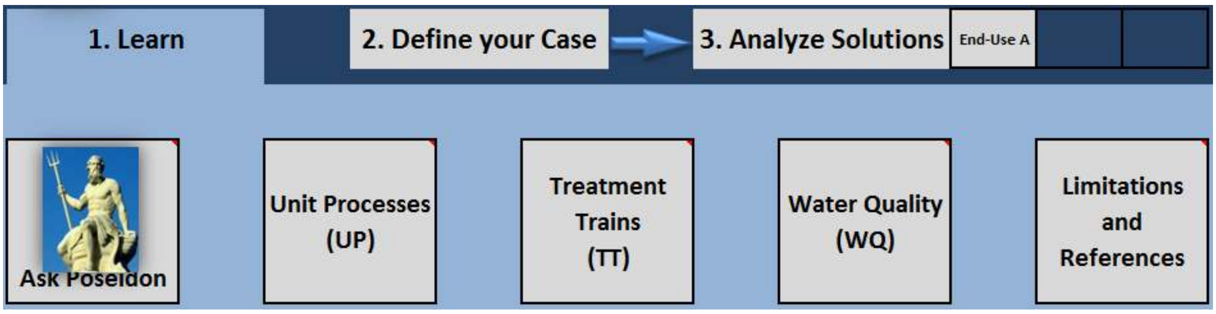
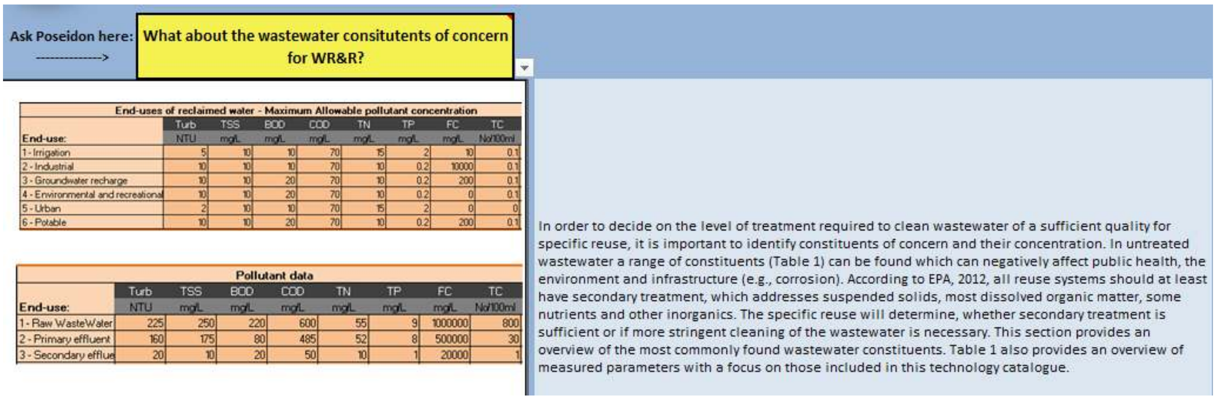


Figure 8-3: Learn.

2.2. Ask Poseidon

You will find a selection of different questions about the tool and some abbreviations you might not be familiar with. By selecting one of the questions, the tool will automatically give you the answer in form of a picture or chart, together with a short description.



End-uses of reclaimed water - Maximum Allowable pollutant concentration

End-use:	Turb NTU	TSS mg/L	BOD mg/L	COD mg/L	TN mg/L	TP mg/L	FC mg/L	TC No/100ml
1 - Irrigation	5	10	10	70	15	2	10	0.1
2 - Industrial	10	10	10	70	10	0.2	10000	0.1
3 - Groundwater recharge	10	10	20	70	10	0.2	200	0.1
4 - Environmental and recreational	10	10	20	70	10	0.2	0	0.1
5 - Urban	2	10	10	70	15	2	0	0
6 - Potable	10	10	20	70	10	0.2	200	0.1

Pollutant data

End-use:	Turb NTU	TSS mg/L	BOD mg/L	COD mg/L	TN mg/L	TP mg/L	FC mg/L	TC No/100ml
1 - Raw WasteWater	225	250	220	600	55	9	1000000	800
2 - Primary effluent	160	175	80	485	52	8	500000	30
3 - Secondary efflue	20	10	20	50	10	1	20000	1

Figure 8-4: Ask Poseidon.

2.3. Unit Processes

The descriptions of the unit processes, which are involved in this tool, can be found in the tool. If you are new to the topic or if you are not sure anymore what a given unit process stands for, go to the Unit Processes tab, and there you will find all the descriptions of every single unit process, along with some illustrating graphics.

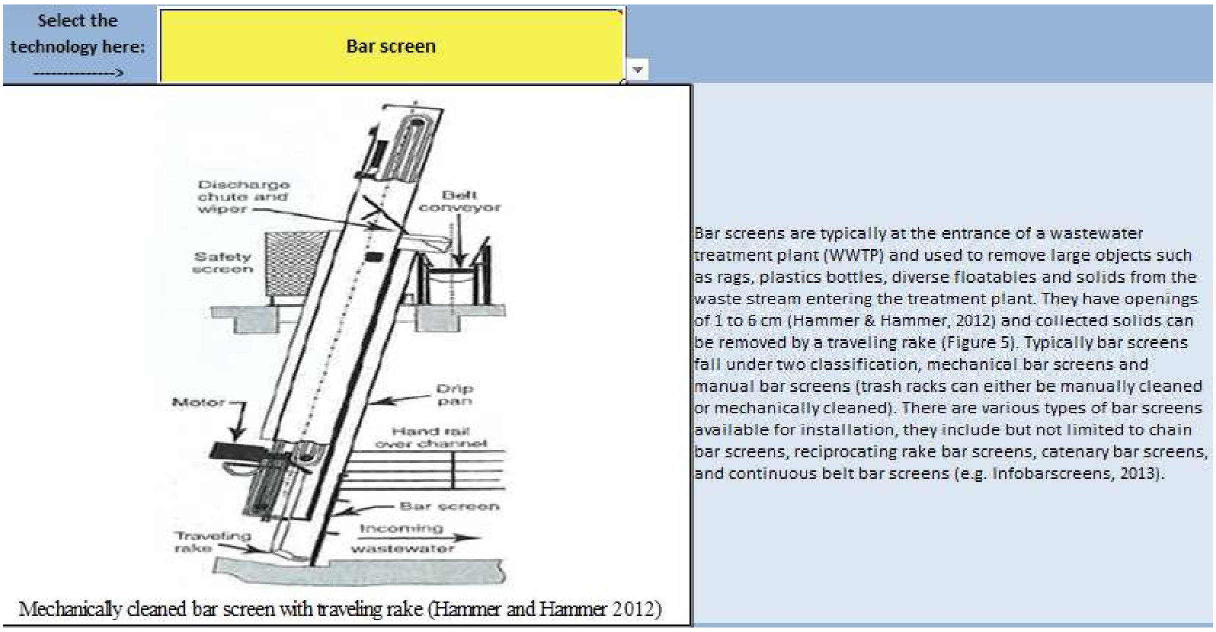


Figure 8-5: Unit processes.

2.4. Treatment Trains

Information on the catalogue of treatment trains included in the tool is presented here. Each treatment train has information on the list of unit processes, some description, and sometimes an example scenario (i.e., a "case study"). Those exemplary cases are facilities which are already realized and in operation. You will also find links to the references where the given treatment trains come from.

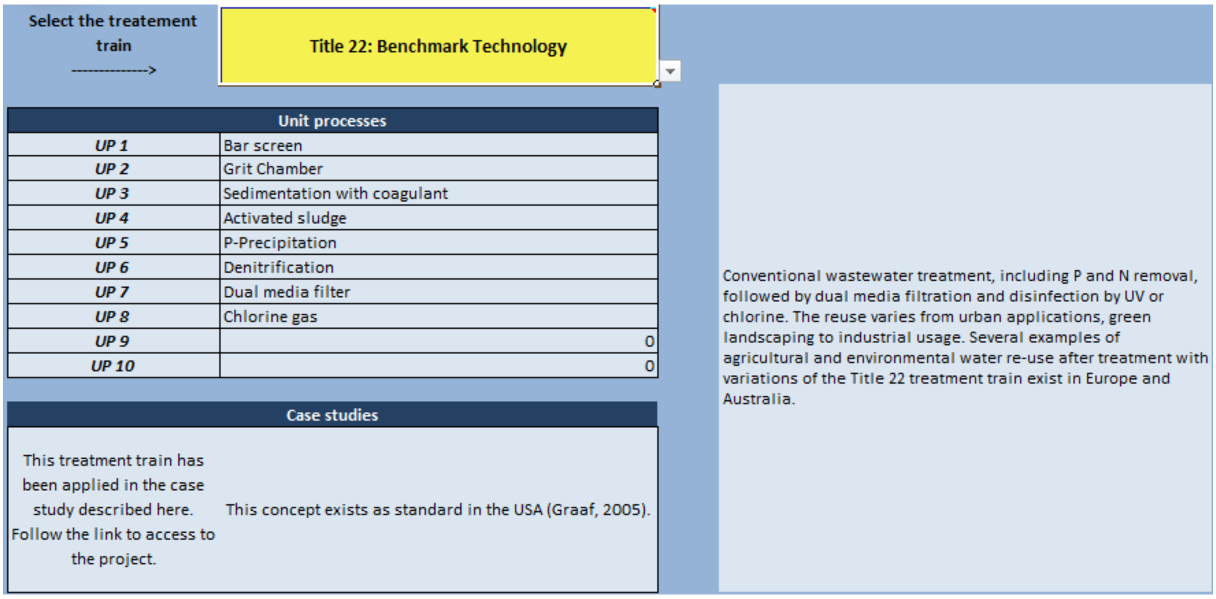


Figure 8-6: Treatment trains.

2.5. Water Quality

You will find all the details about different water quality classes included in Poseidon. There is a short description and references as well. Water quality regulations, recommendations and requirements are a very broad topic and sometimes remain undefined. In addition, compliance with requirements is a separate topic. For this reason, the tool proposes a catalogue of quality classes from several references (USEPA, WHO, national regulations, etc.) as an indication, and the user can either select one of those classes or adapt it to its own local conditions. Some references propose a range of values for selected parameters, and this section allows the user to see what is used for the calculation and where those numbers come from, along with some additional information.

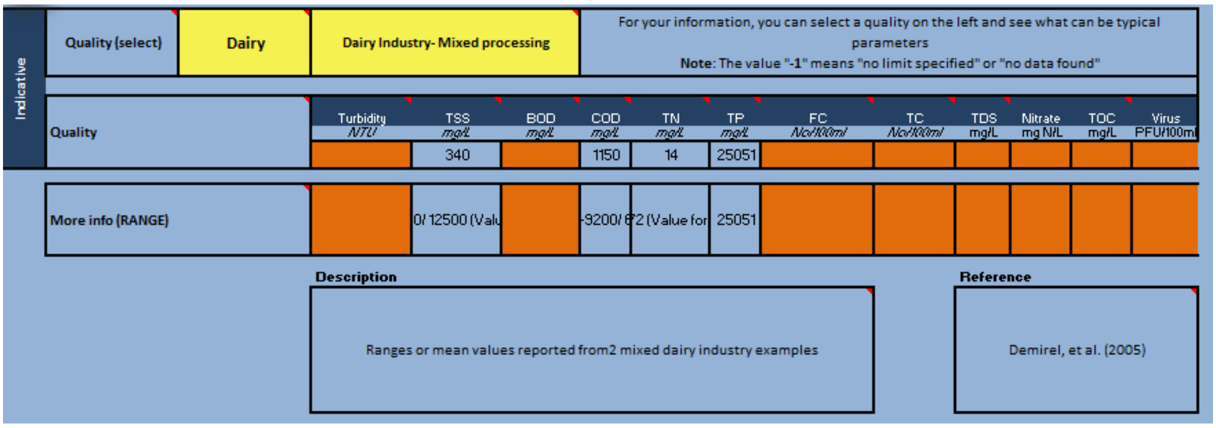


Figure 8-7: Water quality.

2.6. Required Data Input - Basic Mode

The Excel tool is versatile and can be used either in basic or personalization mode (Section 3). In basic mode, the only required data are as follows (see Figure 8-8):

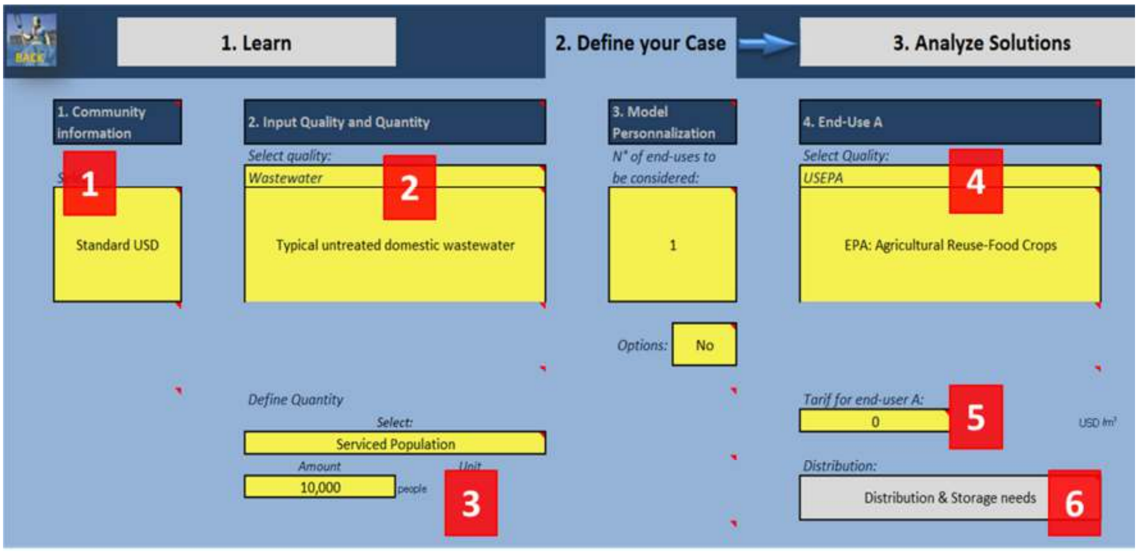


Figure 8-8: Data input in simple mode.

1. **Community information**: What is the currency in the region you would like to apply the tool, and what are labor, electricity and land costs in this context?
2. **Input quality**: What is the quality of the water or wastewater you would like to reuse? You can either choose from a list of pre-defined quality classes or specify up to 12 quality parameters yourself.
3. **Input quantity**: What is the quantity of water or wastewater you intend to reuse?
4. **End-use quality**: What is the quality requirement for your intended end-use of the water after treatment? You can either choose from a list of pre-defined quality classes or specify up to 12 quality parameters yourself.
5. **Tariff for end-user**: Specify the cost the reused water can be sold to the intended end-user.
6. **Distribution & storage needs**: Specify the length of the pipes required and the elevation to calculate the pumping costs. You can also specify whether you need a water or wastewater storage facility.

Based on those input data, the Excel tool will calculate the performance, cost, and other assessment criteria for all the treatment trains included in the system and propose to you the best candidates according to a varied selection and assessment methods as explained in Sections 2.7 and 2.8.

2.7. Calculation and Assessment Algorithm (Informative)

In order to understand the results, the user should have a basic understanding on how the tool performs the calculations before being able to analyze the results (All those calculations are performed automatically, and the user does not see the details while using the tool).

Poseidon contains a catalogue of unit processes (technologies) assembled into a catalogue of treatment trains (i.e., a combination a series of technologies). The treatment trains are based on case studies and contain main benchmarks treatment trains and several additional examples worldwide. One example of treatment train is shown in Figure 8-9. In simple mode, Poseidon contains around 40 unit processes and around 50 treatment trains. There is also the possibility to add unit processes and to create additional treatment trains, leading to an almost unlimited amount of combinations. Those personalization possibilities are described in Section 3

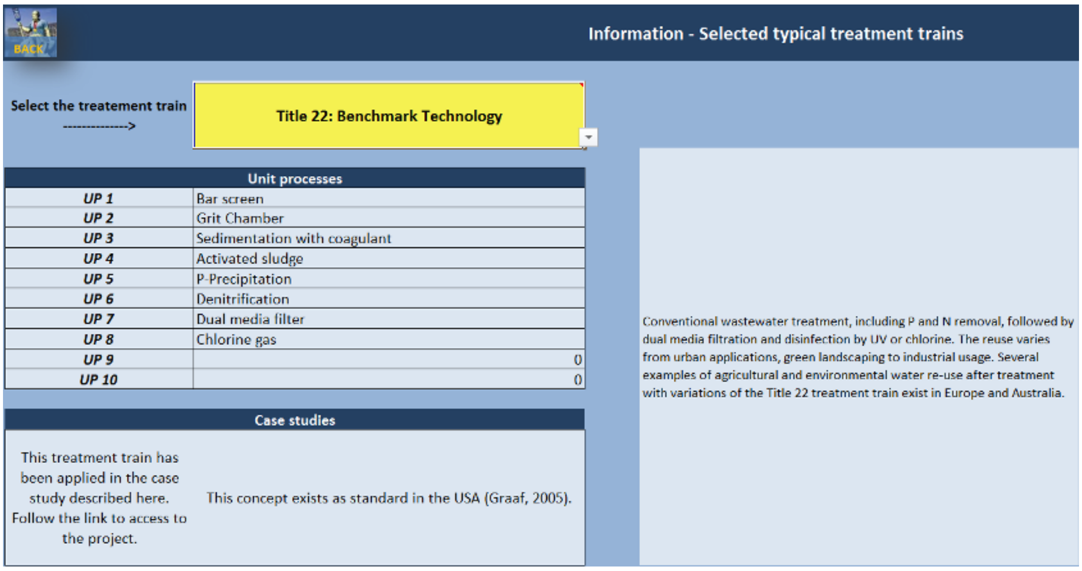


Figure 8-9: Title 22 benchmark technology: example of a treatment train composed of 8 unit processes.

Each unit process, and therefore each treatment train, contains following information:

1. general description of unit process, treatment trains that can be found in the "learn" section of the tool;
2. pollutant removal percentage for each water quality parameter under minimum, average, and maximum performance;
3. quantitative lifecycle costs information in order to calculate the important cost components for each case;
4. additional assessment criteria for the technical assessment, requirements, impacts, cost, and resources, where the values are between 0 and 3 (0 = nil, 1 = low, 2 = medium and 3 = high); and
5. a normalized and aggregated single treatment train score that is calculated based on the weights defined by the user (Figure 8-10). The values are between 0 (*worst*) and 3 (*best*).

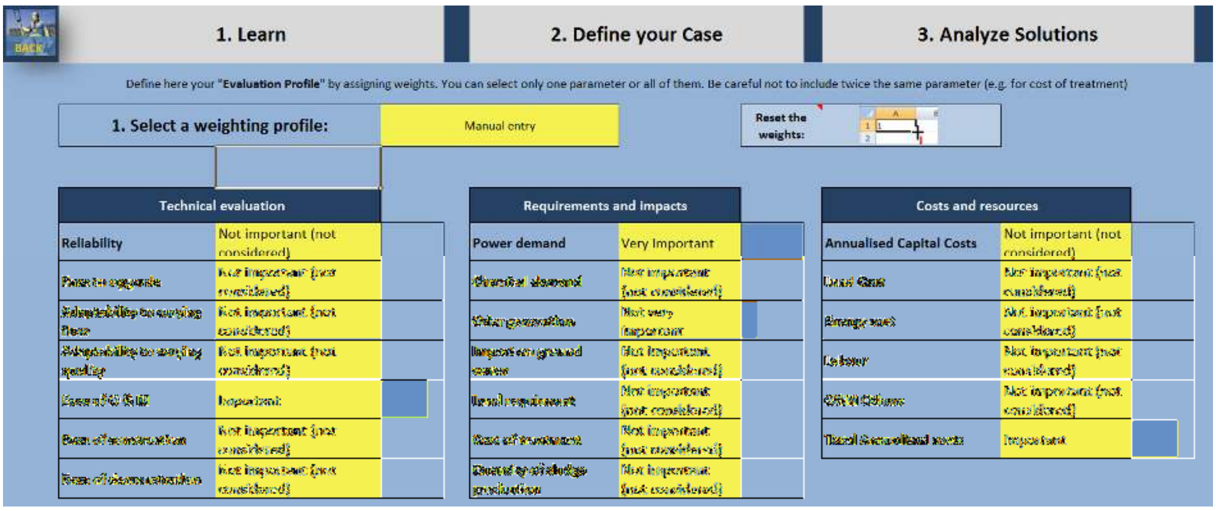


Figure 8-10: Weight the relative importance of different parameters in order to calculate an overall treatment train score.

2.8. Elimination, Ranking and Assessment Process

As described in the previous section, each parameter is calculated for each treatment train included in Poseidon. Those parameters can be divided into three categories:

1. **Technical**: This is the calculation of the pollutant-removal performance for the considered quality parameters. If a given treatment train complies with all the water quality parameters specified for a given end-use, the treatment train is considered compliant.[8]
2. **Economic**: These are the lifecycle treatment costs calculated quantitatively in the selected currency per cubic meter. Such a cost is calculated for each treatment train.
3. **Assessment criteria**: These are all the additional assessment criteria that are normalized, and their values are between 0 and 3 (0 = nil, 1 = low, 2 = medium, and 3 = high). Out of those assessment criteria, another aggregated score is calculated for every treatment train based on the assigned weights by the user, as explained in the previous section.

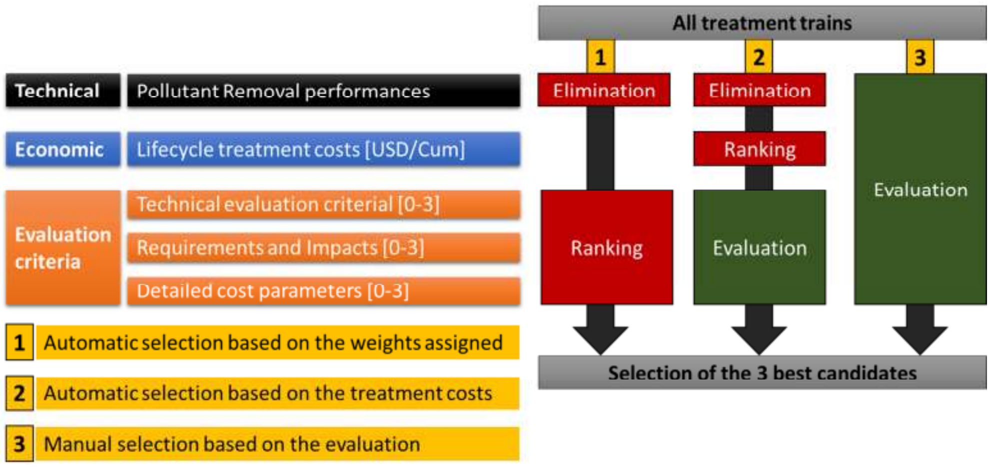


Figure 8-11: Assessment algorithm proposed by the stage II assessment.

Based on those three categories of parameters (technical, economic, and assessment criteria), the user can proceed to three main elimination, ranking, and assessment selections, as represented in Figure 8-11 and Figure 8-12.

[8] Note that for each parameter, three performances are calculated (minimum, average and maximum performance), depending on the operation conditions and external factors. In the selection process, the maximum performance is considered and the user should be aware that under less well-operating treatment trains, the quality might not comply with the water quality required for the end-use.

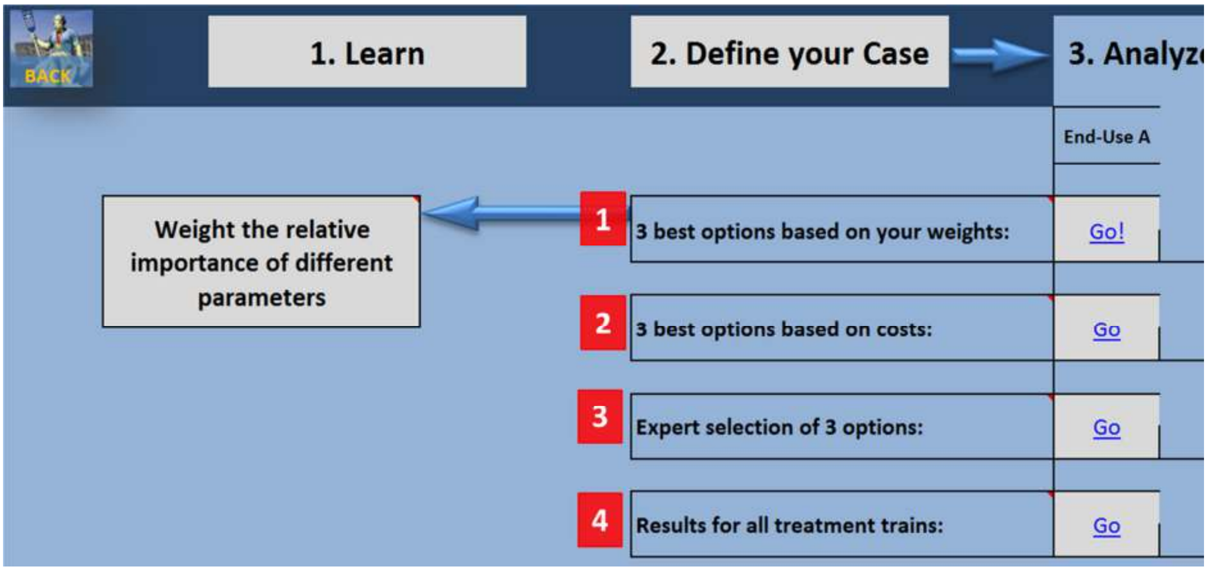


Figure 8-12: Analyze solution screenshot.

1. **Automatic selection based on the weights assigned**: In this mode, all treatment trains not complying with the water quality required are eliminated (under maximum performance). The treatment trains complying with the quality required by the foreseen end-use are ranked according to the aggregated treatment trains' single score, based on the weights assigned by the user. The best three candidates are presented automatically.
2. **Automatic selection based on the treatment costs**: In this mode, all treatment trains not complying with the water quality required are eliminated (under maximum performance). The treatment trains complying with the quality required by the foreseen end-use are ranked according to the lifecycle treatment costs, and the three best treatment trains are presented. In addition, the assessment criteria are displayed but do not affect the ranking.
3. **Manual selection based on the assessment**: In this mode, the user can choose any treatment train included in Poseidon and see the results (technical, economic, and assessment criteria). Non-compliant treatment trains can also be selected, and this mode allows total freedom for comparison.
4. **Results for all treatment trains (no selection)**: This mode does not have any selection but provides a table with all calculated results and allows expert analysis of every calculated parameter.

2.9. Understanding the Results

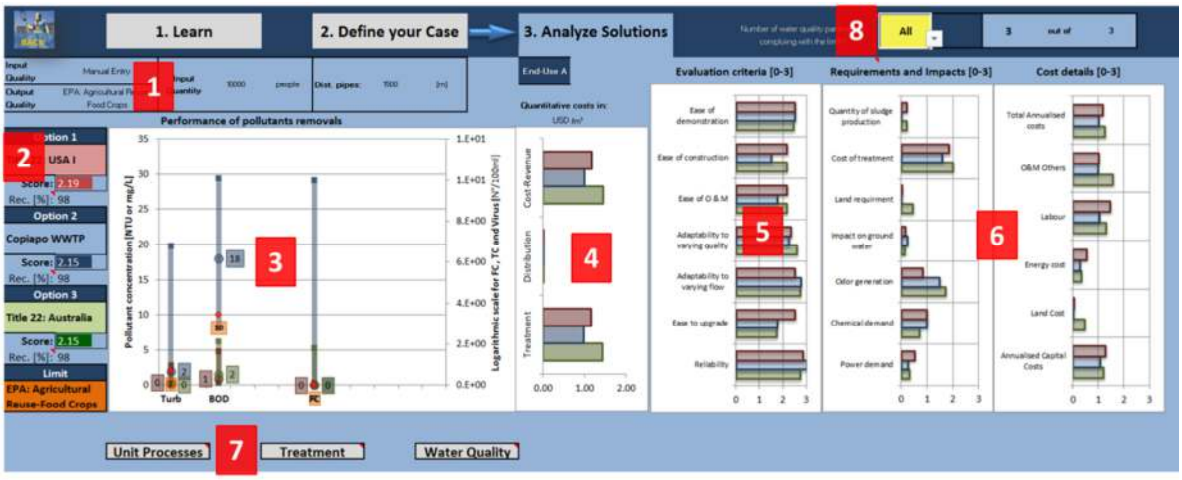


Figure 8-13: Example results sheet.

When looking at the results, most likely the user will start to analyze the graphic shown in Figure 8-13. On this sheet, a range of information is displayed and can be classified into eight points (highlighted in red):

1. The data input are recapitulated (input quality and quantity, output quality, and distribution).
2. The three best options are displayed in three colors (red, blue, green). For each option, the name of the treatment train is displayed with the overall treatment train score based on the assigned weights and the recovery percentage. The limit chosen for the output quality required is indicated in orange.
3. The chart displays the pollutant removal performances under minimum, average, and maximal performance. The limit is indicated in orange. The user can see how well the three options perform, and the user should be aware that depending on the performance of the treatment train, the treatment might not comply with the required quality. There are two scales, one on the right for the highest quality parameters in [NTU] (turbidity) or [mg/l], and with a logarithmic scale for FC, TC and virus, in [n°/100 ml].
4. The quantitative costs are presented in the selected currency per cubic meter. Cost-revenue is the cost of treatment and distribution minus the foreseen selling cost to the end-user. If this value is negative, the option would generate money. The quantitative costs are calculated with the lifecycle cost methodology and include everything (OPEX, CAPEX, interest rate, electricity cost, useful life, etc.).
5. The independent assessment criteria results are displayed. The values are between 0 and 3: (0 = nil, 1 = low, 2 = medium and 3 = high). For the assessment criteria, a high value is considered positive for the calculation of the overall treatment train score based on the weights (displayed under the option name, point 2).
6. The results for requirements, impacts, and costs and are displayed. The values are between 0 and 3 (0 = nil, 1 = low, 2 = medium and 3 = high). For those criteria, a high value is considered negative for the calculation of the overall treatment train score based on the weights (displayed under the option name, point 2).
7. The three buttons are linked to the “Learn” component. Depending on the option proposed, the user can look in the database to see the details of each treatment train, unit process, and water quality class.

8. In case no treatment train complies with the water quality required, the user can choose how many water quality parameters should comply with the requirements (e.g. two out of thee)

In addition, some results are presented in a table form at the bottom of the sheet. The user can also look at the table including all results of all treatment trains, as shown in Figure 8-14.

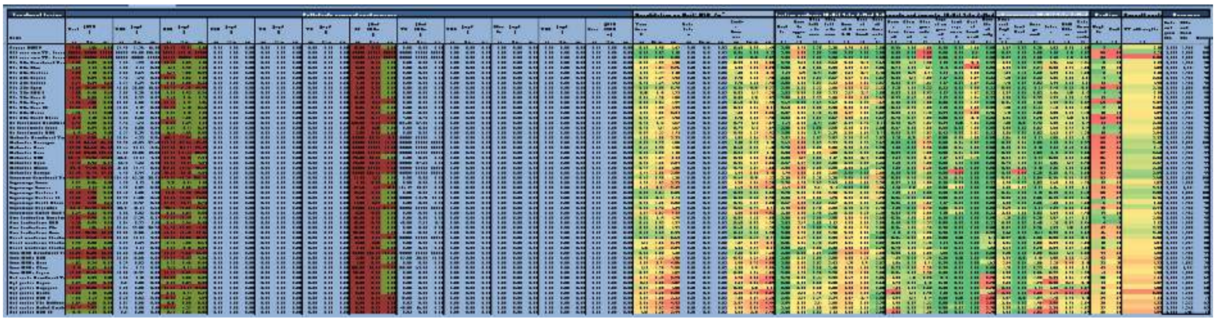


Figure 8-14: Results for all treatment trains displayed in a table.

2.10. Meaning of the Color Coding

In the first 12 columns (factors about the water quality), red is negative and green is positive. If it is green, the reclaimed water is compliant with the selected water quality requirement for the end use. If red, it is not compliant. The rest of the columns show criteria such as quantitative costs, assessments, requirements and impacts, and costs and resources. The colors go from green (the best) to yellow (medium) to red (bad) and represent a ranking for each column.

3. Personalization Features

It is possible to personalize Poseidon in order to meet certain needs. For example, it is possible to change and create community information profiles, define quality classes for the water, consider up to three end uses for the treated water, create custom treatment trains or unit processes, and define or calculate storage and distribution costs.

3.1. Additional Features - Personalization

In the personalization mode, the same analysis can be conducted, but with several additional features (see Figure 8-15).

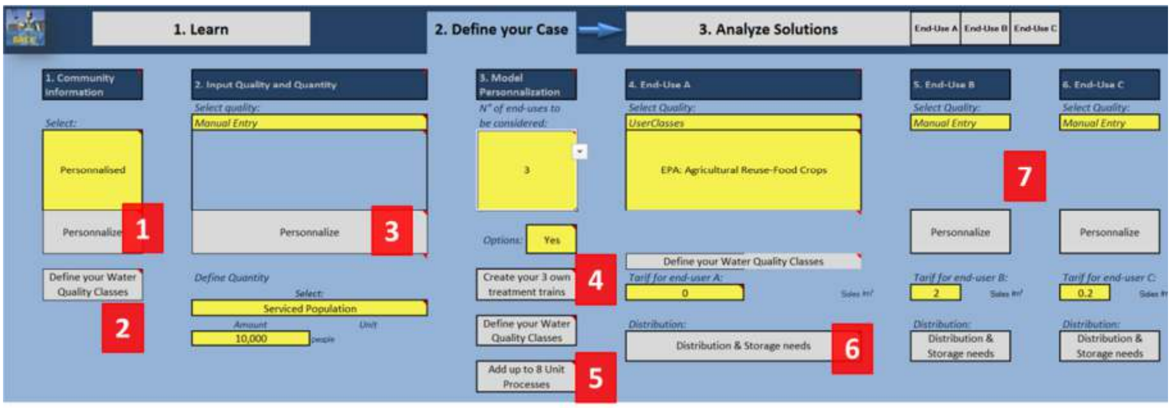


Figure 8-15: Data input personalization.

1. **Personalize community information**: You can define in details different cost components, the interest and discount rates, and so on.
2. **Define your water quality classes A–E**: Here you can define quality classes A–E by specifying the different quality parameters for each class. The defined quality class can then be selected as input data if you choose the quality category *"User Classes."*
3. **Personalize water quality:** You can personalize the water quality for each parameter.
4. **Create your own treatment trains:** It is possible to create your own three treatment trains by assembling up to 10 unit processes from the database included in the Excel tool. The created treatment trains will be considered for the analysis.
5. **Add up to 8 unit processes:** You can add up to 8 additional unit processes (e.g. UASB) to the database. Note that this is an intensive process, as for each new unit process, a large amount of data is required (pollutant removal performances, costs, assessment criteria, etc.).
6. **Distribution and storage needs:** It is possible to change the pipe design criteria by changing the average flow velocity.
7. **End-uses B and C**: You can specify quality and distribution data for two additional end uses and therefore compare up to three different types of intended reuse for an input.

3.2. Procedure to Define Community Information Profiles

This option allows the specification of community information mainly related to costs. The user can specify currencies with the exchange rate set to USD2006 (as a basis for the calculation). Apply following procedure to add new community information:

- Select “Define your case.”
- Choose from point 1 “Community information” the option “Personalized.” A new field, “Personalize,” appears.
- Clicking on this new box redirects the user to a new sheet, where all the fields in yellow can be updated.
- The last row, with the title “Personalized,” can be completed with custom currency information.
- Go back to the page “Define your case” by selecting the box “Back to community selection.”

Standard USD	Currency [CUR]	Exchange rate to USD 2006 [CUR/USD2006]	Land cost [CUR/ha]	Electricity cost [CUR/kWh]	Personal cost [CUR/person-hour]	Discount rate	Piping	Controls & Instrumentation	Site electrical	Site development	Site works	Engineering	Contingency
Standard Community based on USD 2006.	USD	1	10000	0.05	20	8%	8%	8%	9%	8%	6%	12%	15%
Argentina – A-Peso	**Currency**	**Exchange rate to USD 2006**	**Land cost**	**Electricity cost**	**Personal cost**	**Discount rate**	**Piping**	**Controls & Instrumentation**	**Site electrical**	**Site development**	**Site works**	**Engineering**	**Contingency**
Argentina - A-Peso	ARS	3.07	46,006.55	0.15	61.34	8%	8%	8%	9%	8%	6%	12%	15%
Argentina – USD	**Currency**	**Exchange rate to USD 2006**	**Land cost**	**Electricity cost**	**Personal cost**	**Discount rate**	**Piping**	**Controls & Instrumentation**	**Site electrical**	**Site development**	**Site works**	**Engineering**	**Contingency**
Argentina - USD	USD	1.00	15,000.00	0.05	20.00	8%	8%	8%	9%	8%	6%	12%	15%
Chile – C-PESO	**Currency**	**Exchange rate to USD 2006**	**Land cost**	**Electricity cost**	**Personal cost**	**Discount rate**	**Piping**	**Controls & Instrumentation**	**Site electrical**	**Site development**	**Site works**	**Engineering**	**Contingency**
Chile - C-PESO	CLP	525.51	5,255,052.85	76.20	10,510.11	8%	8%	8%	9%	8%	6%	12%	15%
Chile – USD	**Currency**	**Exchange rate to USD 2006**	**Land cost**	**Electricity cost**	**Personal cost**	**Discount rate**	**Piping**	**Controls & Instrumentation**	**Site electrical**	**Site development**	**Site works**	**Engineering**	**Contingency**
Chile - USD	USD	1.00	10,000.00	0.15	20.00	8%	8%	8%	9%	8%	6%	12%	15%
Brazil – REALS	**Currency**	**Exchange rate to USD 2006**	**Land cost**	**Electricity cost**	**Personal cost**	**Discount rate**	**Piping**	**Controls & Instrumentation**	**Site electrical**	**Site development**	**Site works**	**Engineering**	**Contingency**
Brazil - REALS	BRL	2.41	28,888.98	0.29	48.13	8%	8%	8%	9%	8%	6%	12%	15%
Brazil – USD	**Currency**	**Exchange rate to USD 2006**	**Land cost**	**Electricity cost**	**Personal cost**	**Discount rate**	**Piping**	**Controls & Instrumentation**	**Site electrical**	**Site development**	**Site works**	**Engineering**	**Contingency**
Brazil - USD	USD	1.00	12,004.00	0.12	20.00	8%	8%	8%	9%	8%	6%	12%	15%
Mexico – M-PESO	**Currency**	**Exchange rate to USD 2006**	**Land cost**	**Electricity cost**	**Personal cost**	**Discount rate**	**Piping**	**Controls & Instrumentation**	**Site electrical**	**Site development**	**Site works**	**Engineering**	**Contingency**
Mexico - M-PESO	MXN	10.76625793	107662.5793	1.356548499	215.3251586	8%	8%	8%	9%	8%	6%	12%	15%
Mexico – USD	**Currency**	**Exchange rate to USD 2006**	**Land cost**	**Electricity cost**	**Personal cost**	**Discount rate**	**Piping**	**Controls & Instrumentation**	**Site electrical**	**Site development**	**Site works**	**Engineering**	**Contingency**
Mexico - USD	USD	1.00	10,000.00	0.13	20.00	8%	8%	8%	9%	8%	6%	12%	15%
Personnalised	**Currency**	**Exchange rate to USD 2006**	**Land cost**	**Electricity cost**	**Personal cost**	**Discount rate**	**Piping**	**Controls & Instrumentation**	**Site electrical**	**Site development**	**Site works**	**Engineering**	**Contingency**
Peru	Soles												

Figure 8-16: Community information – specify the different parameters.

3.3. Define Your Water Quality Classes A–E

Data entry - Create your own water quality classes (A-E)

Indicative	Quality (select)	Argentina	ARG - Water for agricultural Irrigation(non-food crops)	For your information, you can select a quality on the left and see what can be typical parameters. **Note**: The value "-1" means "no limit specified" or "no data found"

	Turb	TSS	BOD	COD	TN	TP	FC	TC	TDS	Nitrate	TOC	Virus
Quality	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	No/100ml	No/100ml	mg/L	mg N/L	mg/L	PFU/100ml
		50	30		30	5			500	30		
Class A	Turb	TSS	BOD	COD	TN	TP	FC	TC	TDS	Nitrate	TOC	Virus
Water quality **very low** (it cannot be reused for any purpose neither discharged and needs treatment).	500	500	440	1200	[illegible]	[illegible]	2000000	[illegible]	[illegible]	[illegible]	30	[illegible]
Class B	Turb	TSS	BOD	COD	TN	TP	FC	TC	TDS	Nitrate	TOC	Virus
Water quality is **low** (it cannot be reused for any purpose but can be discharged according to the national regulations).	[illegible]	100	100	200	-1	-1	-1	25	-1	-1	-1	-1
Class C	Turb	TSS	BOD	COD	TN	TP	FC	TC	TDS	Nitrate	TOC	Virus
Water quality is **medium** (it could be reused for restricted [illegible] industrial purposes).	[illegible]	30	30	-1	10	-1	200	[illegible]	-1	-1	-1	-1
Class D	Turb	TSS	BOD	COD	TN	TP	FC	TC	TDS	Nitrate	TOC	Virus
Water quality is **good** ([illegible])	-1	[illegible]	[illegible]	100	-1	-1	-1	1000	[illegible]	20	-1	-1
Class E	Turb	TSS	BOD	COD	TN	TP	FC	TC	TDS	Nitrate	TOC	Virus

Define here your own quality classes A-E

Figure 8-17: Water quality classes A–E.

3.4. Procedure to Personalize Water Quality

It is possible to define the exact parameter values of your influent water instead of choosing a category of wastewater with defined values.

	Turb	TSS	BOD	COD	TN	TP	FC	TC	TDS	Nitrate	TOC	Virus
Quality (enter data here if you selected "Manual Entry")	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	No/100ml	No/100ml	mg/L	mg N/L	mg/L	PFU/100ml

Figure 8-18: Define your own water quality classes.

The following procedure has to be undergone:

1. Select “Define your case.”
2. Choose from point 2, “Input Quality and Quantity,” the option “Manual Entry.” A new field, “Personalize,” appears.
3. Clicking on this field opens a new sheet in which the influent wastewater parameters can be entered. Pay attention to match the given units.
4. If one parameter is not defined, enter the value "−1."
5. Go back to the “Define your case” page by selecting the box "Back to define your case study.”

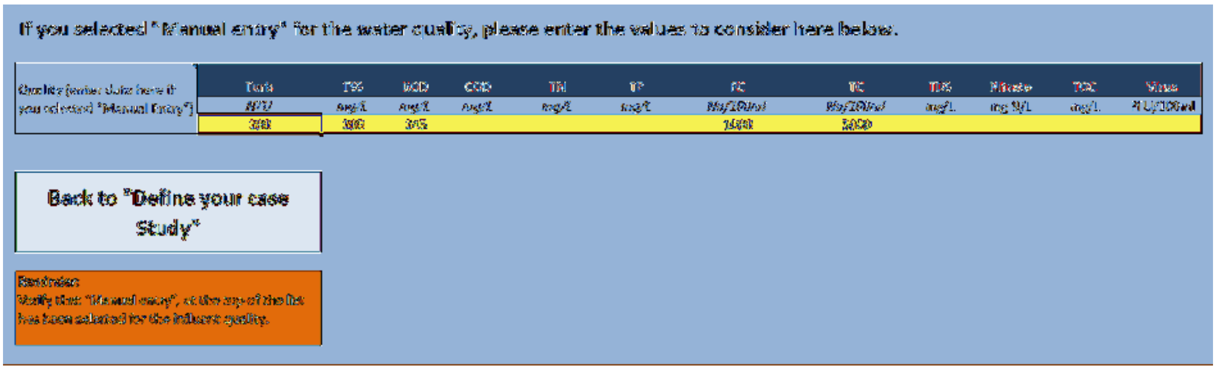


Figure 8-19: Own water quality class – data input.

3.5. Procedure to Create Treatment Trains

Poseidon proposes a catalogue of treatment trains, composed of combinations of single unit processes representing a typical WWTP. It is nevertheless possible to combine the different unit processes in a new, more case-specific treatment train.

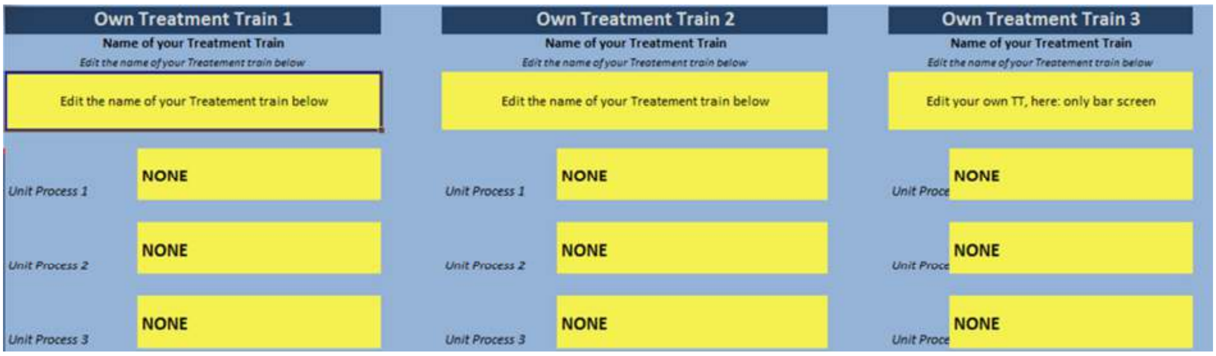


Figure 8-20: Create your own treatment trains.

Select the Excel-sheet 2.3.

1. Change the name of the treatment train in the first yellow box (*Edit your own treatment train*).
2. Describe your own treatment train by selecting the correspondent unit processes beginning on top with “Unit Process 1.” To do so, select the yellow box to the right of the unit process. A shortlist can now be opened. Select the appropriate unit process from this list, and continue with the following step in your treatment train as described.

3. Enter up to 10 unit processes. If not all possibilities are used, leave the last unit process as "NONE." The "Number of Unit Processes" allows a control: The number of entered unit processes should match the number given in the light grey field below your treatment train. Never insert "NONE" between two unit processes.
4. To describe the newly created treatment train, use the yellow box "Description of own treatment train 1."

It is possible to create up to three treatment trains in this way that to be considered in the assessment and ranking processes.

3.6. Procedure to Create Additional Unit Processes

Up to eight additional unit processes can be created and used for the creation of your own treatment trains. To add personalized unit processes, follow the procedure below (see Figure 8-21).

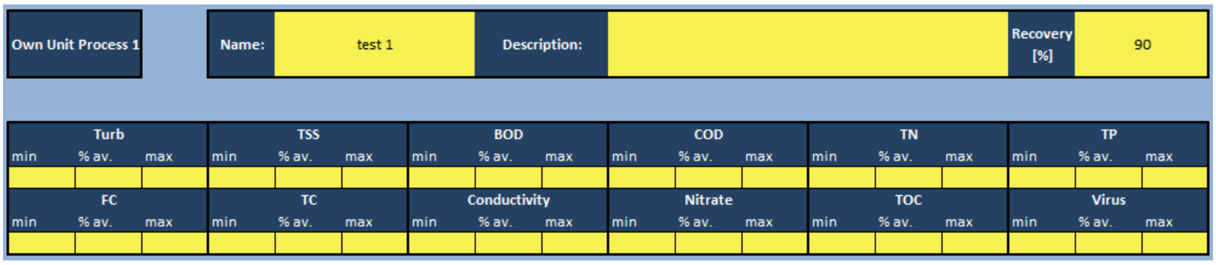


Figure 8-21: Create additional unit process.

1. Select the Excel-sheet 2.5.
2. Change the name of the unit process in the yellow field *test 1*.
3. Add a short description of the unit process in the yellow field right to the denomination.
4. Specify the overall pollutant-removal efficiency. Provide information about the different parameters such as turbidity, TSS, and so on, as well as their range (minimum, average, maximum).
   Note: If not all data are available, it is important to indicate the value for pollutant removal performance at least for the maximum performance, as this value is used in the calculation.
5. Enter values on the assessment indicators and on the costs (the entered value has to be sensible relative to the assessment criteria of the other unit processes included in the catalogue).
6. Enter information related to costs for at least two different flows.

It is possible to create up to eight unit processes in this way. Each of these can be either used as a standalone wastewater treatment or integrated in a treatment train, as described in Section 3.5.

3.7. Procedure to Define Distribution and Storage Needs

Wastewater has to be collected, treated, and stored and, in the end, redistributed. The distribution and storage costs are not to be underestimated. To take them into consideration, follow the procedure below.

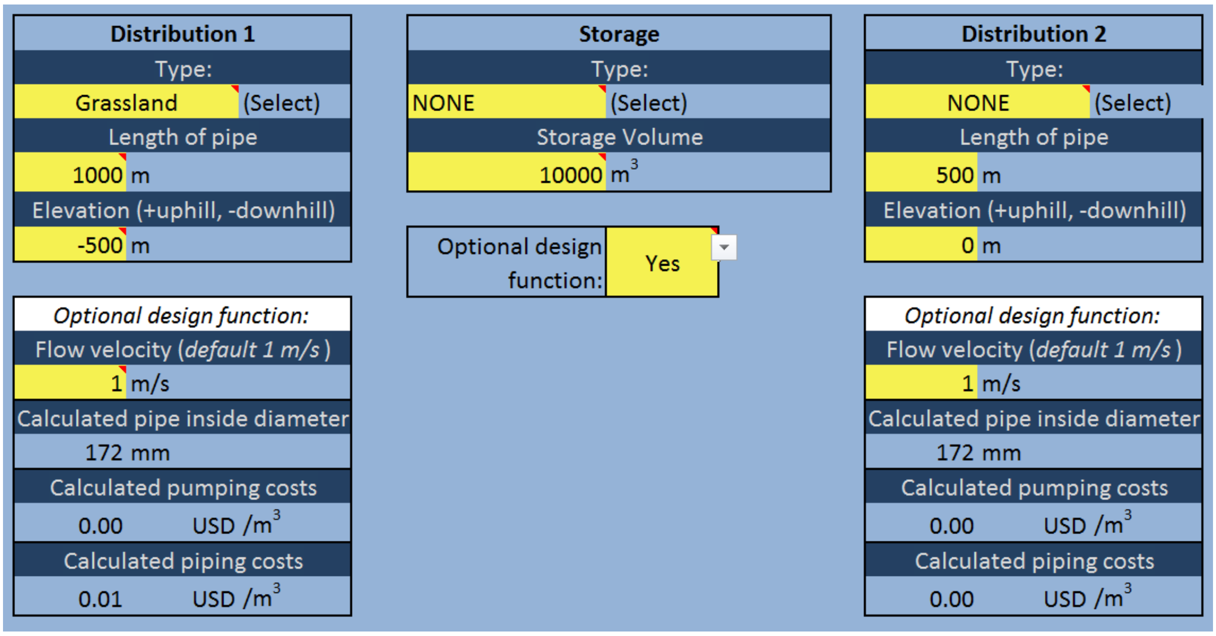


Figure 8-22: Define distribution and storage needs.

3.8. Procedure to Consider More End Uses

If the treated wastewater could be used in more than one application field, it is possible to consider up to three different end-uses. This function is useful if a potential wastewater could be reused exemplarily for agriculture and industrial reuse. The tool can propose adapted treatment trains for both options considering the same influent. To do so, follow the procedure below.

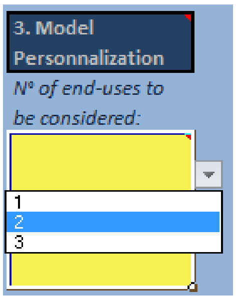


Figure 8-23: N° of end-uses.

1. Select "Define your case."
2. Choose from point 3, "Model Personalization" the option 2 or 3 according to the desired number of end-uses for the wastewater.
3. More fields are added according to the chosen number of end-uses. The end-uses are differentiated in A, B, or C (if three end-uses have been selected).
4. As the tariff and the distribution can vary from one end-use to another, enter the relevant values in the corresponding fields.

4. Typical Examples

4.1. Example 1: Two Potential Water Reuse Scenarios for the Untreated Wastewater from a City

A village in Europe with typical domestic untreated wastewater from 5,000 inhabitants is considered. You would like to analyze how to treat this water for two scenarios and find the best 3 options based on costs of treatment.

Scenario 1: Reuse for aquaculture.

Scenario 2: Reuse for industrial cooling in an industry.

The foreseen WWTP will be at an altitude of 1,000 m above sea level. The foreseen agriculture area is 1 km away in a rural area and has an altitude of 500 m above sea level. The industry is 100 m away from the foreseen WWTP.

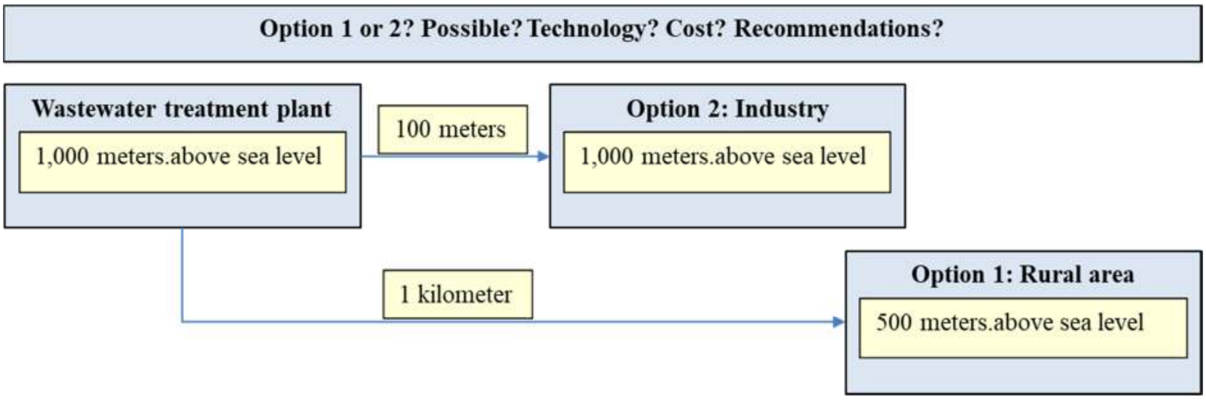


Figure 8-24: Visualization example task

Answer the following questions:

- Are there suitable treatment trains for reuses 1 or 2, or both?
- Which are the best three options based on the costs?
- What are the costs of treatment for those options?
- What are the costs of distribution for option 1?

4.2. Suggested Procedure

Figure 8-25 shows how the tool looks at the beginning of an assessment.

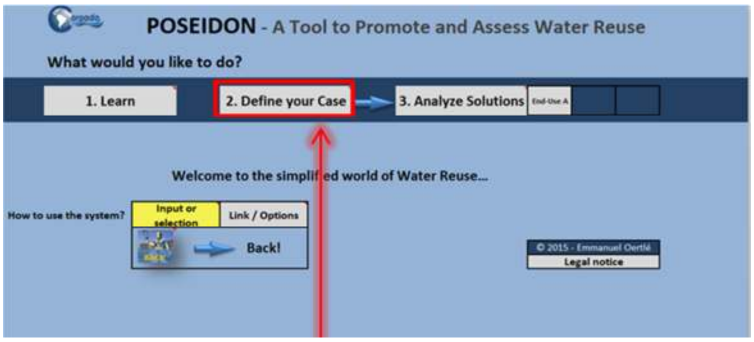


Figure 8-25: Starting point.

First click on the button *"Define your Case"*

Let's start to fill in information

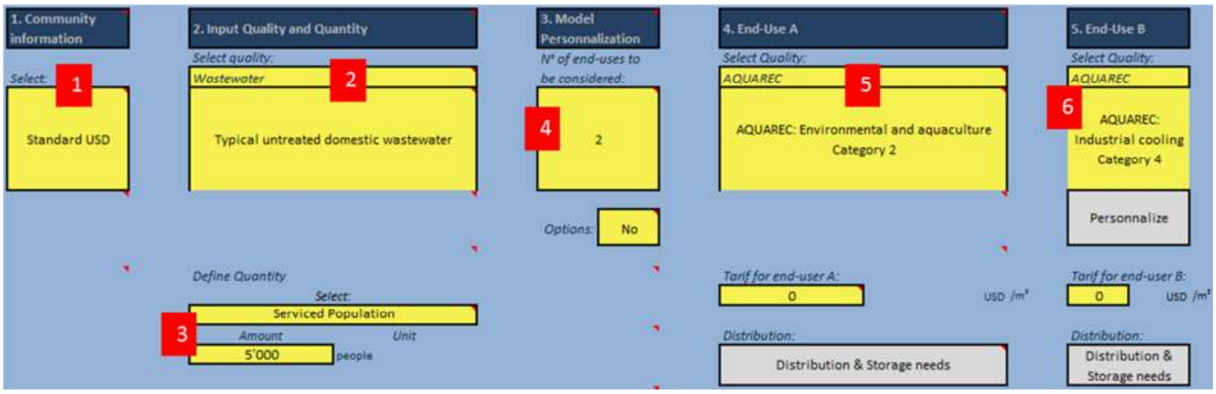


Figure 8-26: Filling in the information.

1. First select “Standard USD”.
2. Select “Wastewater” on the top, and just under it, select ”Typical untreated domestic wastewater.”
3. Select “Serviced Population” and on the bottom, type in “5,000” for the inhabitants.
4. In N° of end-uses to be considered, enter a value of 2, because we have 2 different scenarios in this task.
5. Here choose “AQUAREC” on the top, and just under it, choose “AQUAREC: Environmental and aquaculture Category 2.”
6. Select “AQUAREC” on the top as well, but under it choose “AQUAREC: Industrial cooling Category 4.”

To fill in the information for the first scenario, click the button "Distribution & Storage needs."

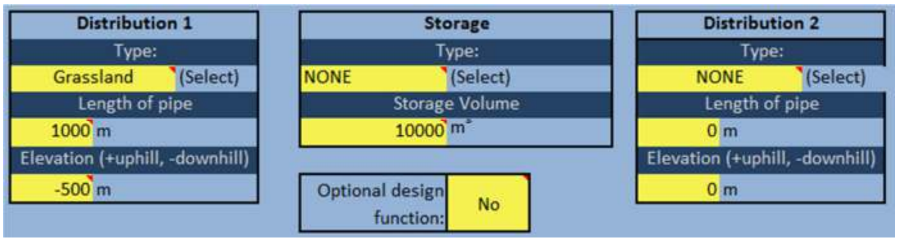


Figure 8-27: Distribution and storage needs.

Now fill in the needed data. Do the same for the other scenario; just click on the same button as before, but under the “5.End-Use B.”

4.3. Suggested Procedure – Analyze the Results

To analyze your solutions, click on the button "3. Analyze Solutions."

You will see the window shown in Figure 8-28.

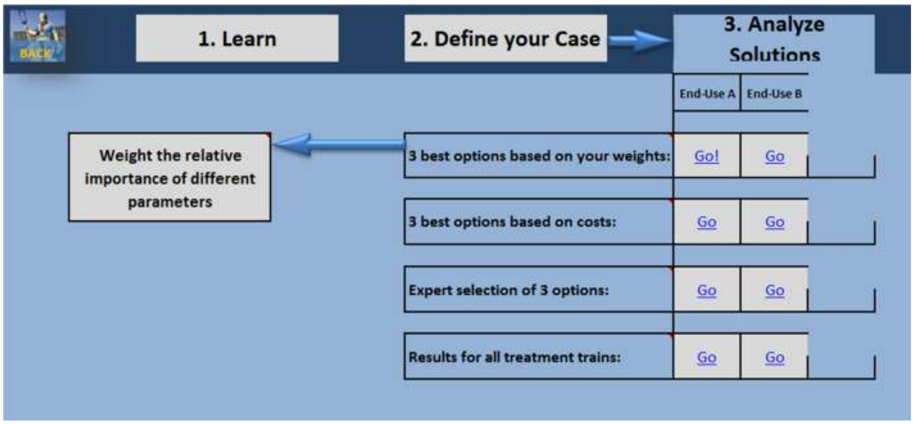


Figure 8-28: 3. Analyze solutions.

If click on "3. Analyze Solutions." You can select one of the following buttons to see your results (see Figure 8-29).

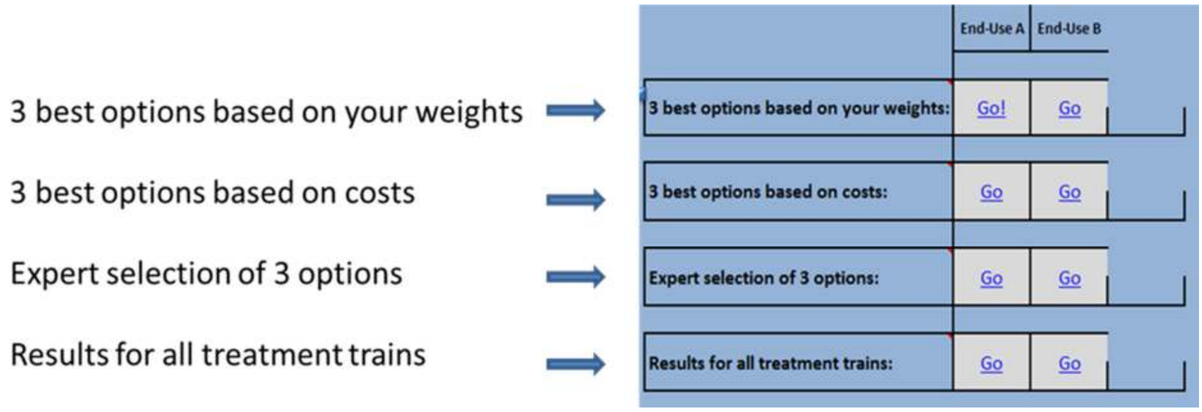


Figure 8-29: Different options in "3. Analyze Solutions."

For example if you click the leftmost "Go" (see Figure 8-30), you will see the three best options based on costs for the 1st scenario.

Figure 8-30: Three best options based on costs.

If you click the "Go" on the right side, you will see the same, but adapted to the 2nd scenario.

Table 8-1: Table with results

4.4. Questions & Answers

1. Are there suitable treatment trains for reuses 1 and/or 2?	Yes, there are a lot of suitable treatments for reuses for both of the scenarios.
2. Which are the best 3 options based on the costs?	1st scenario (reuse for aquaculture): Option 1: Title 22: Belgium Option 2: Soil treatment: Israel Option 3: Soil treatment: Benchmark 2nd scenario (reuse for industrial cooling in an industry): Option 1: Title 22: Belgium Option 2: Soil treatment: Israel Option 3: Soil treatment: Benchmark
3. What are the costs of treatment for those options?	Click on “3 best options based on costs,” and you will see the costs of treatment in the table (in this case in USD/m^3; other currencies are available for selection). Belgium: 1.00 [USD/m^3] Israel: 1.37 [USD/m^3] Benchmark: 1.40 [USD/m^3]

4. What are the costs of distribution for option 1?	Click on the same button as in question 3: Distribution costs are 0.02 [USD/m^3].

Remarks and analysis: For this case, it appears that the treatment train Title 22 Belgium both complies with intended reuse and offers the best treatment costs. There are some additional treatment trains that would be cheaper, but these treatments apparently would not comply with the water quality requirements indicated. If a treatment train based on Title 22: Belgium would be implemented in this fictive European village, it would comply with both scenarios (industrial and agricultural reuse), and it could be a good option to consider both reuses with a single treatment. The industry would probably also pay for the reclaimed water, and it would make sense to initiate some more detailed design and feasibility studies for this case.

4.5. Example 2: Comparison of Different Treatment Trains

Compare the following three treatment trains for the treatment of typical untreated domestic wastewater from 5,000 inhabitants:

1. Treatment train 1: Title 22 Benchmark technology;
2. Treatment train 2: bar screen, grit chamber, sedimentation with coagulant, activated sludge, chlorine gas; and
3. Treatment train 3: Maturation pond, maturation pond, and chlorine dioxide.

Suggested Procedure

To fill in all the information, go first to "2. Define your Case."

There you can fill in the 5,000 inhabitants, as you have done in task 1.

For the next step, click on “Create your own 3 treatment trains.”

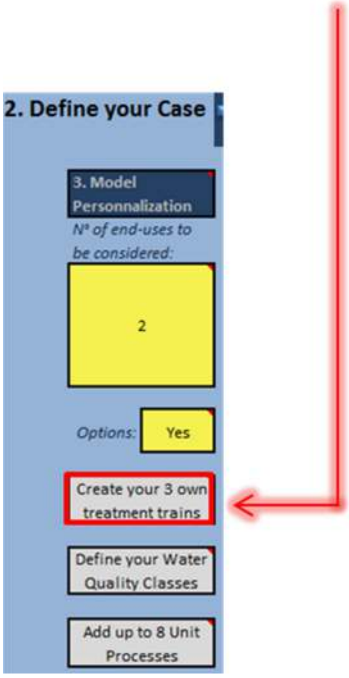


Figure 8-31: Create your own 3 treatment trains.

Now fill in all the data; you have to create two new treatment trains, because the first treatment train, "Title 22 Benchmark technology," must be entered somewhere else. You can call the second treatment train "TT2" and the third, "TT3."

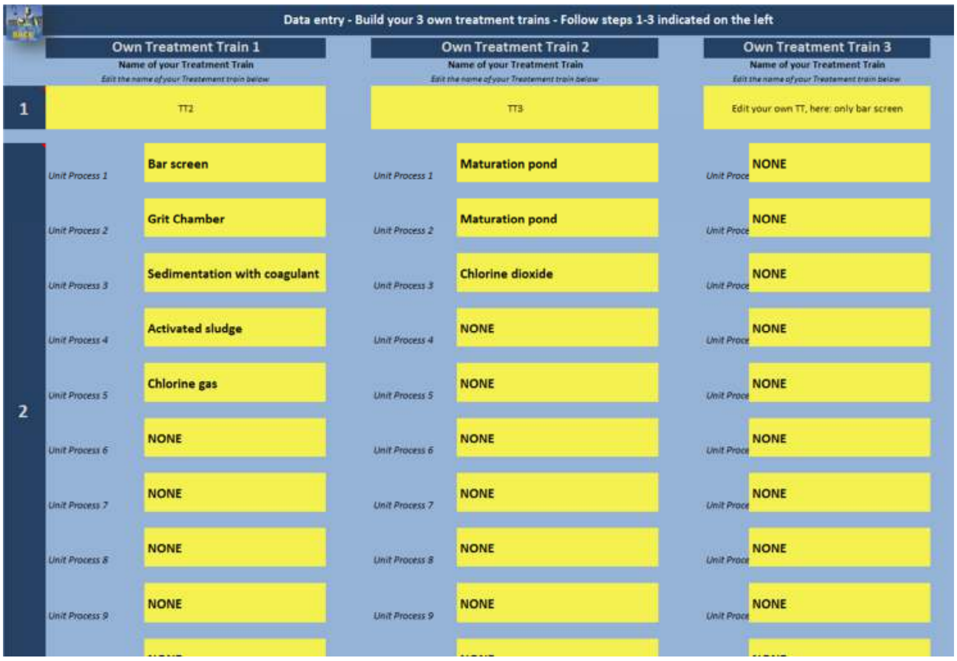


Figure 8-32: Data entry for your own three treatment trains.

Now, go back and click on "3. Analyze Solutions."

There, click on "Go," by the "Expert selection of 3 options."

You will come to the page with your results, once there, you have to change the treatment trains on the left side in the middle and fill in the required three treatment trains:

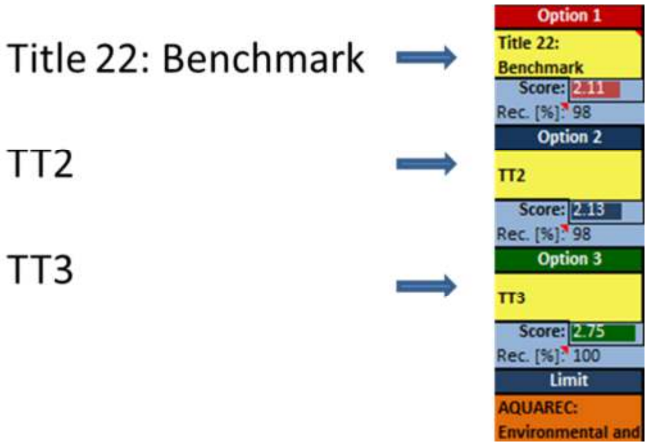
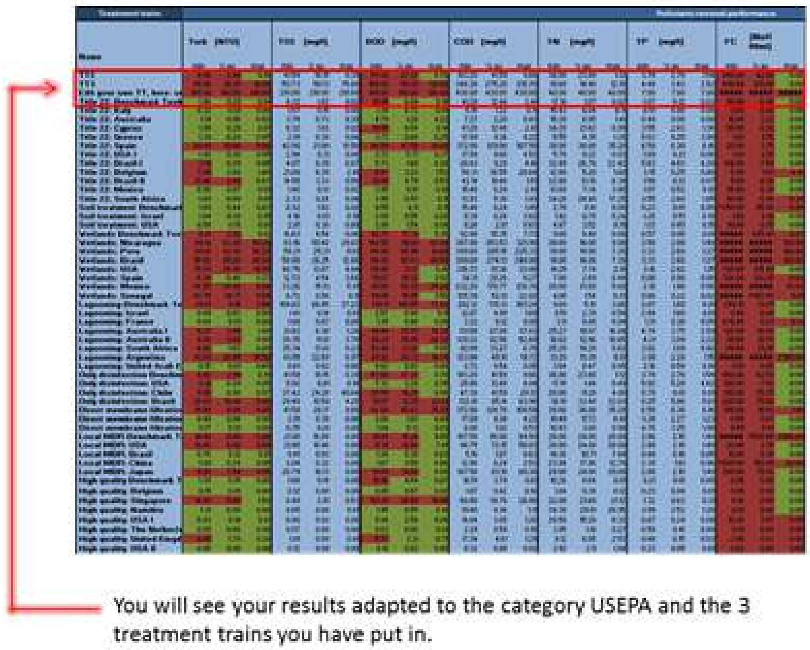


Figure 8-33: Title 22 Benchmark, TT2, TT3.

4.6. Questions & Answers

1. Are the three treatment trains compliant with EPA agricultural reuse – food crop quality class?	For the first task, go to "2. Define your Case" and select, in “4. End-Use A,” the option “USEPA”; under "USEPA," you choose “Agricultural Reuse - Food Crops” as a quality class:  Next, go to “3. Analyze Solutions,” and click on the “GO”" button on “Results for all Treatment Trains.”

	 If the results are green, the option is compliant, if they are red, it is not compliant.
2. What are the treatment costs of the three treatment trains?	Select "Expert selection of 3 options" in "Analyze solutions," where you will find the cost of treatment for the three treatment trains.
3. What would you recommend?	Here, TT2 and TT3 would be cheaper, but Title 22 Benchmark works better if you look at the table. I would therefore choose the solution built in Title 22 Benchmark.

5. Conclusions

Poseidon is a tool to promote and asses water reuse. Different parameters can be personalized and adapted in this tool per user. The values calculated by Poseidon should not be considered absolute values but only as indicators. The accuracy is not guaranteed. The given results show different possibilities to adapt or enhance the treatment of wastewater, but only the implementation in "real life" with adapted monitoring of the treatment can produce accurate values for a given treatment plant.

6. Glossary

Term	Definition *(applied to the use and understanding of Poseidon)*
Input	The wastewater that has to be treated before being reused

Term	**Definition** ***(applied to the use and understanding of Poseidon)***
Unit Processes	Single water treatment technologies (primary, secondary, tertiary treatment and disinfection technologies)
Treatment Trains	Series of unit processes combined in a so-called treatment train or treatment chain
End-use	The intended reuse of reclaimed water after its treatment with an adequate treatment train (e.g. agricultural, industrial, potable reuse or environmental recharge)
Quality class	Defined by several quality parameters included in the tool (e.g. turbidity, biological oxygen demand, etc.); those included in Poseidon either represent typical water quality of wastewaters or limits based on guidelines and recommendations for reuse
Weighting	Can be assigned to the different assessment criteria in order to calculate an overall treatment train score (single indicator) that considers the relative importance of different criteria based on specific cases
Distribution	Transport of wastewater and water in pipes or open channels; depending on elevation, distribution involves pumping
Wastewater	Water which has been polluted by human activities
Wastewater treatment	Improvement of water quality by applying a number of methods or technologies
Water reuse	Beneficial use of reclaimed water
Greywater	Wastewater from households or office buildings (bathing, cleaning, laundry etc.) without fecal contamination, i.e. all streams except for the wastewater from toilets
Blackwater	Wastewater and sewage from toilets
Primary treatment	Usually first step in cleaning process involving removal of solids, oils, and greases by flotation, sedimentation, and screening
Secondary treatment	Removal of dissolved suspended biological matter, which typically involves biological processes by microorganisms (activated sludge, membrane bioreactors, etc.)
Tertiary treatment	Cleaning to a high level of purity or removal of specific contaminants (e.g. heavy metals); can include disinfection
Water reclamation	Cleaning of wastewater to a purity that can be used for specific purposes

Term	**Definition *(applied to the use and understanding of Poseidon)***
Direct reuse	Direct use of reclaimed water for a specific purpose
Indirect reuse	Reuse of wastewater which has been previously mixed and diluted with fresh water by discharge into receiving water bodies

APPENDIX IV WATER UTILITY COMPASS – HANDBOOK

Water Utility Compass (WU-Compass) calculates a water balance and the typical performance indicators for your water utility, considering the data reliability (95% confidence limit), and it assesses water utility efficiency in order to develop an action plan with the proposal of adequate measures. The following steps should be followed: First, enter some general data from your water utility in Section 1 (tabs 1.1 and 1.2) and answer a questionnaire for the efficiency and potential analysis (tabs 1.3 and 1.4). Section 2 presents the water balance, performance indicators, a what-if analysis, and more outputs. In Section 3, a draft of an action plan can be created based on the potential analysis and suggested measures based on the assessment from the previous sections. Tab 3.3 presents an overview of main results. In addition, Section 4 provides further information, such as a glossary, references, and links to other documents for further reading.

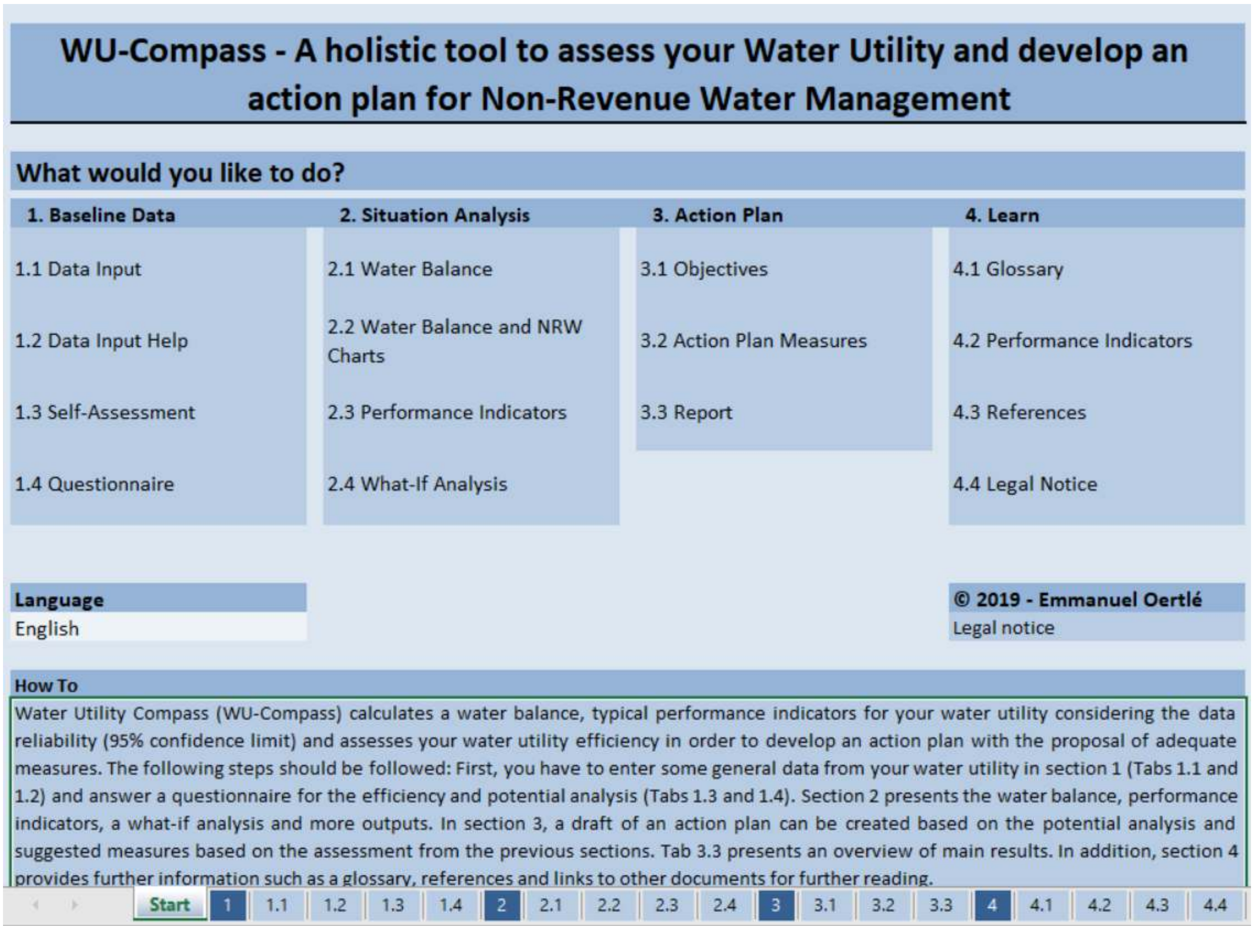


Figure 8-34: Start tab and user navigation panel.

1. Baseline Data

1.1. Data Input

You cannot manage what you cannot measure. One of the keys for efficient management is therefore data. The first step under tab 1.1 is to provide and enter data that will be the basis for all further analysis. For every data input, the data source and corresponding error margin should be included. Tab 1.2 can help with the calculations of aggregated values as well as the corresponding errors. The following data have to be provided (* for mandatory data):

- general indications,
- system input volume,
- authorized consumption,
- water losses (especially apparent losses),
- network information,
- management and monitoring, and
- financial data.

Home			
1. Baseline Data	2. Situation Analysis	3. Action Plan	4. Learn
1.1 Data Input	1.2 Data Input Help	1.3 Self-Assessment	1.4 Questionnaire

(*) required field (¹),(²) Two different input options: fill in either the total apparent losses (¹) or the detailed fields with the number (²).
You can use the tables in 1.2 to help you with the calculations of aggregated values as well as the corresponding errors and link them with formulas.

0. Personal Indications	Unit	Value
Name of utility / Area considered		Neustadt
Reference Period		2016
Duration (Measurement period)*	Days	365
Country		Neuland
Country type*		Developed country

1.1 System Input Volume	Unit	Value	Data source	Error margin [+/-%]	Manual input
Own sources*	[m³]	2,445,194	Specify error	1.4	1.4
Water imported	[m³]		Measured	2.0	
Water exported	[m³]		Measured	2.0	
Total	[m³]	2,445,194		1.4	

1.2 Authorized Consumption	Unit	Value	Data source	Error margin [+/-%]	Manual input
Billed metered*	[m³]	1,261,482	Specify error	1.1	1.1
Billed unmetered*	[m³]	251,768	Estimated	25.0	
Unbilled metered*	[m³]	36,500	Measured	2.0	
Unbilled unmetered*	[m³]	48,904	Estimated	25.0	
Total		1,598,654		4.1	

Figure 8-35: Tab 1.1 – Water utility data input (diverse information, water quantities, data source, error).

1.2. Self-Assessment Questionnaire

Tab 1.3 presents the overview of your water utility efficiency. The results of the self-assessment questionnaire from 1.4 are reported and can be adjusted with your own estimation value. The adjusted values are automatically considered in the spider diagram for water utility efficiency. The objective is to define the status and the goal for the 14 categories. The scale is qualitative between 1 (*poor*) and 5 (*excellent*).

		Status [1-5]			Goal [1-5]		
Topic	**From 1.4**	**Adjustment**	**Final**	**From 1.4**	**Adjustment**	**Final**	**Potential**
1. Data & Metering	3.5		3.5	4.5	4.5	4.5	**Medium**
2. Network Documentation	4.5		4.5	4.5		4.5	**n/a**
? 3. Water Balance & Perf. Indic. (PI)	3.0		3.0	4.7		4.7	**High**
? 4. District Metered Areas (DMA)	2.0		2.0	4.0		4.0	**Medium**
? 5. Active Leakage Control (ALC)	2.0		2.0	4.0		4.0	**Medium**
6. Pressure Management (PM)	2.3		2.3	4.0	4.5	4.5	**High**
7. Infrastructure Management (IM)	2.5	3.0	3.0	4.0	3.0	3.0	**n/a**
8. Operation & Maintenance (O&M)	2.0		2.0	4.0		4.0	**Medium**
? 9. Apparent Losses	3.0	2.5	2.5	3.0	3.5	3.5	**Little**
10. Human Resources	1.7		1.7	3.3		3.3	**Medium**
11. Equipment and Budget	3.5		3.5	4.0		4.0	**Little**
12. Organisation	2.7		2.7	3.0		3.0	**Very limited**
13. Managerial Commitment	1.5	2.0	2.0	1.5	2.0	2.0	**n/a**
14. Public Awareness	3.0	2.0	2.0	3.0	2.0	2.0	**n/a**

Figure 8-36: Tab 1.3 - Self-assessment questionnaire for water utility efficiency representation.

Issues / Questions	Your grade	Your goal	1 (poor)	2 (fair)	3 (average)	4 (good)	5 (excellent)	
1.1 Customer Metering	3	4	We have no customer metering.	Only large customers are metered.	We have started with universal customer meters, but at present not all customers have meters installe.d	Nearly all customers are metered, except public fountains, standpipes and similar.	100% of customers are metered.	USAID 2010
1.2 Customer Meter Replacement and Age	n/a	n/a	We have no reliable information on the age of our customer meters.	Many of our customer meteres are older than 10 years. We have not yet introduced a regular replacement policy.	We only change meters if they are obviously not functioning anymore.	We have a meter replacement policy but have not been able to change all meters, hence some of the customer meters are still older than 10 years.	We strictly follow our customer meter replacement policy and replace all meters every 5 to 7 years.	USAID 2010
1.3 Customer Meter Class	n/a	n/a	All customer meters are class A or B.	All customer meters are class B or C.	All customer meters are Class C.	All customer meters are Class C or D.	All customer meters are Class D.	USAID 2010
1.4 Customer Database	n/a	n/a	Customer database has not been updated for a long time.	Customer database is sporadically updated.	The customer database is in the process of being updated.	Customer database is regularly updated by house to house surveys and checks.	Customer database is updated and linked to the GIS.	USAID 2010
1.5 System Input Metering	4	5	Most of our system input is not metered.	Not all, but more than 50% of our system input is metered.	Our system input is metered but we are not sure about the accuracy of these (partly old) meters.	We use mechanical and/or magnetic flow meters that are rarely calibrated for the metering.	We use magnetic flow meters that are regulary calibrated.	USAID 2010
Performing grade [1-5]	**3.5**	**4.5**						

Figure 8-37: Tab 1.4 - Guiding questions and ranking to support the water utility efficiency self-assessment.

2. Situation Analysis

2.1. Water Balance and Non-Revenue Water Charts

This section analyses your data and calculates a water balance, which can be displayed in volume or percentage, considering the reliability of the data and the economic figures. Several results, such as the water balance and potential savings, are presented in different charts.

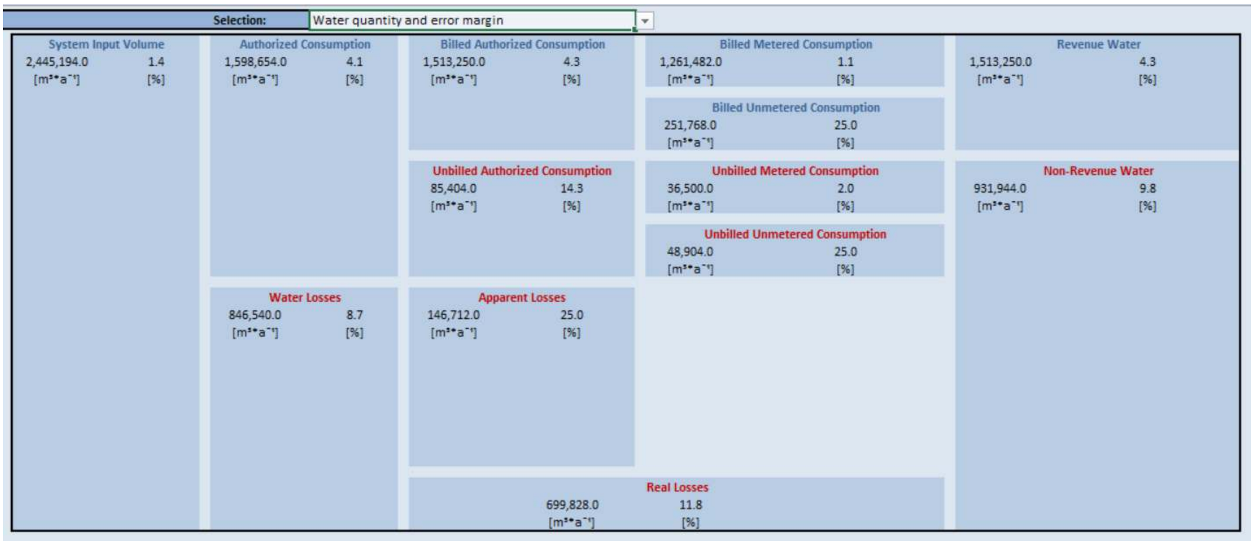
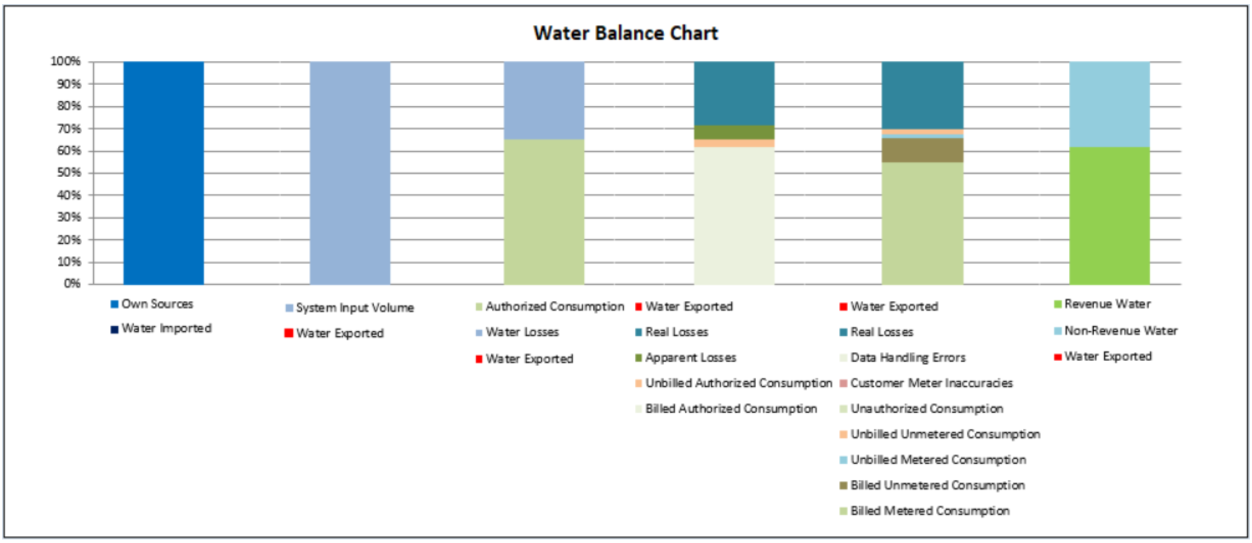
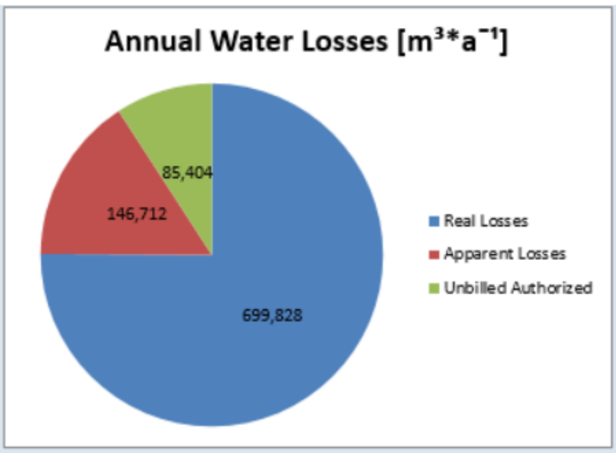


Figure 8-38: Resulting International Water Association water balance including error margin.





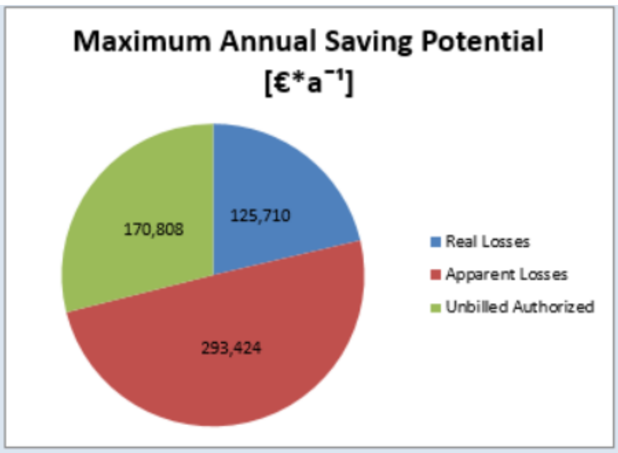


Figure 8-39: Several representations of non-revenue water (NRW) charts. Graphical water balance (top) and annual water losses and savings potential (bottom).

2.2. Performance Indicators

Main performance indicators are calculated and your performing grade is indicated based on international benchmarking. It is possible to calculate your potential savings for different targets that you can define. The different performance indicators calculated are classified into four categories: real losses, unbilled authorized consumption, NRW, and apparent losses.

Real Losses

Performance indicator	Unit	Indicator value	Error [%]	Performing grade	Target value	Target performing grade	Water saving [m^3*a^{-1}]	Water saving [%] of NRW	Water saving [$€*a^{-1}$]
ILI - Infrastructure Leakage Index	[-]	9.8	12.1	D	8	C	129,584.70	13.9	25,916.94
PMI	[-]	1.2	2.0	high					
Real Losses per service conn. per m pressure (w.s.p.)	[$l*conn^{-1}*d^{-1}*m\ H_2O^{-1}$]	11.4	12.1	D					
Real Losses per service conn. (w.s.p.)	[$l*conn^{-1}*d^{-1}$]	492.1	12.0	D					
Losses per main	[$l*km^{-1}*d^{-1}$]	36801.1	11.8	low					

Figure 8-40: Calculated performance indicators, performing grade according to international ranking and foreseen changes with targets set by the user.

2.3. Water Utility Efficiency

The water utility efficiency is displayed for the 14 categories.

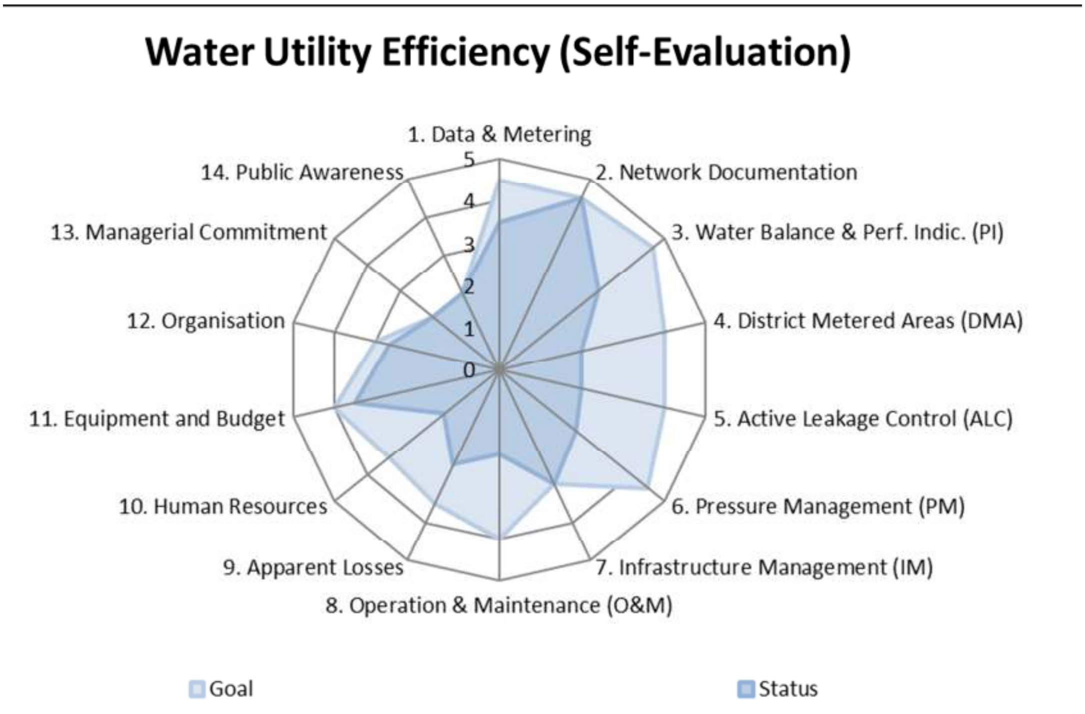


Figure 8-41: Graphical representation of the water utility efficiency based on the self-assessment questionnaire.

2.4. What-If Analysis

Several scenarios can be tested and analyzed, for example the effects of a reduced operating pressure.

If	Unit	Before	After	Change [%]
Real Losses	[m³]	699,828		
Apparent Losses	[m³]	146,712	100,000	-31.8
Unbilled Authorized Consumption	[m³]	85,404		
Average Supply Time	[h*d⁻¹]	24.00		

Then	Before	After	Change [%]
Non-Revenue Water	931,944	885,232	-5.0
Real Losses	699,828		
Annual Financial Losses	589,942	496,518	-15.8
Annual Saved Money		93,424	
ILI	9.82		
Real Losses per service conn. per m pressure (w.s.p.)	11.44		
PMI	1.23		
Apparent Losses per service conn. (w.s.p.)	103.17	70.32	-31.8
Percentage of UAC	3.49		
Percentage of NRW	38.11	36.20	-5.0

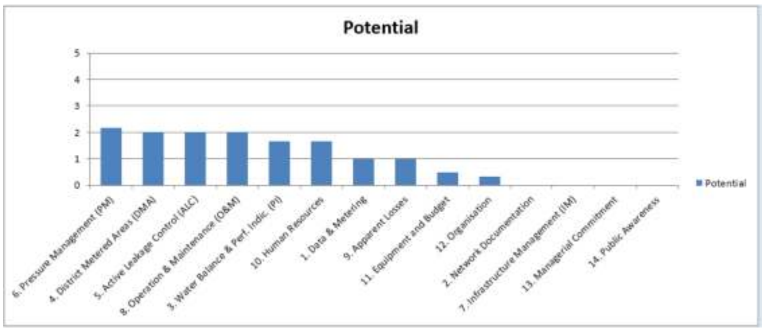
Figure 8-42: What-if analysis calculates change of different values with the change of some parameters.

3. Action Plan

Water-loss reduction is a complex topic with many components. It is therefore important to define a practical strategy that can be implemented with the resources at your disposal. In this section, you can start by defining your mission and selecting a few areas you want to focus on as priorities. Then, lists of possible measures are proposed to tackle these areas based on the questionnaire from tab 1.4. At the end you will have a rough sketch for an action plan that you can easily export together with the charts in Chapter 3 to use in presentations, reports, and other supports in your daily work.

3.1. Define Priority Areas

Think about your mission and subdivide it into multiple strategic objectives. You can base your choice on the potential in the different categories. Try to focus only on the most relevant and important areas.



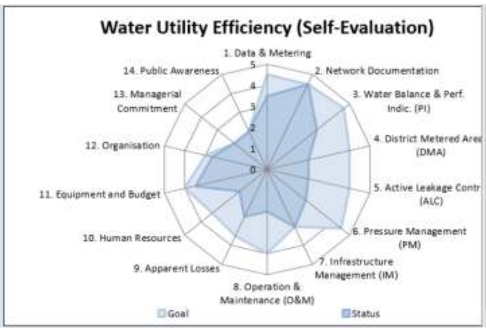


Figure 8-43: Potential and water utility efficiency as decision support for the definition of priority areas.

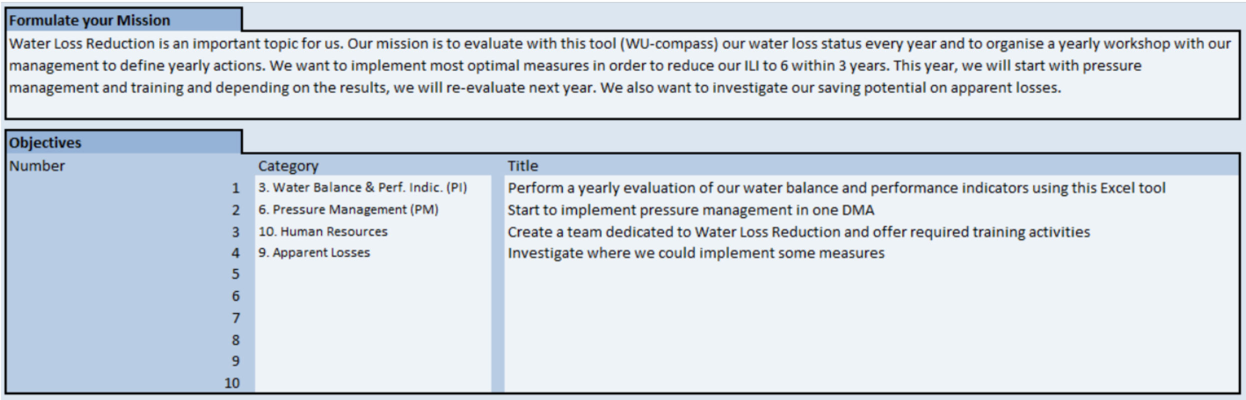


Figure 8-44: Tab 3.1 – Mission and main objectives definition in the selected categories.

3.2. Selection of Adapted Measures

In tab 3.2, you can go through each objective and define several measures to tackle them. We also present a few appropriate, standard measures based on the questionnaire. To add a measure automatically suggested on the left, just enter its number in the corresponding column on the right.

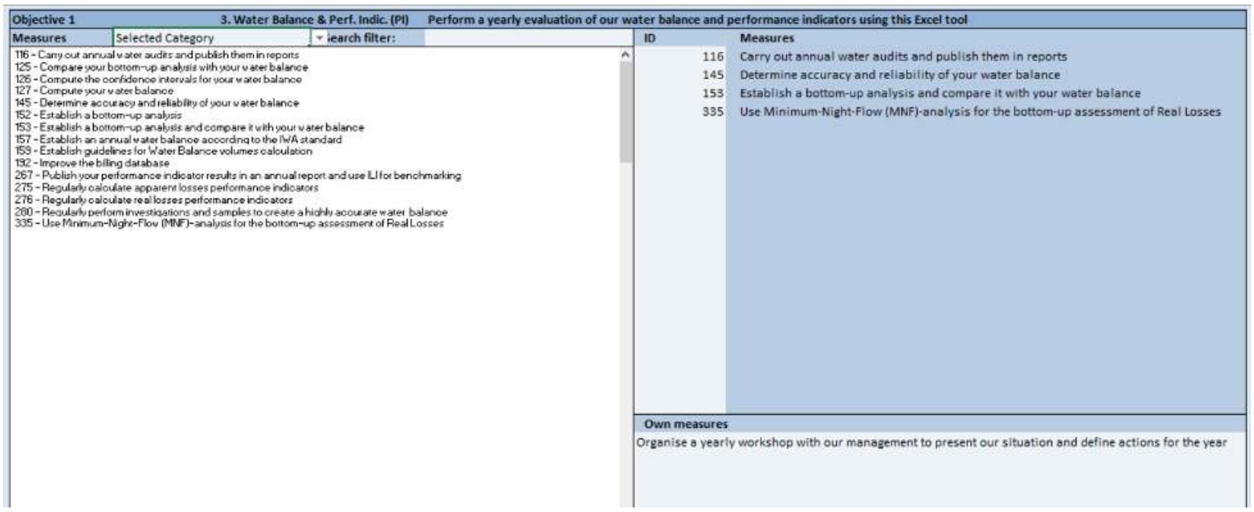


Figure 8-45: Tab 3.2 – For each main objective, selection of corresponding measures.

3.3. Action Plan

Tab 3.3 is has the form of a report that summarizes the key findings from the assessment conducted with Water Utility Compass. You can copy and paste the results to insert them into PowerPoint Presentations or other materials at your convenience. Please remember the results are always only as good as the input data you provided, and the author of Water Utility Compass cannot be held liable for any misinterpretation of the results.

Action plan

Mission

Water Loss Reduction is an important topic for us. Our mission is to evaluate with this tool (WU-compass) our water loss status every year and to organise a yearly workshop with our management to define yearly actions. We want to implement most optimal measures in order to reduce our ILI to 6 within 3 years. This year, we will start with pressure management and training and depending on the results, we will re-evaluate next year. We also want to investigate our saving potential on apparent losses.

What	Details
Objective 1	Perform a yearly evaluation of our water balance and performance indicators using this Excel tool
	Organise a yearly workshop with our management to present our situation and define actions for the year
Documentation	Carry out annual water audits and publish them in reports
Data accuracy	Determine accuracy and reliability of your water balance
Data accuracy	Establish a bottom-up analysis and compare it with your water balance
Bottom-up assessment	Use Minimum-Night-Flow (MNF)-analysis for the bottom-up assessment of Real Losses
Objective 2	Start to implement pressure management in one DMA
Pressure management	Define pressure management zones
Pressure management	Start applying pressure management in the most relevant DMAs
Objective 3	Create a team dedicated to Water Loss Reduction and offer required training activities
	Create a dedicated Water Loss Management Team
Staff	Incentivize good work
Staff	Introduce training programs for different specialized teams
Objective 4	Investigate where we could implement some measures
	Investigate in more details the reduction potential of apparent losses
Customer meters	Improve your measurements of unbilled authorized consumption

Figure 8-46: Resulting action plan.

APPENDIX V POSEIDON – WATER QUALITY CLASSES TABLES

The content of this appendix has been published as supplementary material to the publication presented in Appendix I (Emmanuel Oertlé et al., 2019), publicly available on the Zenodo repository: Oertlé, Emmanuel. (2018). Water Quality Classes - Recommended Water Quality Based on Guideline and Typical Wastewater Qualities (Version 1.0.0) [Data set]. Zenodo. http://doi.org/10.5281/zenodo.1252341

This dataset compiles water quality standards for different end-uses based on the most prominent guidelines. The value "−1" signifies no limit specified or no data available. The dataset also contains a list of typical wastewater qualities for several types of wastewater to be reused. The dataset contains the following two documents:

- Water Quality Classes – Typical Wastewater Qualities (Dataset) (as a PDF), and
- Water Quality Classes – Recommended Water Quality Based on Most Prominent and International Guidelines (Dataset) (as a PDF).

Section 1: Typical Wastewater Quality (Input) That Is Intended for Reuse

The table below indicates a list of typical wastewater qualities for several types of wastewater to be reused. The user can either manually define the quality of the "input flow" or choose from the list below. The value "−1" means no data available, not applicable, or not relevant.

Table 8-2: Typical Wastewater Quality (Input) That Is Intended for Reuse

Wastewater qualities of potential input	**Turb**	**TSS**	**BOD**	**COD**	**TN**	**TP**	**FC**	**TC**	**TDS**	**Nitrate**	**TOC**	**Virus**	**Reference / *Comments***

	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	CFU/ 100 ml	CFU/ 100 ml	mg/L	mg N/L	mg/L	PFU/ 100 ml	
Municipal Wastewater													
Typical untreated domestic wastewater	100	210	190	430	40	7	10^4–10^5	10^7–10^8	720	0	140	10^1–10^4	(Asano et al., 2007) *Typical composition of untreated domestic wastewater. Note: there is no typical wastewater; values should only be used as guide!* *Data presented are for medium-strengths wastewater based on average flow of 460 L/cap*day and include constituents added by commercial institutional, and industrial sources.*
Untreated domestic wastewater *(ranges)*	−1	120–400	110–350	250–800	20–70	4–12	10^3–10^7	10^6–10^9	270–860	0- trace	80–260	−1	(Asano et al., 2007)
Primary effluent	88	131	149	−1	−1	5.1	−1	−1	−1	0.1	72	−1	*Constituents remaining after primary treatment. Primary treatment consisted of a rotary drum screen , followed by disk screens*
Secondary effluent-water hyacinths	14	9.8	13 *(CBOD value)*	−1	−1	3.4	−1	−1	−1	1.4	14	−1	(Asano et al., 2007) / *Constituents remaining after secondary treatment. Secondary treatment was with water hyacinths*
Secondary effluent-CAS	2–15	5–25	5.25	40–80	15–35	4–10	−1	10^4–10^5	500–700	10–30	10–40	10^1–10^3	(Asano et al., 2007) / *Constituents remaining after secondary treatment. Secondary treatment was conventional activated sludge (CAS).*
Secondary effluent-CAS + filtration	0.5–4	2–8	<5–20	30–70	15–35	4–8	−1	10^3–10^5	500–700	10–30	8–30	10^1–10^3	(Asano et al., 2007) / *Constituents remaining after secondary treatment. Secondary treatment was conventional*

Wastewater qualities of potential input	**Turb**	**TSS**	**BOD**	**COD**	**TN**	**TP**	**FC**	**TC**	**TDS**	**Nitrate**	**TOC**	**Virus**	**Reference / *Comments***
	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	CFU/ 100 ml	CFU/ 100 ml	mg/L	mg N/L	mg/L	PFU/ 100 ml	
													activated sludge (CAS) with filtration
Secondary effluent- activated sludge + BNR	2–8	5–20	5–15	20–40	3–8	1–2	−1	10^4–10^5	500–700	2–8	8–20	10^1–10^3	(Asano et al., 2007) / *Constituents remaining after secondary treatment. Secondary treatment was activated sludge with biological nutrient removal (BNR) for the removal of nitrogen and phosphorus*
Secondary effluent- activated sludge + BNR+ filtration	0.3–2	1–4	1–5	20–30	2–5	2	−1	10^4–10^5	500–700	1–5	1–5	10^1–10^3	(Asano et al., 2007) / *Constituents remaining after secondary treatment. Secondary treatment was activated sludge with biological nutrient removal (for the removal of nitrogen and phosphorus) and filtration*
Secondary effluent- membrane bioreactor	1	2	<1–5	<10–30	<10	<0.3–5	−1	<100	500–700	10	0.5–5	10^0–10^3	(Asano et al., 2007) / *Constituents remaining after secondary treatment. Secondary treatment was membrane bioreactor*
Secondary effluent- activated sludge + MF + RO	0.01–1	1	1	2–10	1	0.5	−1	0	5–40	1	0.1–1	0	(Asano et al., 2007) / *Constituents remaining after secondary treatment. Secondary treatment was activated sludge with microfiltration (MF) and reverse osmosis (RO).*
Tertiary effluent	0.5	1.3	4.3 *(CBOD value)*	−1	−1	0.1	−1	−1	−1	1.7	7.1	−1	(Asano et al., 2007) / *Constituents remaining after tertiary treatment. Tertiary treatment consisted of lime precipitation and depth filtration*

Wastewater qualities of potential input	**Turb**	**TSS**	**BOD**	**COD**	**TN**	**TP**	**FC**	**TC**	**TDS**	**Nitrate**	**TOC**	**Virus**	**Reference / *Comments***
	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	CFU/ 100 ml	CFU/ 100 ml	mg/L	mg N/L	mg/L	PFU/ 100 ml	
AWT effluent	0.27	−1	−1	−1	−1	0.1	−1	−1	−1	0.7	0.6	−1	(Asano et al., 2007) / *Constituents remaining after advanced wastewater treatment (AWT).*
Industrial Wastewater													
Textile industry:													
Textile Industry-India	−1	−1	713 (500–1,010)	2125 (1,600 – 3,200)	−1	−1	−1	−1	5,738 (4,040 – 7,500)	354 (120–627)	−1	−1	(Hussain, Hussain, & Arif, 2004) / *Average Values and (ranges) from six Indian textile industries*
Textile Industry-Nigeria	−1	400 (49–1,200)	332 (163–645)	1,891 (1,067 – 2,430)	−1	−1	−1	−1	1,181 (250–2,200)	4.4 (Not detectable – 7.97)	−1	−1	(Yusuff & Sonibare, 2004) / *Average Values and (ranges) from five Nigerian textile mills*
Dairy industry:													
Dairy- Industry India	15–30	250–600	350–600	1,500–3,000	−1	−1	−1	−1	800–1,200	−1	−1	−1	(Sarkar, Chakrabarti, Vijaykumar, & Kale, 2006) / *Characteristics of raw dairy wastewater of A.P. Diary in Hyderabad, India*
Dairy Industry-Cheese	−1	500–2,500 *(Value*	588–5,000	1,000–7,500	830 *(Value for*	280	−1	−1	−1	−1	−1	−1	(Demirel, Yenigun, & Onay, 2017) / *Ranges or mean values reported from 3 cheese industry examples*

Wastewater qualities of potential input	**Turb**	**TSS**	**BOD**	**COD**	**TN**	**TP**	**FC**	**TC**	**TDS**	**Nitrate**	**TOC**	**Virus**	**Reference / *Comments***
	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	CFU/100 ml	CFU/100 ml	mg/L	mg N/L	mg/L	PFU/100 ml	
		for SS)			*TKN)*								
Dairy Industry- Cheese whey	−1	1,780 *(Value for SS)*	−1	61,000/ 68,814	980/ 1,462 *(Value for TKN)*	510/ 379	−1	−1	−1	−1	−1	−1	(Demirel et al., 2017) / *Ranges or mean values reported from 2 cheese whey industry examples*
Dairy Industry- Mixed processing	−1	340–1,730/ 12,500 *(Value for SS)*	−1	1,150–9,200/ 63,100	14–272 *(Value for TKN)*	8–68	−1	−1	−1	−1	−1	−1	(Demirel et al., 2017) / *Ranges or mean values reported from 2 mixed dairy industry examples*
Pulp and Paper industry:													
Paper mill	−1	800 *(Value for SS)*	1,600	5,020	11	0.6	−1	−1	−1	−1	−1	−1	(Pokhrel & Viraraghavan, 2017) / *Typical characteristics of wastewater at paper mill*
Brewery industry													
Brewery (Beer) *Typical ranges*	−1	200–1,000	1,200–3,600	2,000–6,000	25–80	10–50	−1	−1	−1	−1	−1	−1	(Oreopoulou et al., 2007)
Winery *Production: 3000*	−1	1,060	8,100	14,150	48.2	5.5	−1	−1	−1	−1	−1	−1	(Oreopoulou et al., 2007) / *Example of one wine producing industry*

Wastewater qualities of potential input	Turb	TSS	BOD	COD	TN	TP	FC	TC	TDS	Nitrate	TOC	Virus	Reference / *Comments*
	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	CFU/ 100 ml	CFU/ 100 ml	mg/L	mg N/L	mg/L	PFU/ 100 ml	
m^3/year													
Winery *Production: 6000 m^3/year*	−1	1,960–5,800	5,540–11,340	9,240–17,900	74–260	16–68	−1	−1	−1	−1	−1	−1	(Oreopoulou et al., 2007) / *Example of one wine producing industry*

Notes: "Turb" stands for "Turbidity", "TSS" stands for "Total suspended solids", "BOD" stands for "Biological oxygen demand", "COD" stands for "Chemical oxygen demand", "TN" stands for "Total nitrogen", "TP" stands for "Total phosphorous", "FC" stands for "Fecal coliform", "TC" stands for "Total coliform", "TDS" stands for "Total dissolved solids", "TOC" stands for "Total organic carbon".

Section 2: Recommended Water Quality Based on Guidelines

The table below compiles water quality standards for different end-uses based on different international guidelines. The value "−1" signifies no limit specified or no data available.

Table 8-3: Recommended Water Quality Based on Guidelines

End-use:	Turb	TSS	BOD	COD	TN	TP	FC	TC	TDS	Nitrate	TOC	Virus	Helminths	*Comments*
	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	CFU/100 ml	CFU/100 ml	mg/L	mg N/L	mg/L	PFU/100 ml	eggs/L	
United States Environmental Protection Agency (US EPA) guidelines, 2012 Many US states have rules, regulations or guidelines for a wide range of reclaimed water end uses and prescribe different requirements for different reuses. Minimum suggested regulatory guidelines are presented as follows. Guidelines refer to the use of treated municipal wastewater (reclaimed water). *<u>Remarks:</u> Recommended coliform limits are median values determined from the bacteriological results of the last 7 days for which analyses have been completed. The number of FC organisms should not exceed 800 CFU/100 ml in any sample.* *Additional standards included for all reuse categories: pH: 6.0–9.0; Minimum CL_2 residual: 1 mg/L*														
EPA: Urban Reuse-*unrestricted* Table 4.4, p.4–9	2	−1	10	−1	−1	−1	0	−1	−1	−1	−1	−1	−1	*<u>Definition</u>: Use of reclaimed water in non-potable applications in municipal settings where public access is not restricted.* *<u>Treatment:</u> Secondary, filtration, disinfection*
EPA: Urban Reuse-*restricted* Table 4.4, p.4–9	−1	30	30	−1	−1	−1	200	−1	−1	−1	−1	−1	−1	*<u>Definition:</u> Use of reclaimed water in non-potable applications in municipal settings where public access is restricted by physical/institutional barriers* *<u>Treatment:</u> Secondary, disinfection*
EPA: Agricultural Reuse-	2	−1	10	−1	−1	−1	0	−1	−1	−1	−1	−1	−1	*<u>Definition:</u> Use of reclaimed water for surface or spray irrigation of food crops eaten raw*

End-use:	**Turb**	**TSS**	**BOD**	**COD**	**TN**	**TP**	**FC**	**TC**	**TDS**	**Nitrate**	**TOC**	**Virus**	**Helminths**	***Comments***
	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	CFU/100 ml	CFU/100 ml	mg/L	mg N/L	mg/L	PFU/100 ml	eggs/L	
Food Crops Table 4.4, p.4–9														*Treatment: Secondary, filtration, disinfection*
EPA: Agricultural Reuse- *Processed food crops and Non-food crops* Table 4.4, p.4–9	−1	30	30	−1	−1	−1	200	−1	−1	−1	−1	−1	−1	*Definition: Use of reclaimed water for surface or spray irrigation of food crops processed prior to consumption and non-food crops like fodder, fiber etc.* *Treatment: Secondary, disinfection*
EPA: Impoundments- *unrestricted* Table 4.4, p.4–10	2	−1	10	−1	−1	−1	0	−1	−1	−1	−1	−1	−1	*Definition: Use of reclaimed water in an impoundment in which no limitations are imposed on body contact* *Treatment: Secondary, filtration, disinfection*
EPA: Impoundments- *restricted* Table 4.4, p.4–10	−1	30	30	−1	−1	−1	200	−1	−1	−1	−1	−1	−1	*Definition: Use of reclaimed water in an impoundment where bod-contact is restricted* *Treatment: Secondary, disinfection*
EPA: Environmental Reuse Table 4.4, p.4–10	−1	30	30	−1	−1	−1	200	−1	−1	−1	−1	−1	−1	*Definition: Use of reclaimed water to create wetlands, enhance natural wetlands or sustain stream flows* *Treatment: Variable, secondary, and disinfection*
EPA: Industrial Reuse- *Once-through cooling*	−1	30	30	−1	−1	−1	200	−1	−1	−1	−1	−1	−1	*Treatment: Secondary*
EPA: Industrial Reuse- *Recirculating Cooling Towers* Table 4.4, p.4_+10	−1	30	30	−1	−1	−1	200	−1	−1	−1	−1	−1	−1	*Treatment: Secondary, disinfection*

End-use:	Turb	TSS	BOD	COD	TN	TP	FC	TC	TDS	Nitrate	TOC	Virus	Helminths	Comments
	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	CFU/100 ml	CFU/100 ml	mg/L	mg N/L	mg/L	PFU/100 ml	eggs/L	
EPA: Groundwater Recharge- *Indirect potable reuse* Table 4.4, p.4–11	2	−1	−1	−1	−1	−1	0	−1	−1	−1	2	−1	−1	*<u>Definition:</u> Groundwater recharge by spreading into potable aquifers or by injection into potable aquifers and augmentation of surface water supply reservoirs* *<u>Treatment:</u> Secondary, filtration, disinfection, advanced wastewater treatment or soil aquifer treatment*

Texas water reuse standards (Example indicated in US EPA guidelines, 2012)

<u>Remarks:</u> Recommended coliform limits are 30 days geometric mean values. The maximum of FC organisms in any samples is indicated in brackets.

End-use:	Turb	TSS	BOD	COD	TN	TP	FC	TC	TDS	Nitrate	TOC	Virus	Helminths	Comments
Texas EPA: Urban Reuse-*unrestricted* Table 4.7, p.4–26	3	−1	5	−1	−1	−1	20 (75)	−1	−1	−1	−1	−1	−1	*Add. Parameter: Enterococci: 4 CFU/100 mL (max. 9 CFU/100 mL)*
Texas EPA: Urban Reuse-*restricted* Table 4.8, p.4–27	−1	−1	20	−1	−1	−1	200 (800)	−1	−1	−1	−1	−1	−1	*BOD: 20 mg/L without pond; 30 mg/L with pond* *Add. Parameter: Enterococci: 35 CFU/100 mL (max. 89 CFU/100 mL)*
Texas EPA: Agricultural Reuse-*Food Crops* Table 4.9, p.4–28	3	−1	5	−1	−1	−1	20 (75)	−1	−1	−1	−1	−1	−1	*Add. Parameter: Enterococci: 4 CFU/100 mL (max. 9 CFU/100 mL)*
Texas EPA: Agricultural Reuse-*Processed food crops and Non-food crops* Table 4.10, p.4–29	−1	−1	20	−1	−1	−1	200 (800)	−1	−1	−1	−1	−1	−1	*BOD: 20 mg/L without pond; 30 mg/L with pond* *Add. Parameter: Enterococci: 35 CFU/100 mL (max. 89 CFU/100 mL)*
Texas EPA: Impoundments-	3	−1	5	−1	−1	−1	20 (75)	−1	−1	−1	−1	−1	−1	*Add. Parameter: Enterococci: 4 CFU/100 ml (max. 9 CFU/100 mL)*

End-use:	**Turb**	**TSS**	**BOD**	**COD**	**TN**	**TP**	**FC**	**TC**	**TDS**	**Nitrate**	**TOC**	**Virus**	**Helminths**	***Comments***
	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	CFU/100 ml	CFU/100 ml	mg/L	mg N/L	mg/L	PFU/100 ml	eggs/L	
unrestricted Table 4.11, p.4–30														
Texas EPA: Impoundments-*restricted* Table 4.12, p.4–31	−1	−1	20	−1	−1	−1	200 (800)	−1	−1	−1	−1	−1	−1	*BOD: 20 mg/L without pond; 30 mg/L with pond* *Add. Parameter: Enterococci: 35 CFU/100 mL (max. 89 CFU/100 mL)*
Texas EPA: Environmental Reuse Table 4.13, p.4–32	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	*Not regulated*
Texas EPA: Industrial Reuse- *Recirculating Cooling Towers* Table 4.14, p.4–33	−1	−1	20	−1	−1	−1	200 (800)	−1	−1	−1	−1	−1	−1	*BOD: 20 mg/L without pond; 30 mg/L with pond* *Add. Parameter: Enterococci: 35 CFU/100 mL (max. 89 CFU/100 mL)*
Texas EPA: Groundwater Recharge- *Indirect potable reuse* Table 4.16, p.4–35	3	−1	5	−1	−1	−1	20 (75)	−1	−1	−1	−1	−1	−1	*Add. Parameter: Enterococci: 4 CFU/100 mL (max. 9 CFU/100 mL)*

California water reuse standards (Example indicated in US EPA guidelines, 2012)

<u>Remarks:</u> Recommended coliform limits are median values determined from the bacteriological results of the last 7 days for which analyses have been completed. (Otherwise indicated in brackets.

California EPA: Urban Reuse- *unrestricted*	2	−1	−1	−1	−1	−1	−1	2.2	−1	−1	−1	−1	−1	*For media filters: 2 NTU (avg.)/10 NTU (max.)* *For membrane filters: 0.2 NTU (avg.)/0.5 NTU (max.)*

End-use:	**Turb**	**TSS**	**BOD**	**COD**	**TN**	**TP**	**FC**	**TC**	**TDS**	**Nitrate**	**TOC**	**Virus**	**Helminths**	***Comments***
	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	CFU/100 ml	CFU/100 ml	mg/L	mg N/L	mg/L	PFU/100 ml	eggs/L	
Table 4.7, p.4–26														*TC: 240/100 ml (max.)*
California EPA: Urban Reuse-*restricted* Table 4.784, p.4–27	−1	−1	−1	−1	−1	−1	−1	23	−1	−1	−1	−1	−1	*TC: 240/100 ml (max.)*
California EPA: Agricultural Reuse-*Food Crops* Table 4.9, p.4–28	2	−1	−1	−1	−1	−1	−1	2.2	−1	−1	−1	−1	−1	*For media filters: 2 NTU (avg.)/10 NTU (max.)* *For membrane filters: 0.2 NTU (avg.)/0.5 NTU (max.)* *TC: 240/100 ml (max.)*
California EPA: Agricultural Reuse-*Processed food crops and Non-food crops* Table 4.10, p.4–29	−1	−1	−1	−1	10	−1	−1	−1	−1	−1	−1	−1	−1	*TC is not specified in the Californian standards.*
California EPA: Impoundments-*unrestricted* Table 4.11, p.4–30	2	−1	−1	−1	−1	−1	−1	2.2	−1	−1	−1	−1	−1	*For media filters: 2 NTU (avg.)/10 NTU (max.)* *For membrane filters: 0.2 NTU (avg.)/ 0.5 NTU (max.)* *TC: 240/100 ml (max.)* *Supplemental pathogen monitoring*
California EPA: Impoundments-*restricted* Table 4.12, p.4–31	−1	−1	−1	−1	−1	−1	−1	2.2	−1	−1	−1	−1	−1	*TC: 23/100 ml (not more than one sample exceeds this value in 30d)*
California EPA: Environmental Reuse	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	*Not regulated*

End-use:	**Turb**	**TSS**	**BOD**	**COD**	**TN**	**TP**	**FC**	**TC**	**TDS**	**Nitrate**	**TOC**	**Virus**	**Helminths**	***Comments***
	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	CFU/100 ml	CFU/100 ml	mg/L	mg N/L	mg/L	PFU/100 ml	eggs/L	
Table 4.13, p.4–32														
California EPA: Industrial Reuse- *Once-through cooling* Table 4.14, p.4–33	2	−1	−1	−1	−1	−1	−1	2.2	−1	−1	−1	−1	−1	*For media filters: 2 NTU (avg.)/10 NTU (max.)* *For membrane filters: 0.2 NTU (avg.)/0.5 NTU (max.)* *TC: 240/100 ml (max.)*
California EPA: Groundwater Recharge- *Indirect potable reuse* Table 4.16, p.4–35	2	−1	−1	−1	10 avg. of 4 consec. samples	−1	−1	2.2	−1	−1	0.5	−1	−1	*For media filters: 2 NTU (avg.)/10 NTU (max.)* *For membrane filters: 0.2 NTU (avg.)/0.5 NTU (max.)* *TC: 240/100 ml (max.)* *Pathogen monitoring is not required but virus removal rates are prescribed by treatment requirements*

World Health Organization (WHO) guidelines, 2006; Vol. 2–4

The WHO guidelines for the *safe use of wastewater, excreta and greywater* (presented in 4 volumes) are designed to protect the health of farmers (and their families), local communities and product consumers. Overly strict standards may not be suitable in developing countries. The guidelines propose maximum limits or maximum ranges for E.coli and helminths in wastewater and greywater for different reuse purposes that have been set to meet health based targets (i.e. not to exceed 10^{-6} DALY per person per year).

Remarks: Recommended standard for E.coli per 100 ml are arithmetic means and are indicated under the FC parameter in the table below. E.coli is approximately equivalent to 90% of the FCs.

WHO: Use of wastewater in agriculture-*unrestricted* Vol.2, Chapter 4.2, p.63–67	−1	−1	−1	−1	−1	−1	10^3–10^4	−1	−1	−1	−1	−1	1	*Definition: Irrigation with wastewater of all agricultural crops* *Standards for E.coli in CFU/100 mL:* *Root crops:10^3 ; Leaf crops: 10^4 ; Drip irrigation, high growing crops: 10^5*

End-use:	Turb	TSS	BOD	COD	TN	TP	FC	TC	TDS	Nitrate	TOC	Virus	Helminths	*Comments*
	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	CFU/100 ml	CFU/100 ml	mg/L	mg N/L	mg/L	PFU/100 ml	eggs/L	
WHO: Use of wastewater in agriculture-*restricted-highly mechanized irrigation* Vol.2, Chapter 4.2, p.67–69	−1	−1	−1	−1	−1	−1	10^5	−1	−1	−1	−1	−1	1	*Definition: Irrigation with wastewater of all agricultural crops except crops eaten unprocessed/raw (like lettuce).* *Standards for E.coli in CFU/100 mL:* *Labor-intensive irrigation: 10^4 ; High mechanized agriculture: 10^5 ; Drip irrigation, high growing crops: 10^5*
WHO: Use of wastewater in agriculture- *restricted-labor intensive irrigation* Vol.2, Chapter 4.2, p.67–69	−1	−1	−1	−1	−1	−1	10^3–10^4	−1	−1	−1	−1	−1	1	*Definition: Irrigation of all agricultural crops except crops eaten unprocessed/raw (like lettuce).* *Standards for E.coli in CFU/100 mL:* *Labor-intensive irrigation: 10^4 ; High mechanized agriculture: 10^5*
WHO: Use of wastewater in aquaculture Vol.3, Table 4.1, p.41	−1	−1	−1	−1	−1	−1	10^4–10^5	−1	−1	−1	−1	−1	1	*Standards for E.coli in CFU/100 mL:* *Consumers: 10^5 ;Workers: 10^4* *No trematode eggs detectable*
WHO: Use of grey water in agriculture-*unrestricted* Vol.4. Table 4.2, p.63	−1	−1	−1	−1	−1	−1	10^3–10^4	−1	−1	−1	−1	−1	1	*Definition: Irrigation with grey water of all agricultural crops* *Standards for E.coli in CFU/100 mL:* *High growing crops or Drip irrigation: 10^4*
WHO: Use of grey water in agriculture-*restricted* Vol.4. Table 4.2, p.63	−1	−1	−1	−1	−1	−1	10^5	−1	−1	−1	−1	−1	1	*Definition: Irrigation with grey water of all agricultural crops except crops eaten unprocessed/raw (like lettuce).*

Standards for Water Reuse in Eastern Mediterranean Region (EMR), based on WHO guidelines 1989

Reference: A compendium of standards for wastewater reuse in the Eastern Mediterranean Region, 2006

End-use:	**Turb**	**TSS**	**BOD**	**COD**	**TN**	**TP**	**FC**	**TC**	**TDS**	**Nitrate**	**TOC**	**Virus**	**Helminths**	***Comments***
	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	CFU/100 ml	CFU/100 ml	mg/L	mg N/L	mg/L	PFU/100 ml	eggs/L	
The compendium provides an overview of the quality standards for the reuse of treated wastewater in countries of the Eastern Mediterranean Region. The WHO in collaboration with the Arab Fund for Economic and Social Development (AFESD) recommended guidelines for wastewater (Category A-C) and greywater (Category A-C) reuse for the Eastern Mediterranean Region in 2003. In addition, Jordanian Standards for wastewater reuse are listed below (JS:893/2002).														
Wastewater: Category A *Unrestricted irrigation*	−1	−1	−1	−1	−1	−1	10^3	−1	−1	−1	−1	−1	0	*Definition: Irrigation with wastewater of vegetable and salad crops eaten uncooked, sport fields, public parks* *Irrigation technique: any* *Exposed group: Workers, consumers, public*
Wastewater: Category B *Restricted irrigation*	−1	−1	−1	−1	−1	−1	10^3/ 10^5	−1	−1	−1	−1	−1	0	*Definition: Irrigation with wastewater of cereal crops, industrial crops, fodder crops, pasture and trees* *Irrigation technique: spray or sprinkler (10^5 E.coli CFU/mL); Flood or furrow (10^3 E.coli CFU/mL)* *Exposed group: Workers, nearby communities*
Wastewater: Category C	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	*Definition: Localized irrigation with wastewater of crops in category B if exposure of workers and the public does not occur.* *Irrigation technique: Trickle, drip or bubbler* *Exposed group: None* *No water quality measures have to be met*
Greywater: Category A	−1	140	240	−1	−1	−1	10^3	−1	−1	−1	−1	−1	−1	*Definition: Irrigation with greywater of ornamental fruit trees and fodder crops*
Greywater: Category B	−1	20	20	−1	−1	−1	200	−1	−1	−1	−1	−1	−1	*Definition: Irrigation with greywater of vegetables likely to be eaten uncooked.*

End-use:	Turb	TSS	BOD	COD	TN	TP	FC	TC	TDS	Nitrate	TOC	Virus	Helminths	*Comments*
	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	CFU/100 ml	CFU/100 ml	mg/L	mg N/L	mg/L	PFU/100 ml	eggs/L	
Greywater: Category C	−1	10	10	−1	−1	−1	10	−1	−1	−1	−1	−1	−1	*Definition: Greywater used for toilet flushing*
JS:893/2002- Discharge to streams	−1	60	60	150	70	−1	10^3	−1	1,500	45	−1	−1	1	*Definition: Discharge of wastewater to streams, wadis and water storage area* *E.coli counts (FC) are given in MPN/100 mL*
JS:893/2002- Groundwater recharge	2	50	15	50	45	−1	2.2	−1	1,500	30	−1	−1	1	*Definition: Wastewater used for groundwater recharge* *E.coli counts (FC) are given in MPN/100 mL*
JS:893/2002- Agricultural irrigation *Group A*	10	50	30	100	45	−1	100	−1	−1	30	−1	−1	1	*Definition: Irrigation with wastewater for cooked vegetables, parking areas, playgrounds and side of roads inside cities* *E.coli counts (FC) are given in MPN/100 mL*
JS:893/2002- Agricultural irrigation *Group B*	−1	150	200	500	70	−1	10^3	−1	−1	45	−1	−1	1	*Definition: Irrigation with wastewater for plenteous trees and green areas, side of roads outside cities* *E.coli counts (FC) are given in MPN/100 mL*
JS:893/2002- Agricultural irrigation *Group C*	−1	150	300	500	70	−1	−1	−1	−1	45	−1	−1	1	*Definition: Irrigation with wastewater for field crops, industrial crops and forestry*

Water quality criteria AQUAREC project , 2006

Seven quality categories (I to VII) for different types of reuses (4 categories) are proposed and microbial and chemical limits for each category are compiled

End-use:	**Turb**	**TSS**	**BOD**	**COD**	**TN**	**TP**	**FC**	**TC**	**TDS**	**Nitrate**	**TOC**	**Virus**	**Helminths**	***Comments***
	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	CFU/100 ml	CFU/100 ml	mg/L	mg N/L	mg/L	PFU/100 ml	eggs/L	

Microbial parameters include: Total bacteria, fecal coliforms, *Clostridium perfringens*, *Legionella, Enterococci, Salmonella*, Enteroviruses, *Coliphages*, *Cryptosporidium* and *Giardia*, Nematode eggs, *T. Saginata, T.solium*

Fecal coliforms counts for microbial categories in CFU/100 mL:

I: absent II: <20–<1,000 III: absent–<1,000 IV: absent–10,000 V: absent–<10,000 VI: <200–<10,000 VII: absent–10,000

Nematode egg counts for microbial categories in eggs/L:

I: <1–10 II: <1 III: <1 IV: <1 V: <1 VI: <1 VII: <1

Enterovirus counts for microbial categories in pfu/L:

I: absent–10 II: absent–10 III: <1–<100 IV: not defined V: not defined VI: <100 VII: <1–0.04

AQUAREC: Private, urban irrigation *Category 1*	−1	10	10–20	100	−1	2–5	abs.−10,000	−1	1,650–2,400 *(3,000 microS/cm)*	−1	100	abs.-<100	<1–10	*Specific final uses (according to microbial categories):* *I: Residential uses* *II: Bathing water* *III: Urban uses (irrigation of landscape areas, street cleaning, fire-fighting) and unrestricted irrigation* *IV: Irrigation of industrial crops and animal fodder, restricted irrigation* *V: Irrigation of forested areas and restricted access areas* *Additional Total Kjeldahl N: 15–20 mg/L*
AQUAREC: Environmental and aquaculture	−1	10	10–20	70–100	−1	0.2	abs.−10,000	−1	1,650–2,400 *(3,000 microS/*	−1	70–100	<100	<1	*Specific final uses (according to microbial categories):* *IV: Impoundments, water bodies and streams for recreational use with access (except*

End-use:	**Turb** NTU	**TSS** mg/L	**BOD** mg/L	**COD** mg/L	**TN** mg/L	**TP** mg/L	**FC** CFU/100 ml	**TC** CFU/100 ml	**TDS** mg/L	**Nitrate** mg N/L	**TOC** mg/L	**Virus** PFU/100 ml	**Helminths** eggs/L	***Comments***
Category 2									*cm)*					*bathing)* *V: Impoundments, water bodies and streams for recreational use with access (except bathing)* *VI: Surface water quality, water bodies and streams for recreational use with restricted access* *Total Kjeldahl N: 10–20 mg/L*
AQUAREC: Indirect aquifer recharge *Category 3*	−1	−1	−1	70–100	−1	−1	abs.-<10,000	−1	385–560 *(700 microS/cm)*0	25	70–100	−1	<1	*Specific final uses (according to microbial categories):* *V: Aquifer recharge by localized percolation through the soil*
AQUAREC: Industrial cooling *Category 4*	−1	10	−1	70	−1	0.2	abs.−10,000	−1	−1	−1	70	<1 – 0.04	<1	*Specific final uses (according to microbial categories):* *VII: Industrial cooling except for the food industry* *Total Kjeldahl N: 10 mg/L*

Notes: "Turb" stands for "Turbidity", "TSS" stands for "Total suspended solids", "BOD" stands for "Biological oxygen demand", "COD" stands for "Chemical oxygen demand", "TN" stands for "Total nitrogen", "TP" stands for "Total phosphorous", "FC" stands for "Fecal coliform", "TC" stands for "Total coliform", "TDS" stands for "Total dissolved solids", "TOC" stands for "Total organic carbon".

APPENDIX VI POSEIDON – UNIT PROCESSES FACTSHEETS

1. Preliminary Treatment

The first steps in the treatment of municipal wastewater usually include flow measurement, screening, pumping, and grit removal. Flow measurement is essential for all wastewater and water-reuse treatment plants and is commonly done by a Parshall flume, which allows the calculation of volumetric flow rates based on the height of the water head in a specially designed channel.

1.1. Bar Screens

Bar screens are typically at the entrance of a WWTP and used to remove large objects such as rags, plastics bottles, diverse floatables and solids from the waste stream entering the treatment plant. They have openings of 1–6 cm (Hammer & Hammer, 2012b) and collected solids can be removed by a traveling rake (Figure 8-47). Typically, bar screens fall under two classifications, *mechanical* and *manual screens* (trash racks can either be manually cleaned or mechanically cleaned). There are various types of bar screens available for installation; they include but are not limited to *chain bar screens*, *reciprocating rake bar screens*, *catenary bar screens*, and *continuous belt bar screens* (Infobarscreens, 2013).

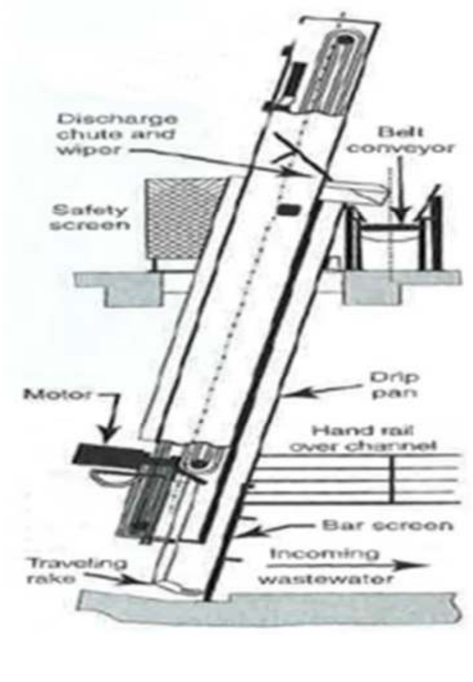


Figure 8-47: Mechanically cleaned bar screen with traveling rake (Hammer & Hammer, 2012b).

1.2. Screening

In order to remove greater quantities of papers, plastic, and so on, perforated plates or filter belts can be used to screen influent wastewater. Coarse screen types have openings of 6 mm or larger, finer screens of approximately 1.5–6 mm (US-EPA, 1994). Applications that typically use fine screens are pre-treatment in conjunction with a coarse bar screen, primary treatment instead of primary clarifiers, and pre-treatment at combined sewer overflows. When clogging of trickling filters presents the potential for a problem, it is common to use fine screens upstream of the trickling filters to remove solids from the primary effluent (Infobarscreens, 2013). The finer screens are required if non-biodegradable fibrous material and hair have to be removed (Hammer & Hammer, 2012b). Cleaning of the screens can happen by brush, water spray, or a combination of the two. In most cases, periodic cleaning of brushes by plant staff is required. Fine screen units can be installed instead of bar screens or in series with bar screens. Series of progressively finer screens can help reduce organic load (Hammer & Hammer, 2012b). The fine screens that are used in pre-treatment and primary treatment are as follows: band screens (effective for fine screening applications that have high flows), static wedgewire screens (typically installed in smaller treatment plants), rotary drum screens (effective for applications that require big solids separation and small energy usage), and step screens (cost effective solids separation).

Advantages: Protection of membranes in tertiary treatment; very low equipment maintenance (manually cleaned screens); mechanically cleaned screens have lower labor costs than do manually cleaned screens

Disadvantages: Head loss (ranges between 0.8–1.4 m)

Pre-treatment: Bar screens or raw wastewater

Figure 8-48: The tangential flow screen utilizes the natural motion of the water to screen and collect particles (Infobarscreens, 2013).

1.3. Grit Chamber

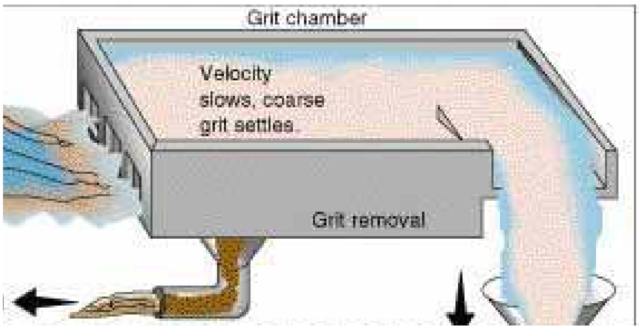


Figure 8-49: Raw sewage moves from the grit chamber to primary treatment (Gende, 2017).

Advantages: Protection of downstream processes from increased abrasion; prevention of clogging; aerated grit chambers have consistent removal efficiencies over a wide range of flows, and aeration may reduce septic conditions and thus increase the performance of downstream unit processes; vortex type grit chambers remove a high percentage of fine grit, have consistent removal efficiencies over a wide range of flows, and have a small footprint. The head loss is also very small; detritus tanks do not require flow control and head loss is minimal; horizontal flow grit chambers are flexible and simple to construct; hydrocyclones remove grit, and suspended solids and may ideally remove as many solids as a primary clarifier (US-EPA, 1994).

Disadvantages: Increased head loss could in some cases require additional pumping; aerated grit chambers can emit volatile organics and odors and require more power than do other grit removal processes; vortex-type systems often require deep excavation due to their height, and clogging can be an issue; detritus tanks are not easily adjustable to varying flow, and large quantities of organic material are removed, thus requiring washing and classifying of grit; horizontal flow grit chambers are not easily adjustable to varying flow, they remove excessive amounts of organic matter if flow is not effectively controlled, and they have massive head loss; hydrocyclones require energy since they use pumps (US-EPA, 1994).

Pre-treatment: Bar screens or coarse and fine screens

1.4. Equalization Tank

The wastewater received at many WWTPs can vary considerably in volume and level of pollution. Therefore may WWTPs have to install equalization tanks, in which wastewater is stored for a certain period prior to treatment in order to generate a stable flow (Figure 8-50). Aside from equalizing wastewater flow (volume per time), equalization basins also provide a more stable quality of influent wastewater. Both aspects are important to maximize the efficiency of downstream processes and to control their operation. Equalization tanks are usually equipped with agitators or aerators for mixing and prevention of settling of suspended solids.

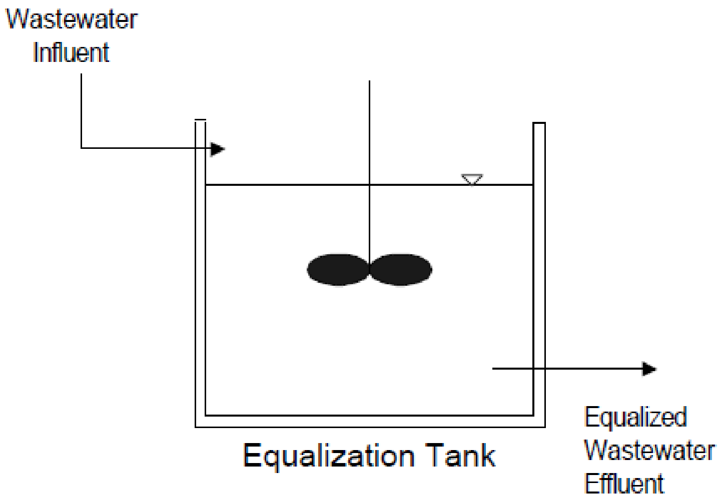


Figure 8-50: Diagram of a typical equalization tank (US-EPA, 1996).

2. Secondary Treatment

2.1. Sedimentation without Coagulant

All waters contain dissolved and suspended particles. Sedimentation is one of the processes used to separate the suspended solids portion from the water. Sedimentation (settling) tanks that receive wastewater prior to biological process units are called primary clarifiers (Figure 8-51). In these tanks, sewage is separated into settled sewage and sludge by providing quiescent, slow-motion flow conditions. The sedimentation performance is related to the effective surface area, and greater suspended solids removal performance can be achieved with plate separator sedimentation systems. In these systems, inclined parallel plates divide the tank into integral sections in which particles settle and slide to a sludge collector (hopper) at the bottom (Bryan, Chambers, & Cooper, 1995). Sludge is periodically removed from the hopper for disposal. The effectiveness of sedimentation depends heavily on the type of wastewater supplied and whether contaminants are dissolved or suspended. While for instance for municipal wastewater BOD may be largely from dissolved organics and BOD removal below 20%, the removal efficiency can be up to 60%

for some industrial wastewaters containing more suspended solids. Rectangular tanks are usually used where space is limited. However, circular basins are generally preferred in new construction because of their superior performance and lower maintenance costs (Hammer & Hammer, 2012b).

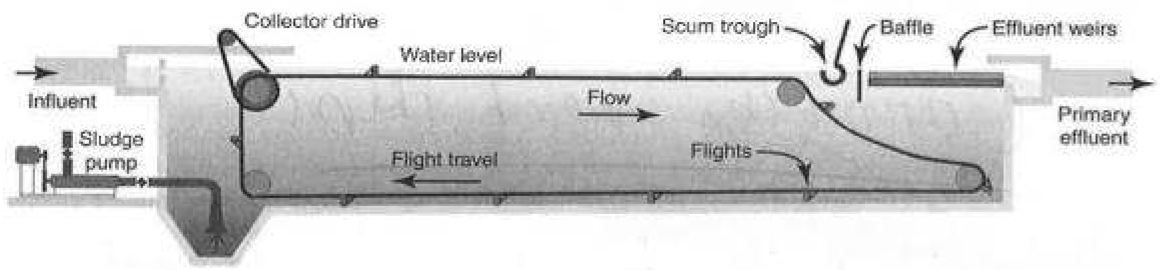


Figure 8-51: Longitudinal section of a rectangular primary clarifier. Settled solids are moved to the sludge pump at the influent end of the clarifier and floating matter to a scum through, where it is removed by pumping (Hammer & Hammer, 2012b).

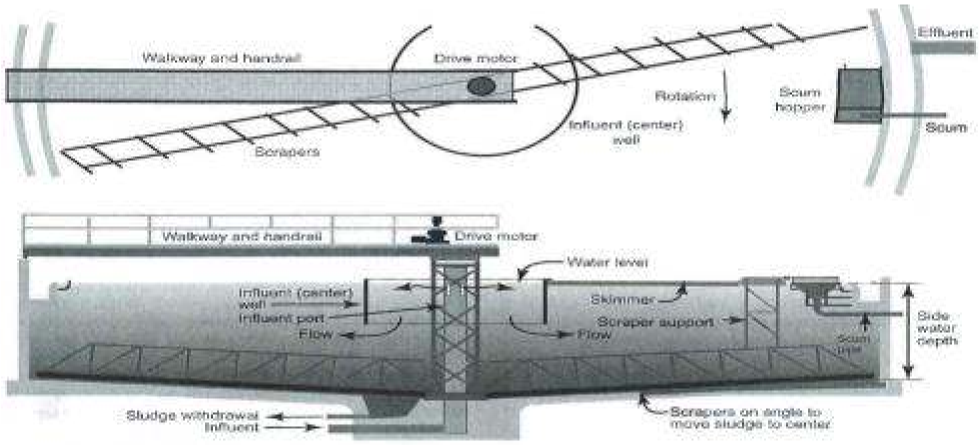


Figure 8-52: Partial plan view (above) and section through (below) circular primary clarifier (Hammer & Hammer, 2012b).

Advantages: No chemicals required

Disadvantages: Low efficiencies for dissolved contaminants; efficiencies highly dependent on influent wastewater composition

Pre-treatment: Preliminary treatment (bar screens; fine screens); raw wastewater can be applied

2.2. Sedimentation with Coagulant

Coagulation, flocculation, and sedimentation occur in successive steps: coagulation destabilizes the particle's charges by using, for example, ferric chloride ($FeCl_3$) or alum ($Al_2(SO_4)_3$). After neutralization of the charges, the small particles can stick together in so-called "microflocs." The coagulation process usually lasts 1–3 minutes with strong and rapid mixing. The second step, flocculation, occurs afterwards with gentle mixing, and the microflocs' particle size increases to that of visible suspended particles. When the particles reach an optimal size and a good strength, the sedimentation step can start. This method can be used to reduce loads for subsequent biological unit processes and temporarily avoid the expansion of secondary treatment units, and it is used in some cases to remove suspended solids before discharge them into oceans. In addition, a polymer with a high molecular weight can enhance flocculation and solid capture (Hammer & Hammer, 2012b)**.**

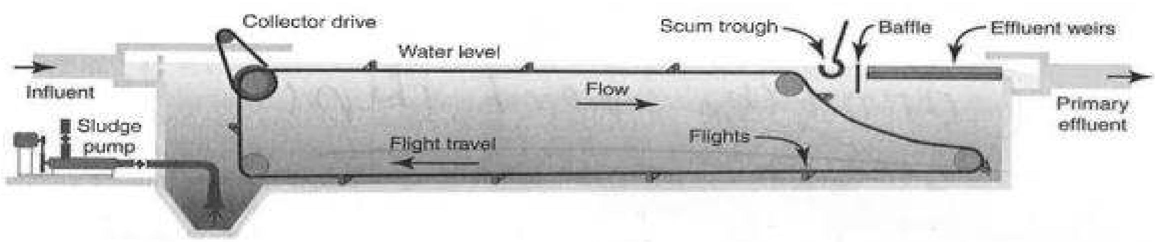


Figure 8-53: Longitudinal section of a rectangular primary clarifier. Settled solids are moved to the sludge pump at the influent end of the clarifier and floating matter to a scum through, where it is removed by pumping (Hammer & Hammer, 2012b).

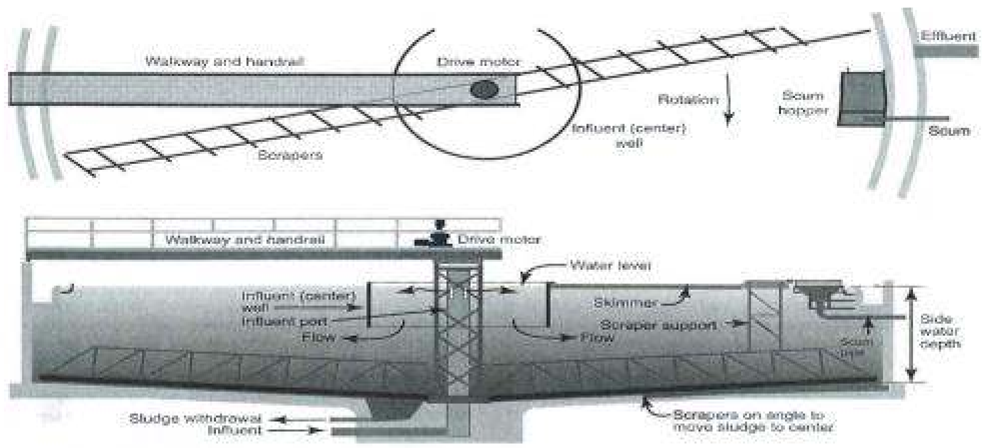


Figure 8-54: Partial plan view (above) and section through (below) circular primary clarifier (Hammer & Hammer, 2012b).

Advantages: Compared to sedimentation without coagulant higher suspended solid removal rates and therewith related parameters of removal efficiencies (BOD, COD etc.); adaptability to varying flow

Disadvantages: Higher power and chemical demand compared to sedimentation without coagulant; higher cost and sludge production compared to sedimentation without coagulant

Pre-treatment: Preliminary treatment (bar screens; fine screens); raw wastewater can be applied

2.3. Anaerobic Stabilization Ponds

Waste stabilization ponds (WSPs), often referred to as oxidation ponds or lagoons, are holding basins used for secondary wastewater (sewage effluents) treatment where decomposition of organic matter is processed naturally (i.e. biologically processed). The activity in the WSP is a complex symbiosis of bacteria and algae, which stabilizes the waste and reduces pathogens. Stabilization ponds can be classified as aerobic, aerated, anaerobic, or facultative ponds according to the type of biological activity taking place in them (Figure 8-55).

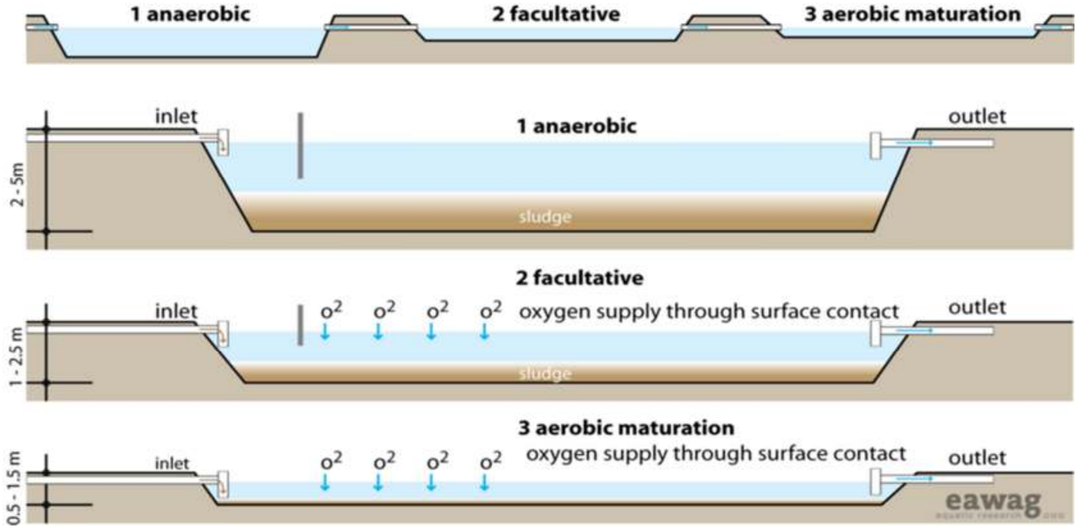


Figure 8-55: Cross section through a possible sequence of maturation ponds (upper panel), an anaerobic pond (second panel), a facultative pond (third panel) and an aerobic pond (lower panel) (Sandec & EAWAG, 2013).

2.4. Activated Sludge Processes

A variety of processes, designs, and mechanisms exist for wastewater treatment using activated sludge. The processes use dissolved oxygen to promote the growth of microorganisms that substantially remove organic material (US-EPA, 2004b). Activated sludge treatment refers to the suspension of microorganisms in the wastewater, which accelerates natural biological oxidation processes and effectively removes soluble and also some insoluble pollutants from the water (Landcom, 2006). The wastewater is supplied with air, providing oxygen for microbial degradation of wastewater organics. Anoxic zones can be added, in which nitrate (instead of oxygen) is used to oxidize organic matter. In this case, nitrogen gas (N_2) is produced. Activated sludge has primarily been used to reduce the BOD and TSS from wastewaters. There is a high number of different designs, which may in addition provide reduction of TN and other variables. Settling tanks following biological treatment (secondary sedimentation) are similar to primary clarifiers.

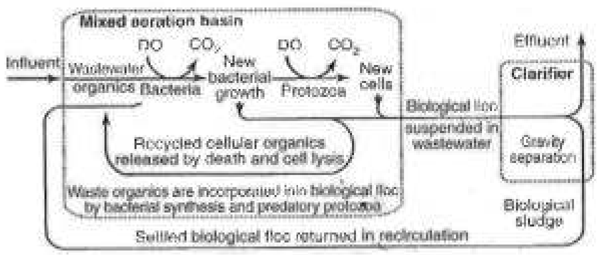


Figure 8-56: Schematic representation of the activated sludge process followed by secondary sedimentation (clarifier) (Hammer & Hammer, 2012b).

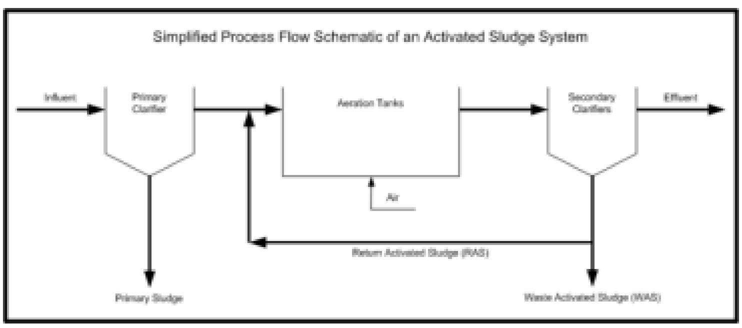


Figure 8-57: Simplified process flow schematic of an activated sludge system (Fuller, 2018).

Pre-treatment: Primary treatment

2.5. Low Loaded Activated Sludge without de-N + Sec Sedim

After entering a tank, the sewage is mixed with microorganisms and with dissolved oxygen for microbial degradation of wastewater organics. The low loaded activated sludge process shows a F/M ratio 0.2–0.5 (BOD/day)/(MLSS) and a sludge age of 5–15 days. For a process without de-nitrification is no anoxic zone added. Settling tanks following biological treatment (secondary sedimentation) are similar to primary clarifiers.

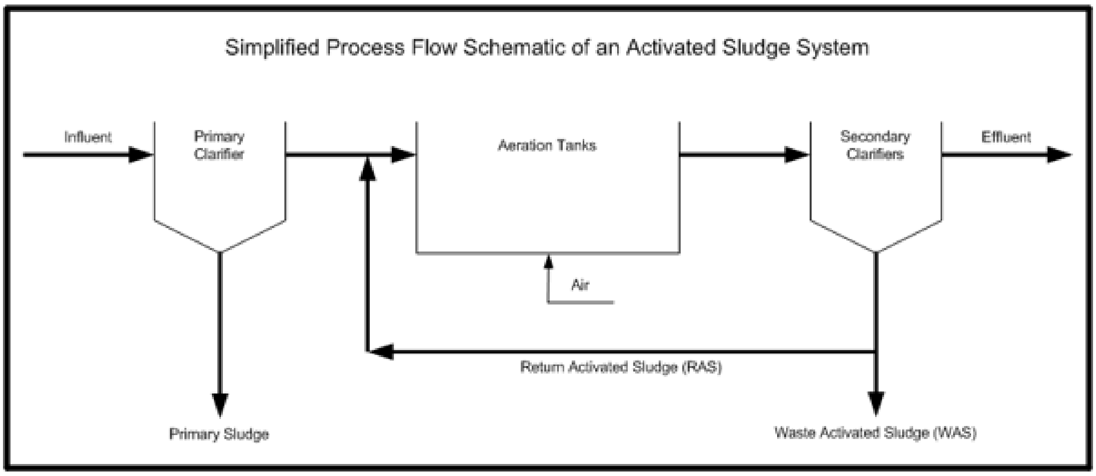


Figure 8-58: Simplified process flow schematic of an activated sludge system (Fuller, 2018).

Advantages: No chemicals needed (Van Der Graaf et al., 2005)

Disadvantages: High power requirements (Van Der Graaf et al., 2005)

Food-to-Mass (FM) ratio: Important parameter in the activated sludge process; describes the relation between the BOD and MLSS

BOD: Bacterial food

MLSS: Amount of biomass in the reactor (Meniscus)

Pre-treatment: Primary treatment

2.6. Low Loaded Activated Sludge with de-N + sec. Sedim

After entering a tank, the sewage is mixed with microorganisms and with dissolved oxygen for microbial degradation of wastewater organics. The low loaded activated sludge process shows an F/M ratio 0.2–0.5 (BOD/day)/MLSS and a sludge age of 5–15 days (Hammer & Hammer, 2012b). In the anoxic zone, nitrate is used by facultative bacteria to oxidize BOD by releasing nitrogen gas (N_2). Settling tanks following biological treatment (secondary sedimentation) are similar to primary clarifiers.

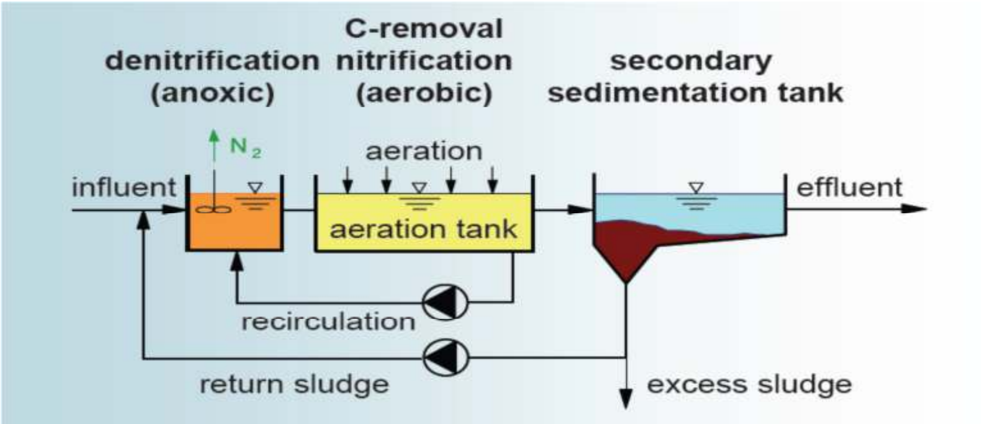


Figure 8-59: Process chart low loaded activated sludge w de-N + sec. Sedimentation (Kroiss, 2008).

Advantages: No chemicals needed (Joksimović, 2005)

Disadvantages: High power requirements (Joksimović, 2005)

Pre-treatment: Primary treatment

2.7. High Loaded Activated Sludge + Sec. Sedim

The difference between high loaded activated sludge and low loaded activated sludge is the F/M ratio. The F/M ratio for high loaded activated sludge is 0.5–1.0 ((BOD/day)/(MLSS)). The sludge age is 3–10 days (Hammer & Hammer, 2012b). Settling tanks following biological treatment (secondary sedimentation) are similar to primary clarifiers.

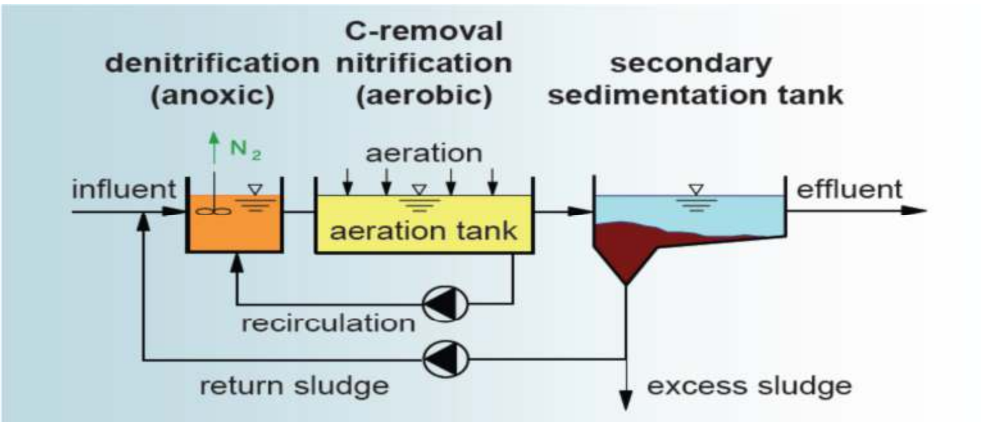


Figure 8-60: Process chart low loaded activated sludge w de-N + sec. sedimentation (Kroiss, 2008).

Advantages: Less energy and no chemicals needed (Joksimović, 2005)

Disadvantages: Higher sludge production (Joksimović, 2005)

Pre-treatment: Primary treatment

2.8. Extended Aeration

The extended aeration process is a modified activated sludge process. It includes the removal of biodegradable organic wastes under aerobic conditions. Air and mixing must be supplied mechanically or by aeration. Important for the biological growth is the pH and the concentration of essential nutrients (US-EPA, 2000c). The extended aeration process shows an F/M ratio 0.05–0.2 (BOD/day)/MLSS and a sludge age older than 20 days (Hammer & Hammer, 2012b).

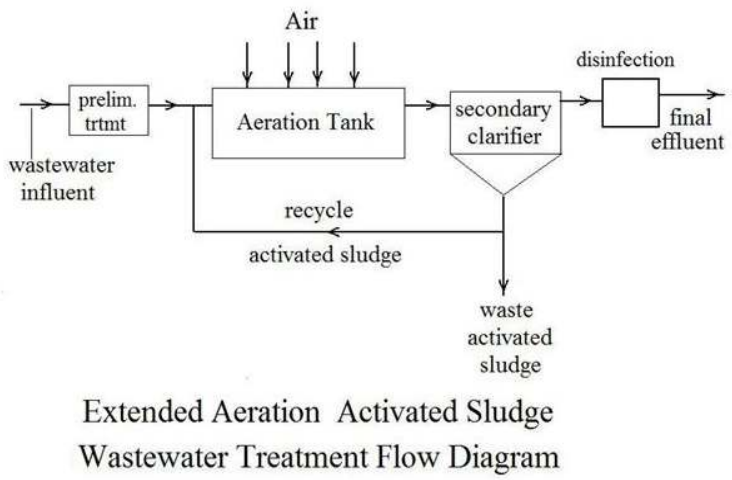


Figure 8-61: Process chart extended aeration (public domain).

Advantages: Easy to operate, does not require a primary sedimentation (US-EPA, 2000c)

Disadvantages: No de-nitrification, requires more energy, needs more space and tankage (US-EPA, 2000c)

2.9. Trickling Filter with Secondary Sedimentation

In contrast to activated sludge systems, the microorganisms used for the cleaning process are attached to a medium (attached-growth process). The microorganisms build a biological film or slime layer of 0.1–0.2 mm thickness and include aerobic, anaerobic and facultative bacteria, fungi, algae, and protozoa (US-EPA, 2000e). Microorganisms from the wastewater attach to the medium and successively increase the thickness of the biological film. As the film thickness increases, oxygen supply to layers closer to the filter decreases, and anaerobic processes dominate. With increasing film thickness, microorganisms can no longer attach more portions of the film of the medium (called sloughing) and need to be removed by a secondary sedimentation system.

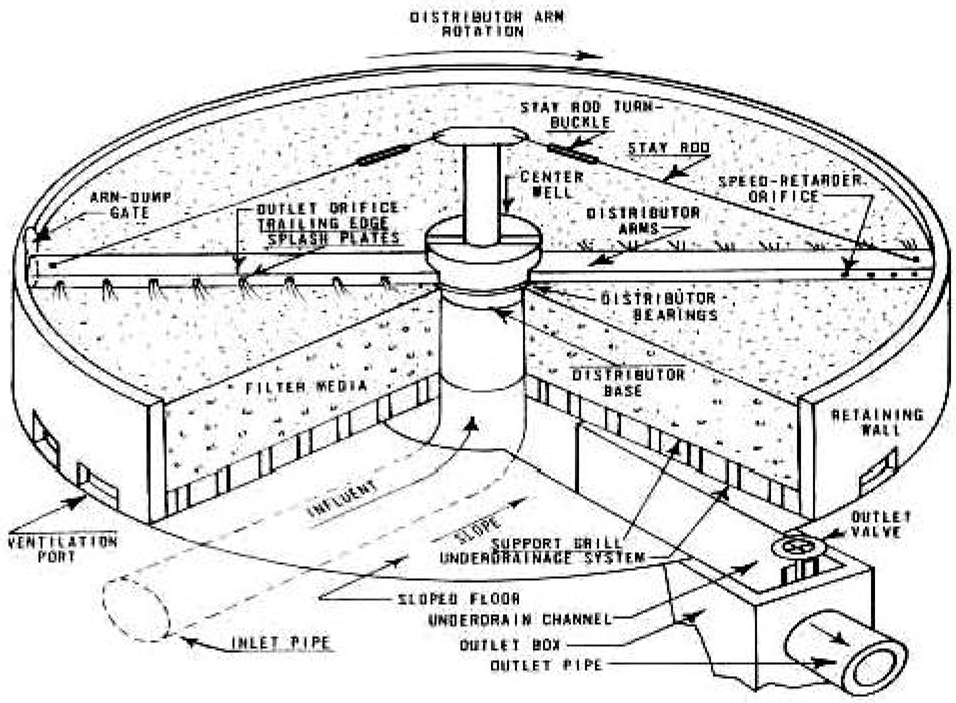


Figure 8-62: Typical trickling filter (US-EPA, 2000e).

Advantages: Simple design; durable elements; moderate power demand; moderate skills needed for operations and maintenance.

Disadvantages: Depending on type of water reuse and local regulations, additional treatment required; clogging and excess biomass accumulation, impairing oxygen supply; flexibility more restricted compared to activated sludge systems; more odor intensive than activated sludge systems; possible problems with aquatic snails

Pre-treatment: Preliminary treatment

3. Tertiary or Advanced Treatment

3.1. Rotating Biological Contactor

The RBC process is a fixed-film wastewater treatment technology used in municipal or industrial wastewater treatment. The unit consists of a round steel or plastic medium on a horizontal shaft in a concrete tank. The medium is slowly rotated in the wastewater, and approximately 40% of the medium is submerged in wastewater (Figure 8-63). Microorganisms biologically degrading organic pollutants attach on the rotating medium and form a fixed film of thin biomass layer. By rotating into the air, oxygen can be absorbed by the microorganisms. Excess biomass continuously falls off the medium and is removed in a subsequent secondary clarifier (Technical University Harburg, 2018).

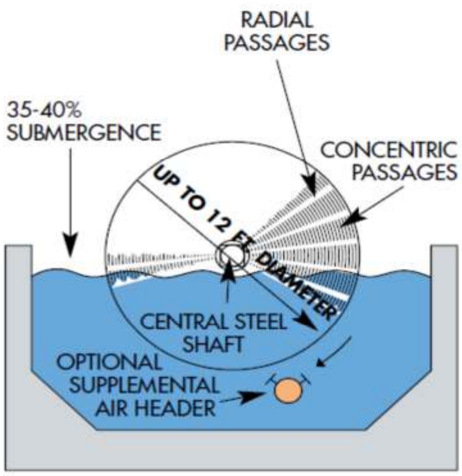


Figure 8-63: Diagram of a rotating biological contactor process (Technical University Harburg, 2018).

Advantages: Minimal maintenance; low energy demand

Pre-treatment: Primary treatment

3.2. Stabilization Ponds: Aerobic, Aerated and Facultative

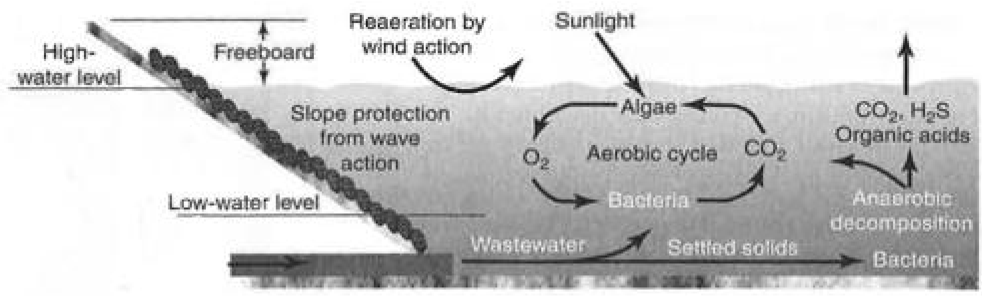


Figure 8-64: Cross section of a facultative stabilization pond showing biological reactions of bacteria and algae (Hammer & Hammer, 2012b).

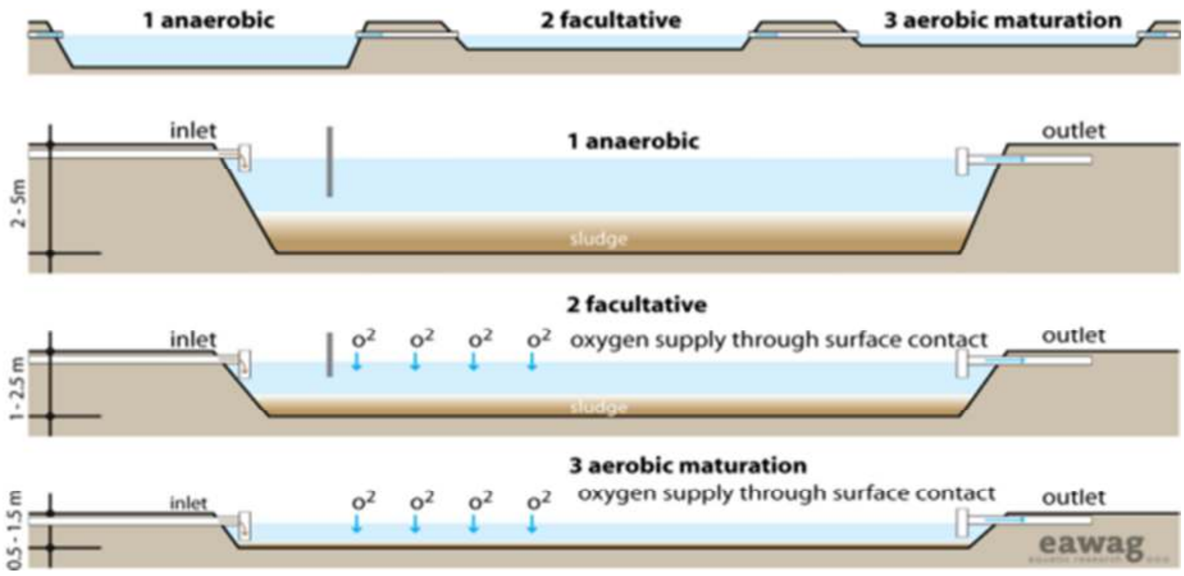


Figure 8-65: Cross section through a possible sequence of maturation ponds (upper panel), an anaerobic pond (second panel), a facultative pond (third panel), and an aerobic pond (lower panel) (Sandec & EAWAG, 2013).

3.3. Membrane Bioreactor

A membrane bioreactor is a combination of biological activated sludge processes with low-pressure membrane technology (microfiltration or ultrafiltration) where the membranes provide a barrier to suspended solids. The membranes provide clarification and filtration functions. The reactor is operated similar to activated sludge processes (S1–3), but without the need of secondary clarification and replacing some tertiary unit processes such as sand filtration. Membrane bioreactors can have to basic configurations (Figure 8-66) with either submerged membranes (permeate) or external circulation (Ravazini et al., 2006).

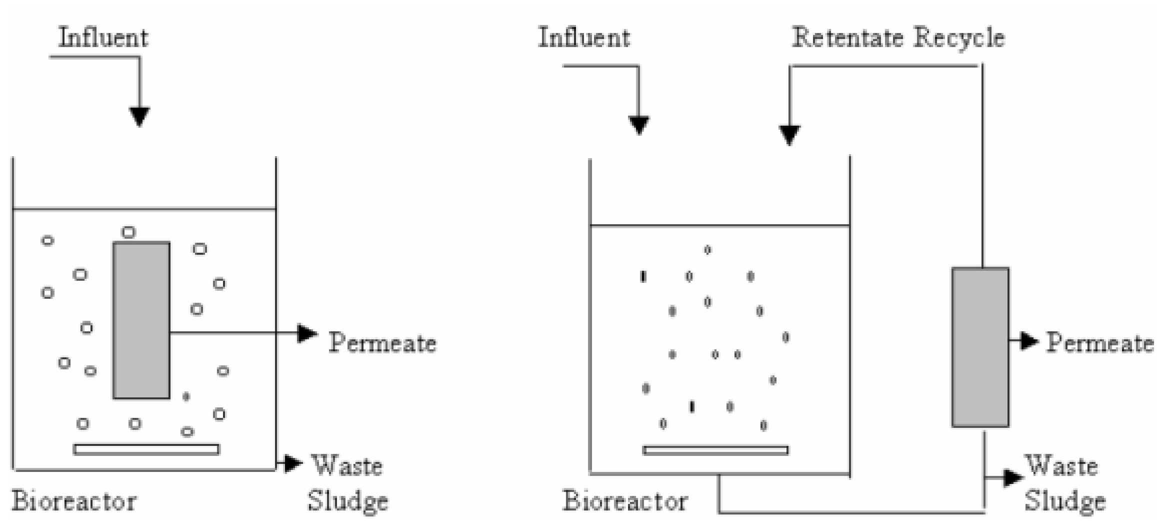


Figure 8-66: Two main configuration of MBR systems: submerged membrane (left panel) and external configuration (side stream, right panel) (Ravazini et al., 2006).

Advantages: Very high-quality effluent, increased process stability (due to increased MLSS and decreased F/M ratio); small size (membranes replace clarifier and conventional filters); flexible extension of existing WWTPs is possible

Disadvantages: Operation cost (membrane life and replacement cost); energy demand of membrane pumps; increased sludge return (Hammer & Hammer, 2012b)

3.4. Constructed: Subsurface and Free-Water-Surface Flow

Most wetlands for wastewater treatment are free water systems in which the water surface is exposed to the atmosphere and include bogs, swamps, and marshes. Subsurface flow wetlands (Figure 8-67, left panel) are specifically designed for treatment or polishing of different types of wastewater. Subsurface wetlands can be constructed as beds or channels with appropriate media, commonly gravel in the U.S. and Europe, and they are planted with vegetation typical for marshes (grasses and emergent aquatic plants). In the subsurface flow system, odors, mosquito infestations, and risk of public contact can be efficiently controlled, while in free-water surface systems (Figure 8-67, right panel), mosquitoes and public access are concerns (US-EPA, 2000f).

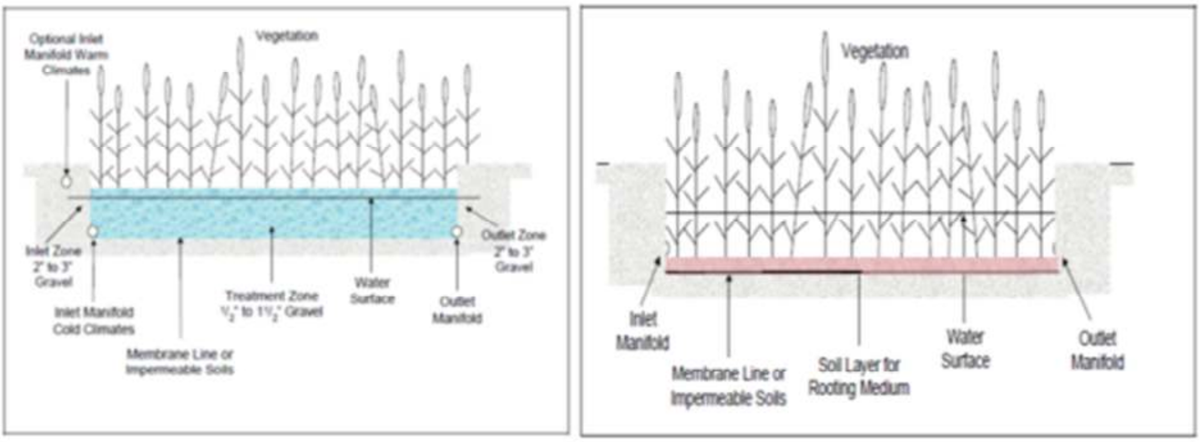


Figure 8-67: Subsurface constructed wetland and free-water-flow constructed wetland (US-EPA, 2000f).

Advantages: Minimum equipment, power and operator needs; very low sludge production; subsurface flow wetlands: effective and reliable for BOD, COD, TSS, metal and some persistent organics removal (US-EPA, 2000f)

Disadvantages: Large land requirement; accumulation of phosphorus, metals and some persistent organic compounds in the sediments; lower removal rates during winter in cold climates

3.5. Constructed Wetlands for Polishing

Constructed wetland polishing, also referred to as maturation or polishing ponds, are used as third-stage natural polishing of effluent from activated sludge or trickling-filter secondary treatment. The wetlands can be constructed as in the unit process “constructed wetland: Subsurface and free-water-surface flow”. A stabilization of the treated water derives from retention in the pool and where suspended solids, BOD, fecal microorganisms, and ammonia are reduced by retention and surface aeration (Hammer & Hammer, 2012b). Detention times range from 10–15 days. The treated effluent can be reused for nature conservation or agriculture (Ravazini et al., 2006).

Figure 8-68: Polishing constructed wetland Everstekoog, Texel, The Netherlands (IEES, 2013).

Advantages: Total nitrate removal achievable when low flows applied (Ravazini et al., 2006)

Disadvantages: Possibility of precipitation events affecting pollutant-removal efficiency

Pre-treatment: Secondary treatment from activated sludge or trickling-filters (Hammer & Hammer, 2012b)

3.6. Enhanced Biological Phosphorus Removal

For biological nitrogen removal, nitrification–denitrification processes are controlled by exposing the wastewater first to anoxic (total oxygen depletion) conditions followed by an aerobic zone. For phosphorous removal, the anoxic zone can be preceded by an anaerobic zone, which promotes the biological release of organic phosphorous and stimulates the phosphorus uptake of bacteria in the aerobic zone (Hammer & Hammer, 2012b). The anaerobic and anoxic zones are mixed by propellers, while the aerated zone (aerobic) is supplied with air by blowers.

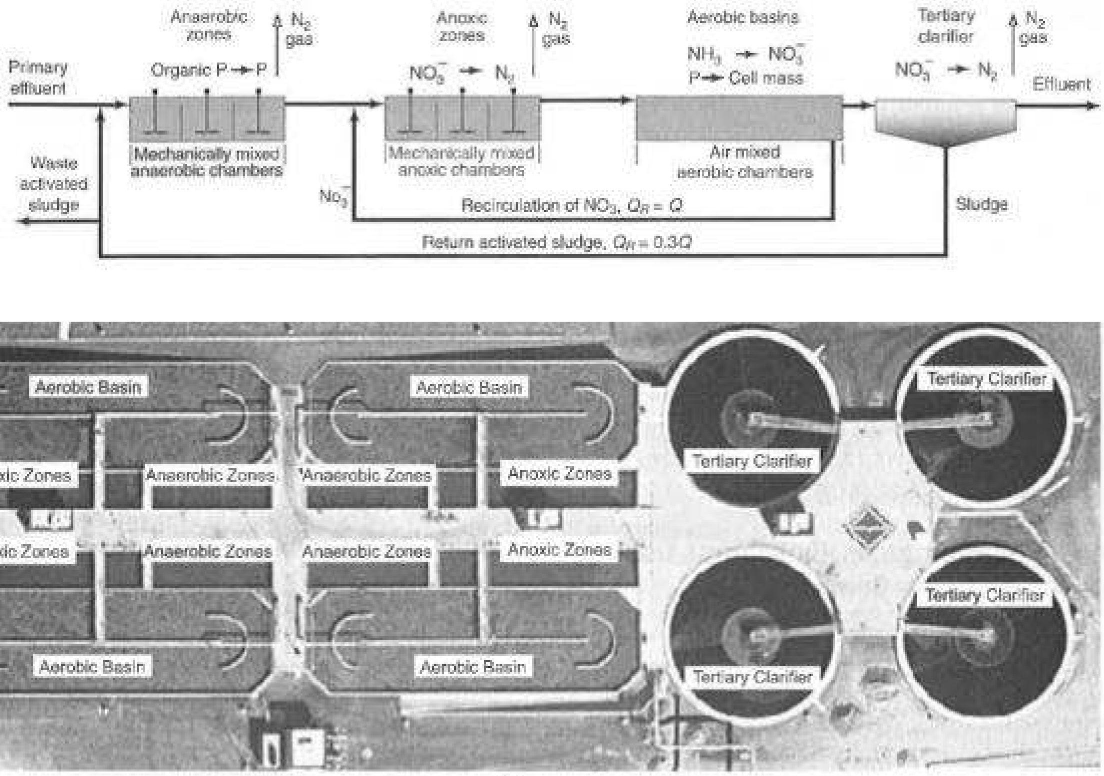


Figure 8-69: A three-stage biological phosphorus and nitrogen removal process. Schematic diagram (upper panel) and basins under operation (lower panel) (Hammer & Hammer, 2012b).

3.7. P-Precipitation

Chemical precipitation refers to the induced settling of dissolved or suspended contaminants during wastewater treatment using a coagulant. The settled substances can then be removed from the remaining wastewater (e.g. by filtration or centrifugation). For phosphorus precipitation, most commonly ferric chloride ($FeCl_3$), alum ($Al_2(SO_4)_3$) or lime (CaO) are used. When ferric chloride or alum is used, the precipitate is a metal phosphate, and the reaction is pH-dependent. The usage of lime requires the addition of sufficient quantities until the wastewater has a pH of at least 10, under which conditions Ca2+ will react with phosphorus to create an insoluble precipitate. The amount of coagulant required cannot be calculated based on P-concentration alone, but on a case-by-case analysis in the laboratory (jar tests), due to competing reactions with other compounds (EPA, 2000c).

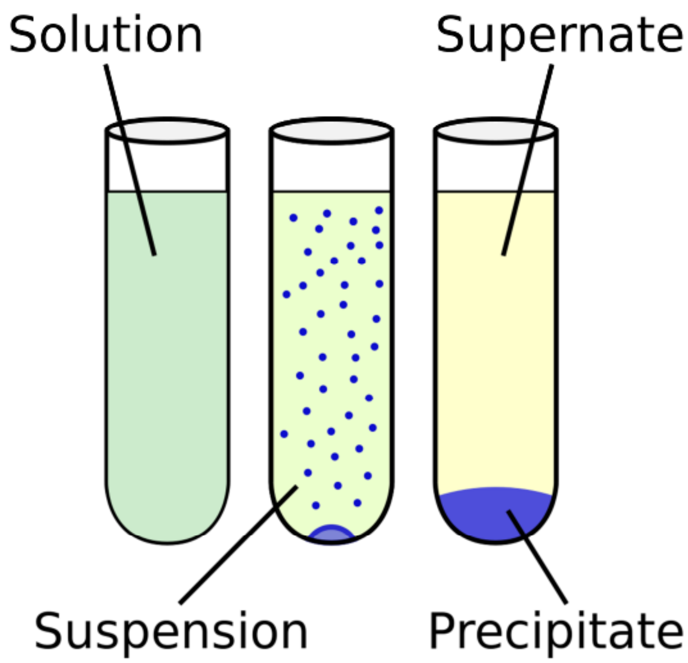


Figure 8-70: P-Precipitation (public domain).

Advantages: Readily available chemicals and equipment; inexpensive lime; low maintenance

Disadvantages: Necessary to determine dosage case by case; corrosive chemicals; possibility of waste sludge increasing by up to 50%, especially with lime (US-EPA, 2000b); large amount of chemicals

Pre-treatment: None necessary; can be applied at different stages during the wastewater treatment process

3.8. Nitrification-Denitrification

Nitrification of wastewater may be necessary if the effluent pollutes receiving water bodies (e.g. for environmental water reuse). The nitrification process converts nitrogen to nitrate form and denitrification removes it from the wastewater by converting it into gaseous nitrogen. For nitrification, usually the most reliable process is suspended-growth aeration after activated sludge treatment, which provides a good growth environment with low BOD and high ammonia values for nitrifying bacteria. After nitrification, a final settling stage removes part of the population of nitrifiers, which can be returned to the aeration tank. While nitrification reduces ammonia and its toxic effects in the effluent, it thus increases nitrate content. By a subsequent denitrification stage, nitrate is converted into gaseous nitrate and removed from the effluent. This conversion is commonly achieved by a biological denitrification tank after nitrification, in which a carbon source (usually methanol) is needed for biological synthesis. Furthermore, after denitrification, a final settling and return of sludge is required.

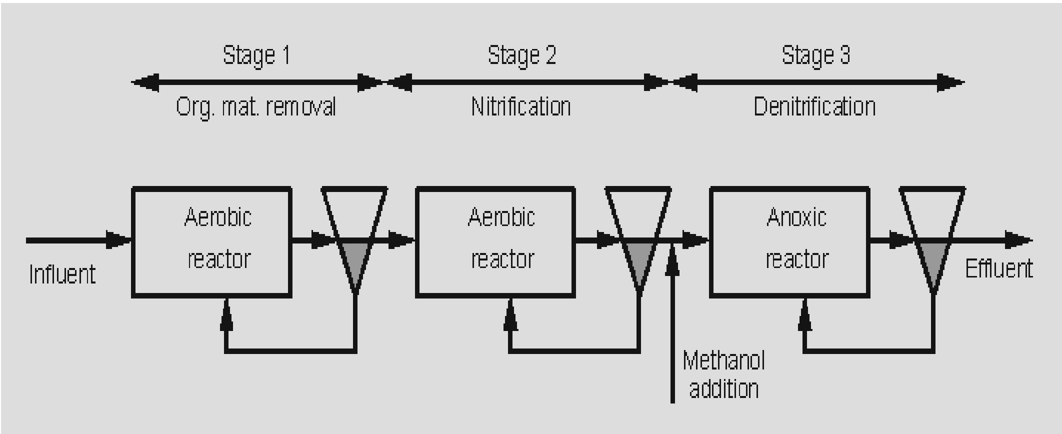


Figure 8-71: Denitrification process (public domain).

3.9. Filtration over Fine Porous Media and Dual Media Filtration

Secondary effluent is applied to the fine porous media filter (i.e., granular media filter), which commonly consists of a coal-sand or mixed (anthracite coal, garnet, and sand) dual-media (Hammer & Hammer, 2012b). The residues removed from the water are cleaned from the filter media by backwashing, which requires a rotating agitator or air scrubbing for improved efficiency. The backwash water is stored in an equalizing tank and returned to the influent at a constant rate. Commonly, two to four filter cells are necessary to provide flexibility for varying flow rates (Hammer & Hammer, 2012b).

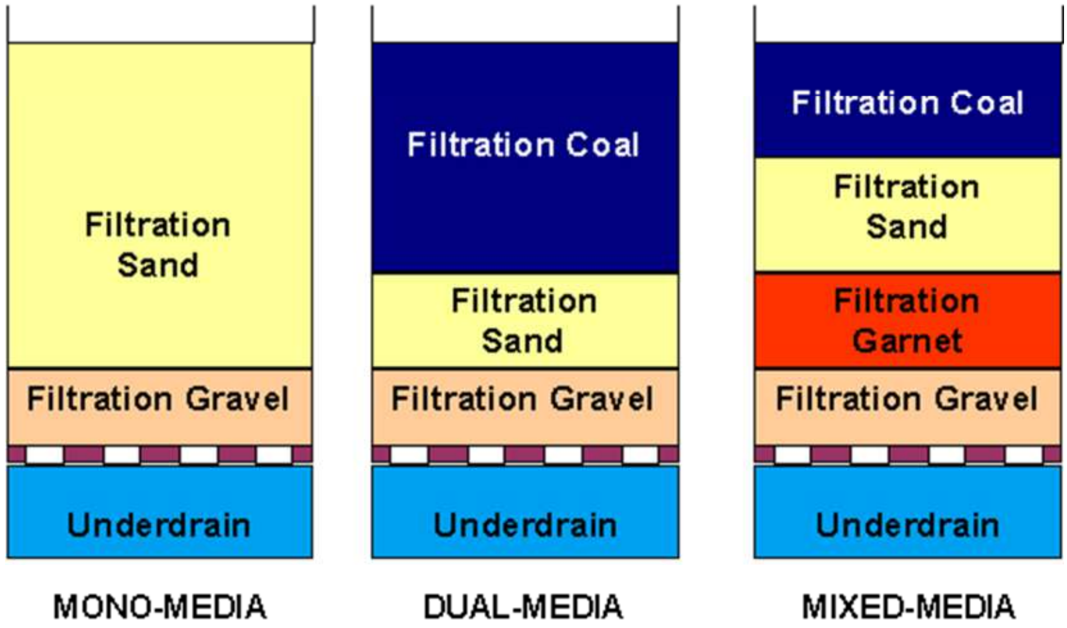


Figure 8-72: Dual media filter (Council, 2019).

3.10. Microfiltration, Ultrafiltration, and Nanofiltration

Microfiltration, ultrafiltration, and nanofiltration are membrane filtration processes with removal capabilities differing in particle size (Figure 8-73). Micro- and ultrafiltration are based on physical straining to remove colloidal and particulate contaminants. Nanofiltration and reverse osmosis use semipermeable membranes to separate dissolved salts, organic molecules, and metal ions (Hammer & Hammer, 2012b). Nanofiltration membranes are able to remove turbidity, microorganisms, hardness, and, to some extent, dissolved salts. The nanofiltration membrane is pressure-driven, and its removal properties lie between ultrafiltration and reverse osmosis (US-EPA, 2004a): "Similar to other membrane processes, a major problem in NF membrane applications is fouling. Several studies have investigated the mechanisms of fouling in NF membranes and suggested methods to minimize and control the fouling of NF membranes" (Hilal, Darwish, Mohammad, & Arabi, 2004). The membrane type (pore size) is chosen based on the particle sizes of contaminants.

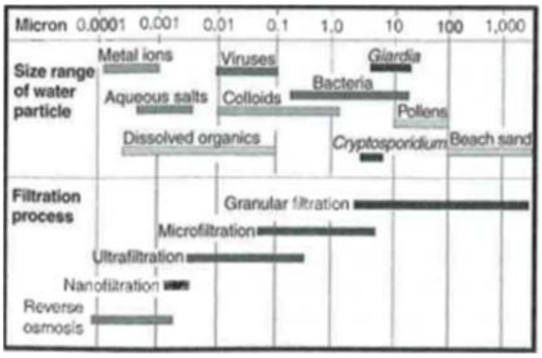


Figure 8-73: Typical sizes of contaminants commonly found in wastewater and removal efficiencies of membranes and reverse osmosis (Hammer & Hammer, 2012b).

Table 8-4 Design criteria and applications for filtration processes and reverse osmosis (adapted from Hammer and Hammer 2012b)

Process	**Operating pressure**	**Recovery (%)**	**Flux (m day^{-1})**	**Applications**
Microfiltration	**0.3–2.8 bar**	**95–98**	**12**	**Suspended solids and bacteria removal**
Ultrafiltration	**1–4 bar**	**80–95**	**0.5–10**	**Virus removal and pre-treatment for reverse osmosis**
Nanofiltration	**5–14 bar**	**70–90**	**0.3–1**	**Special applications**
Reverse osmosis	**10–41 bar**	**70–85**	**0.4–0.8**	**Demineralization, TDS removal**

5.10.1. Microfiltration

Microfiltration by membranes and hollow fibers have become an interesting water disinfection alternative, and costs have decreased in recent years (Davide Bixio et al., 2006).

Advantages: No hazardous by-products; variable cost comparable to UV disinfection of effluent filtered through conventional sand filtration (Davide Bixio et al., 2006); potential for complete removal of bacteria

Disadvantages: Fixed cost higher than UV disinfection

5.10.2. Ultrafiltration

Disadvantages: Higher energy demand than microfiltration

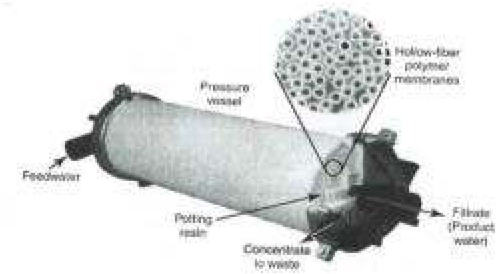


Figure 8-74: Example of a ultrafiltration hollow-fiber module (Hammer & Hammer, 2012b).

5.10.3. Nanofiltration

Advantages: Lower operation pressure than reverse osmosis; high water flux; high retention of multivalent anion salts and an organic molecular above 300 (Hilal et al., 2004)

Disadvantages: Fouling; low recovery (82.5%, Joksimovic 2005)

3.11. Reverse Osmosis

Reverse osmosis is the forced passage of water through a semipermeable membrane against the osmotic pressure gradient. In order to force the passage, an external pressure should be applied to the wastewater. This separates dissolved solids from the water forced through the membrane. Typical pressure ranges used in reverse osmosis applications are 350–800 psi.

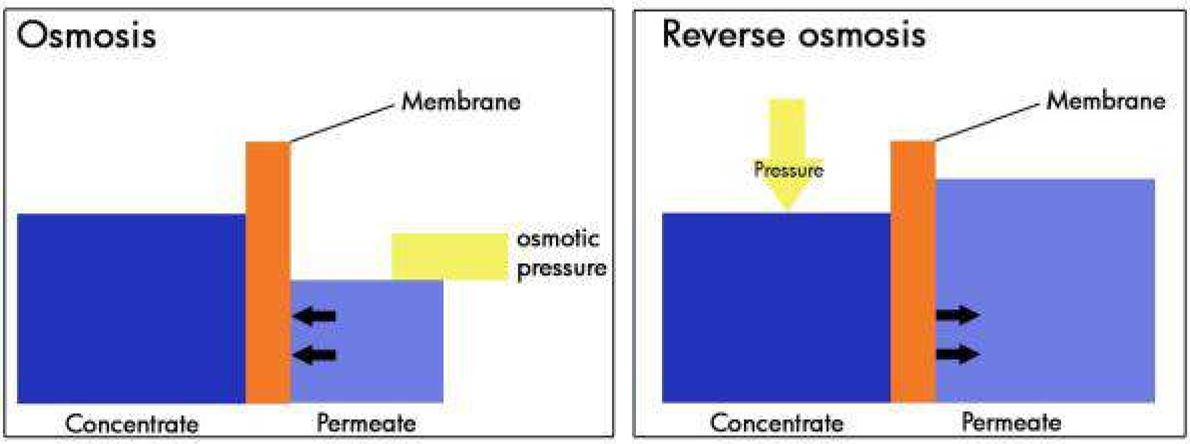


Figure 8-75: Principle of reverse osmosis (Hydrotec, 2013).

Disadvantages: High production concentrates (reject water), a critical economic and environmental problem (Hammer & Hammer, 2012b)

Influent: Especially the removal of solids is an essential pre-treatment requirement for reverse osmosis. A sufficient level of pre-treatment can be achieved either through a series of precipitation, sedimentation, recarbonation, granular-media filtration, and carbon filtration or through microfiltration/ultrafiltration with chemical additions (Hammer & Hammer, 2012b).

3.12. Granular-Activated Carbon and Powdered-Activated Carbon

Granular-activated carbon is an effective treatment process removing biodegradable and refractory organic compounds. Carbon adsorption is usually considered the most effective way to reduce the level of taste and odor in water treatment (Hammer & Hammer, 2012b). Granular-activated carbon works by adsorption of organic compounds onto the carbon. Further substances, which can be removed from reclaimed water by granular-activated carbon, include metal ions such as cadmium, hexavalent chromium, silver, and selenium. From acidic water, some uncharged chemicals including arsenic and antimony can also be removed (US-EPA, 2004a). Activated carbon is produced from carbonaceous materials (charcoal, coconut shells, etc.) through controlled combustion (Hammer & Hammer, 2012b). Powdered activated carbon, as granular activated carbon is also produced from carbonaceous materials (charcoal, nut shells, etc.) through controlled combustion. In its fine power form, powdered-activated carbon it can be applied at any location in the treatment process prior to filtration. Powdered-activated carbon can adsorb organic compounds related to taste and odor of water, but is less effective at absorbing synthetic organic chemicals than is granular-activated carbon (Hammer & Hammer, 2012b).

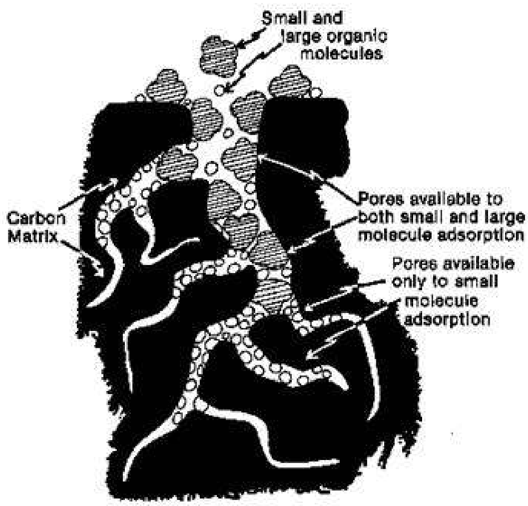


Figure 8-76: Activated carbon matrix (can be used in different forms), source: (Wateen Solutions, 2013).

Advantages: Reliability; proven adsorption efficiency for dissolved organics, especially from industrial sources (US-EPA, 2000d); low space requirements; ease of integration into existing systems

Disadvantages: is The highly corrosive quality of wet granular-activated carbon; disposal if granular-activated carbon is not regenerated; regeneration process most efficient if run 24 hours, thus requiring around-the-clock surveillance (US-EPA, 2000d); afterburners and scrubbers usually required for air emissions from the regeneration furnace

Pre-treatment: Secondary treated wastewater with low suspended solid contents.

3.13. Ion Exchange

In the ion exchange process, anions or cations from the wastewater solution are exchanged with different but equivalently charged ions from a resin bed. Thus, the salts in the solution must be ionized for the process to occur. Exchange beds are usually resins of 0.3–1.2 mm in diameter. Ion exchange is used to remove specific ions such as nitrate, fluoride, arsenic, calcium, magnesium, and other substances. Regeneration of the brine is usually conducted by backwashing with product water followed by flushing with a brine for regeneration to replace the exchanged ions from the resin (Hammer & Hammer, 2012b).

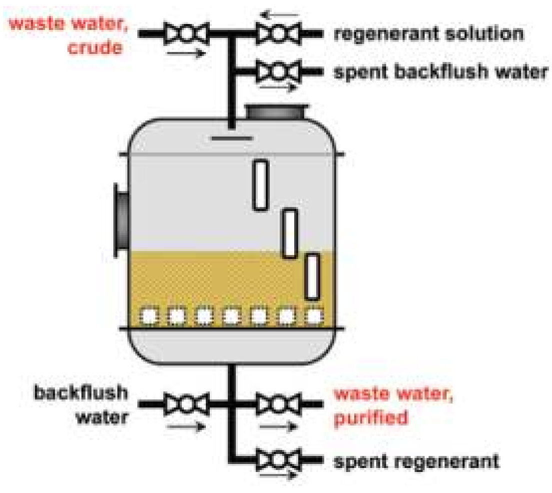


Figure 8-77: Typical ion exchange column used in wastewater treatment (public domain).

Disadvantages: Brine wastewater disposal

3.14. Advanced Oxidation – UV/O_3 and UV/H_2O_2

Photolysis by UV radiation is widely used for disinfection. Ozone (O_3) is used for water disinfection, taste and odor control, and removal of colors in water treatment (Matilainen & Sillanpää, 2010). To overcome the disadvantages of single disinfectants, there have been relatively recent research efforts to combine strong oxidants for better disinfection properties and reduction of emerging pollutants, such as pharmaceutical compounds and their derivates, anti-corrosion agents, hormone active substances, and so on. Two examples considered here are the combination of UV with ozone for improved microorganism removal and UV with peroxone for effective disinfection and dissolved organic matter removal. Furthermore, advanced oxidation may be used to treat wastewater, drinking water, contaminated soils, or sludge for several types of contaminants, including organic pollutants, toxicity, biodegradability improvement, odor and color removal, and destruction of resin in radioactive contaminated sludge (Davide Bixio et al., 2006). The main characteristic, which makes advanced oxidation processes very efficient, is the formation of free hydroxyl radicals ($OH^{\cdot}$), one of the most powerful oxidizing species known.

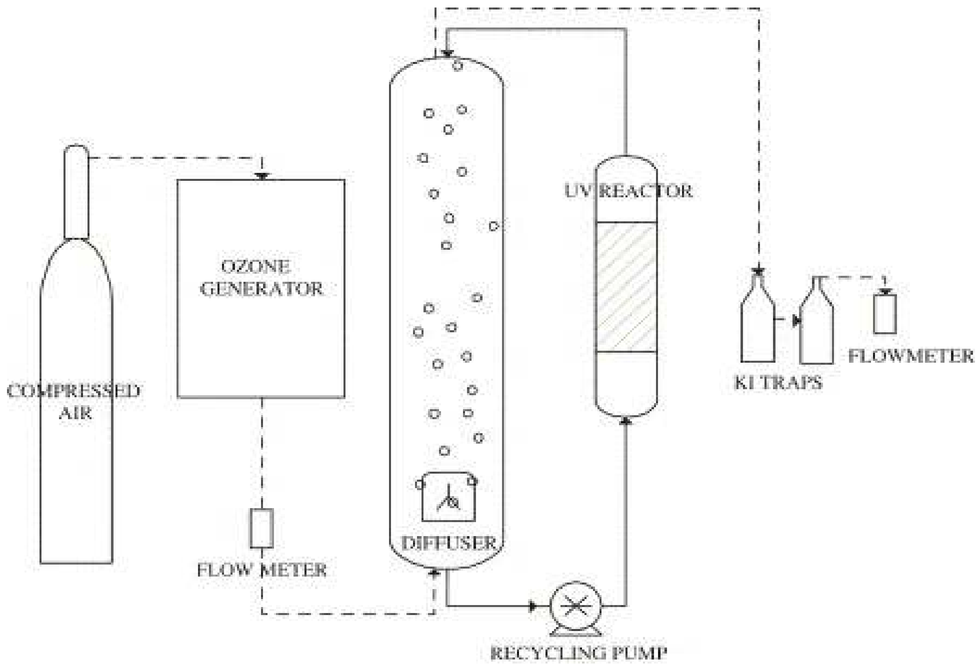


Figure 8-78: Oxidation batch (removal of disinfection by-product precursors with ozone-UV advanced oxidation process) (Chin & Bérubé, 2005).

Advantages: High-quality purified water; (partial) micropollutant removal and degradation

Disadvantages: Formation of by-products possible; expensive

3.15. Soil-Aquifer Treatment

Reclaimed water can be used to preserve groundwater levels, protect coastal aquifers against saltwater intrusion, and store water for future use by groundwater recharge. Infiltration into the aquifer occurs through the spreading of basins where water percolates vertically through the soil or riverbank infiltration. The passage through soil further contributes to purification of the effluent. Soil permeability can be negatively affected by clogging with operation time (Wintgens et al., 2006).

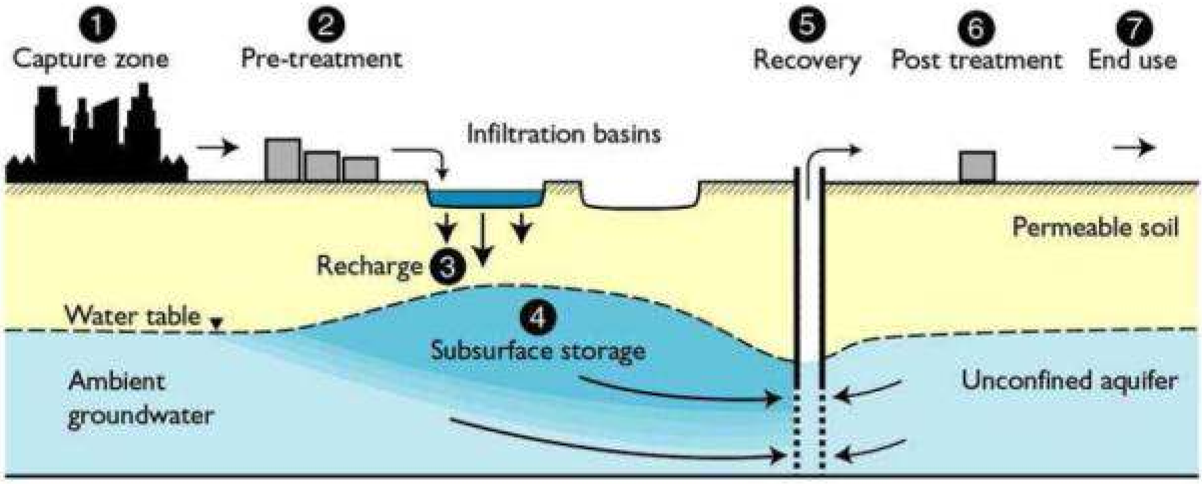


Figure 8-79: Soil-aquifer treatment system for pre-treated wastewater, infiltrating through recharge basins into permeable soil (unsaturated zone) and recharging the groundwater aquifer (Miotli, Barry, Dillon, & Breton, 2010).

3.16. Maturation Pond

Maturation ponds are valuable and simple options to polish secondary effluent. They are used primarily for high-level pathogen removal and, to a minor extent, for additional removal of nutrients (Davide Bixio et al., 2006). If the systems are well designed, effluent quality can comply with WHO guidelines for safe use of wastewater, excreta, and greywater. Maturation ponds receive inflow year around, discharge by overflow, and are usually preceded by a series of anaerobic and facultative ponds (mainly for BOD removal). The hydraulic retention time and design criteria (size, number of ponds and type of flow) define the effluent water quality.

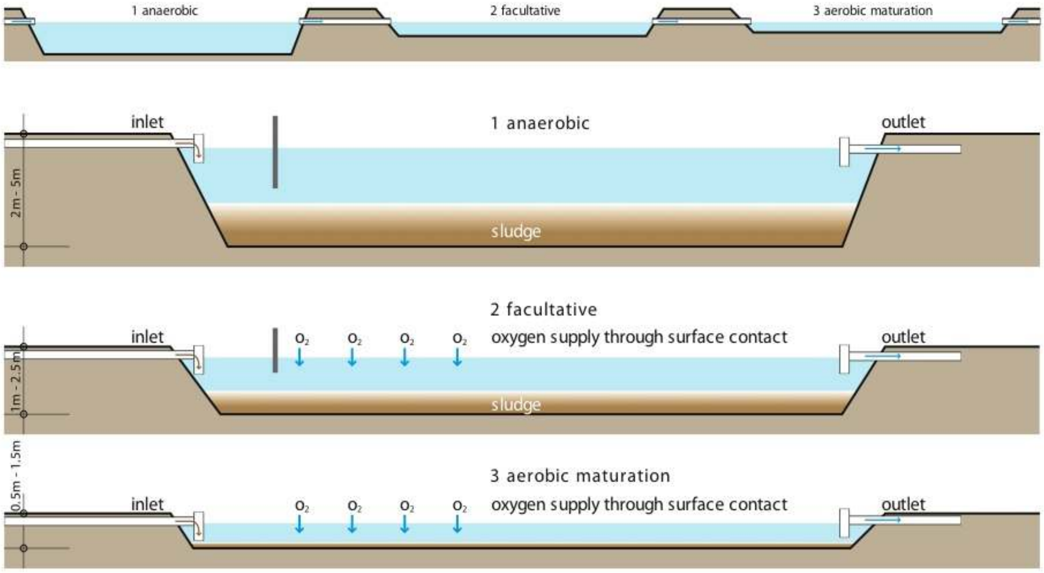


Figure 8-80: Maturation pond (Conradin et al., 2010).

3.17. Flocculation

Flocculation is a chemical process by which suspended solids aggregate to larger clumps ('flocs') (US-EPA, 2004b). These flocs are then easier to remove by subsequent sedimentation and filtration processes.

Ballasted flocculation, known as high-rate clarification, is a physical-chemical treatment that improves settling properties of suspended solids by continuously recycled media and additives. The so-formed microfloc particles should have a gravity greater than 2. Clarification occurs about 10 times faster than with conventional clarification due to decreased settling time. Microsand, a microcarrier, or a chemically enhanced sludge can be used as ballast material. In addition, a coagulant (e.g., ferric sulphate) and an anionic polymer have to be added. The unit has a compact size and is attractive for retrofit and fast applications (US-EPA, 2002).

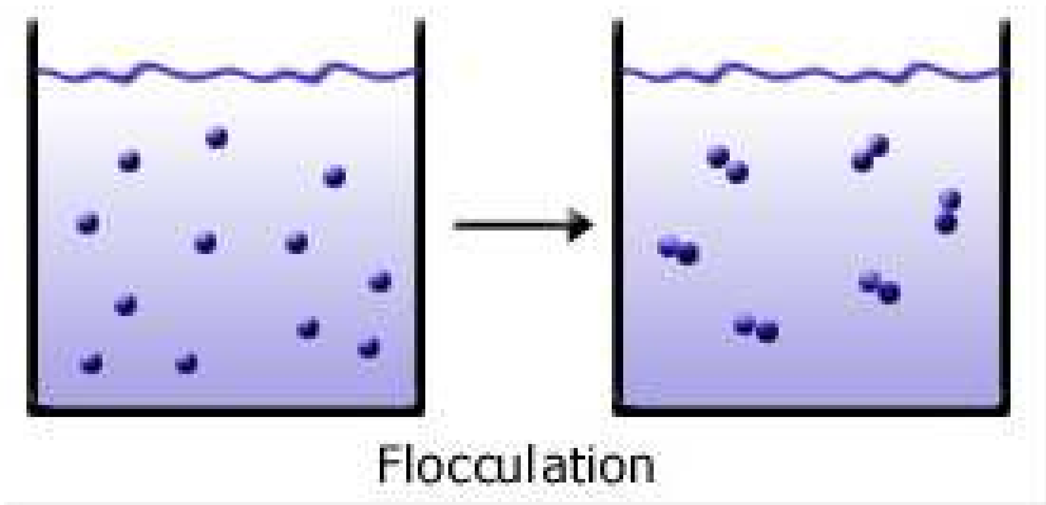


Figure 8-81: Flocculation (College, 2018).

Advantages: Reduced surface area for clarifiers; adjustable to wider range of flows without reducing removal efficiencies

Disadvantages: Requires operator judgement and more complex instrumentation than conventional systems; pumps may be affected by ballast material; lost ballast material must be occasionally replaced

3.18. Electrodialysis

Electrodialysis is a membrane process during which ions are transported through a semipermeable membrane, under the influence of an electric potential (Lenntech, 2018). This process is often used for desalination or to process industrial water, and the technology is applied worldwide.

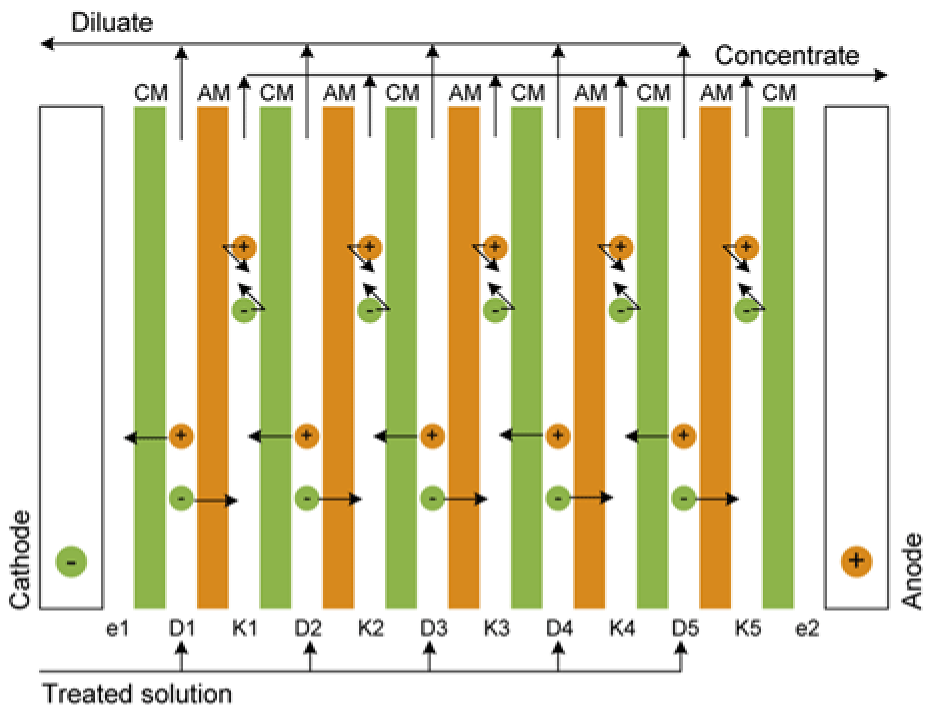


Figure 8-82: Electrodialysis principle (Novasep, 2018).

4. Disinfection

4.1. Ozonation

Ozone is a very strong oxidant and virucide used for water disinfection, taste and odor control, and removal of colors in water treatment (Matilainen & Sillanpää, 2010). Ozone (O_3) is produced by using an energy source to split oxygen (O_2) molecules into oxygen radicals ($O^{\cdot}$). These radicals collide with oxygen molecules and form the unstable ozone molecule. In most WWTPs and wastewater recycling and reuse facilities, ozone is produced by a high-voltage discharge across a dielectric gap containing oxygen gas (US-EPA, 1999b). Since ozone is not stable, it has to be produced onsite.

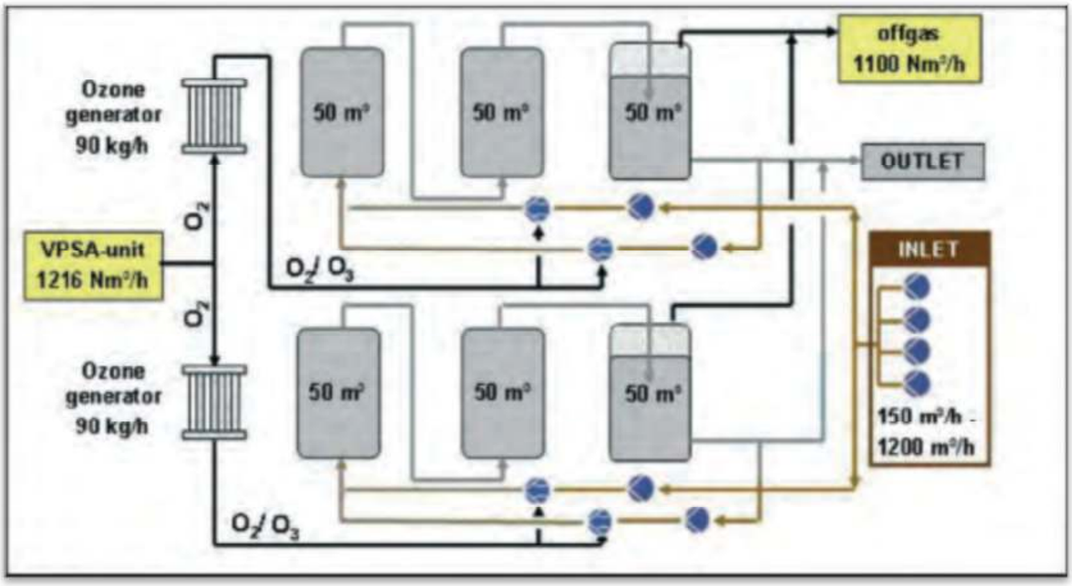


Figure 8-83: Ozonation (D. Bixio et al., 2006).

Advantages: More effective than chlorine against viruses and bacteria (US-EPA, 1999b); short contact time and generally more rapid than chlorination; no potentially harmful by-products like trihalomethanes (THMs); excellent removal of taste and odors

Disadvantages: Similar to chlorine, may not kill cysts and some other large organisms, which should be eliminated by filtration or other procedures prior to treatment; must be generated before use; equipment and operating costs quite high in some cases; for large distribution systems, potential disadvantage of lack of active residuals, as compared to chloride; off-gas from contactor must be destroyed to avoid risk for workers

Pre-treatment: Ozone disinfection is generally used at medium to large sized plants after at least secondary treatment (US-EPA, 1999b).

4.2. Chlorination

Chlorine is the most widely used chemical for disinfection. It is a strong oxidizer, highly corrosive, and its vapor irritates the respiratory tract. Water treatment plants usually use liquid chlorine, which together with water reacts to hypochlorous acid, and in a second step to the hypochlorite ion. At a pH above 8, predominantly the hypochloride ion is present, while a pH below 7 favors hypochlorous acid. The latter more effectively disinfects water by interacting with microbial cell structures. The required chlorine dosage depends on pH, interfering substances, temperature, and contact time, and it is between 8 and 15 mg l^{-1} in well-designed units (Hammer & Hammer, 2012b). While chlorine has a long-standing history as an effective disinfectant against a broad range of pathogens, it has drawbacks including health hazards that need to be effectively monitored (chloric gas) and the possibility of the formation of hazardous by-products such as THMs (EPA, 2012). In WWTPs, chlorine can be added at the raw water intake or prior to sedimentation for pre-chlorination (control of biological growth, disinfection, iron and manganese oxidation, odor control), ahead of filters for intermediate chlorination (control of biological growth, algae control, odor control), at the filter clearwell for post chlorination and before discharge into a distribution system (rechlorination) (US-EPA, 1999a). Chlorine is usually produced off-site, transported, and stored in pressurized steel cylinders.

Chlorine Gas. The most commonly applied form

Chlorine Dioxide. Application of ClO_2, which is produced at the WWTP by mixing sodium chlorite ($NaClO_2$) and chlorine; major disadvantages of that sodium chlorite being expensive and there being the potential of toxic product formation (chlorate and chlorite residuals)

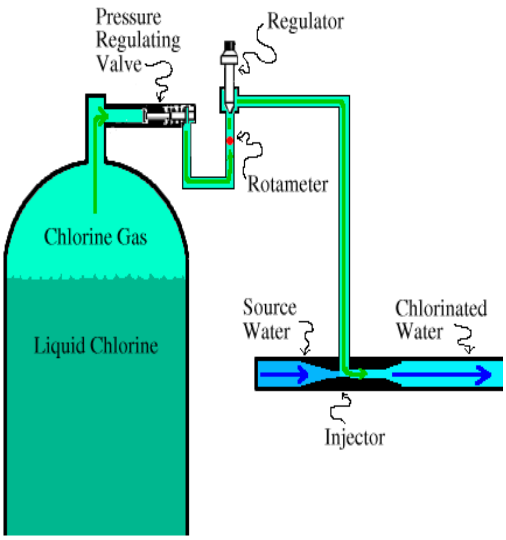


Figure 8-84: Chlorine gas (Camix technologies, 2018).

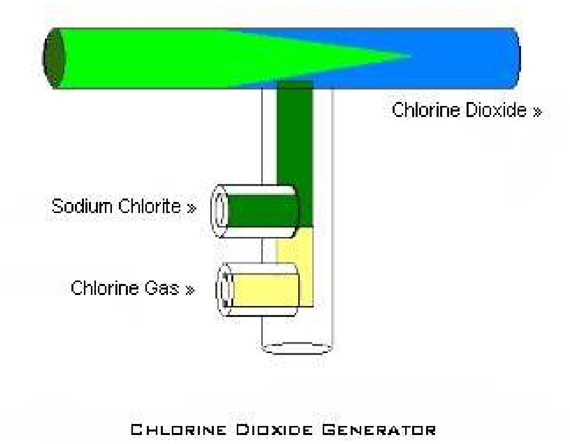


Figure 8-85: Chlorine dioxide (Cip, 2010).

Advantages: Highly effective disinfection; established method; chlorine concentration remaining in the effluent after disinfection its action; can oxidize not only pathogens but certain chemical pollutions; elimination of some odorous components

Disadvantages: Highly corrosive; toxic to aquatic life; hazardous by-products can be formed; some parasites resistant at different life stages to chlorine, including oocysts of *Cryptosporidium parvum*, cysts of *Giardia lamblia*, and eggs of parasitic worms (US-EPA, 2012a)

Pre-treatment: Nitrite minimized to avoid the formation of THMs; TSS minimized before chloride treatment because it can shield some pathogens from chloride action

4.3. Ultraviolet Disinfection

Process description: Ultraviolet photolysis is a widely used process for water disinfection purposes. Ultraviolet radiation has wavelengths between 200 and 300 nm, penetrates water, and damages the DNA of organisms, thus inhibiting their reproduction. Furthermore, UV radiation damages viruses and bacteria in their spore and cyst forms. Ultraviolet transmittance of wastewater depends on the concentration of suspended solids, color, lamp fouling, and others factors. Shielding of microorganisms from UV by clumping or solids is possible.

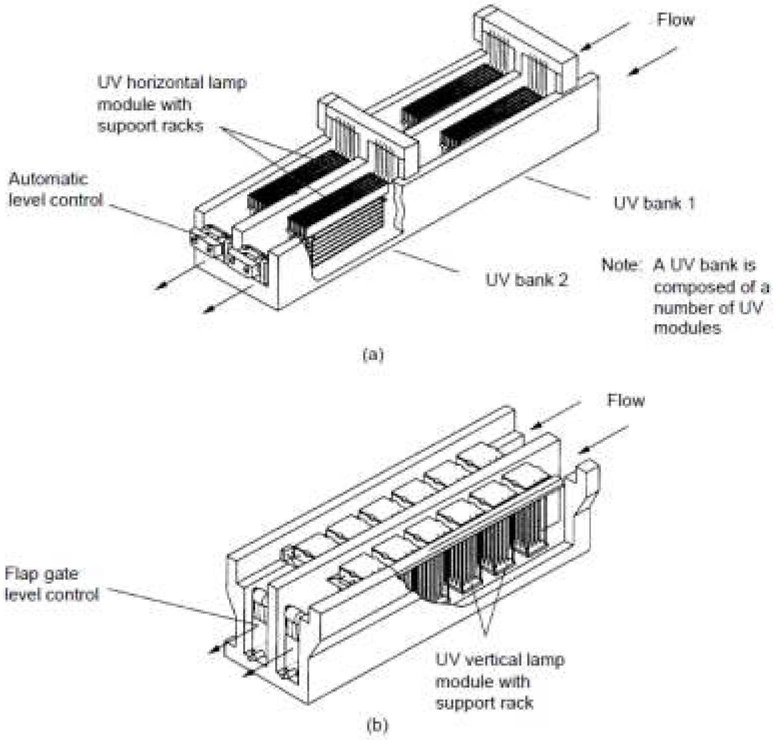


Figure 8-86: Two typical UV disinfection systems.

Advantages: Effective inactivation of many viruses, spores and cysts; no need to store and handle hazardous substances compared to chemical disinfection; easy to operate; short contact time compared to chemical disinfection (ca. 20–30 seconds with low-pressure lamps US-EPA 1999c); not harmful to the environment or to people

Disadvantages: High operating cost; lack of treatment in the case that anything blocks the UV light from reaching the water; water must be free of turbidity; repair of the destructive effect of UV radiation by some organisms through photo-reactivation or dark repair (US-EPA, 1999c)

Influent: Very low turbidity required

APPENDIX VII POSEIDON – UNIT PROCESS DATA

The content of this appendix has been published as supplementary material to the publication presented in Appendix I (Emmanuel Oertlé et al., 2019), publicly available on the Zenodo repository: Oertlé, Emmanuel. (2018). Wastewater Treatment Unit Processes Datasets: Pollutant removal efficiencies, assessment criteria and cost estimations (Version 1.0.0) [Data set]. Zenodo. http://doi.org/10.5281/zenodo.1247434

This dataset provides data on typical pollutant-removal efficiencies, assessment criteria, and cost estimation for 37 common wastewater treatment unit processes. The data is based on literature research, expert workshops, and estimations. The following files are available:

- pollutant removal efficiencies and assessment criteria for wastewater treatment unit processes (dataset) - Microsoft Excel:
- database of pollutant-removal efficiencies for 11 parameters, cost estimation, and assessment criteria;
- pollutant Removal Efficiencies for Wastewater Treatment Unit Processes (Dataset) (as a PDF); and
- assessment Criteria for Wastewater Treatment Unit Processes (Dataset) (as a PDF).

Section VII.I: Table for the First Six Parameters

This table presents the removal efficiency of every unit process for every parameters in [%]. For each parameter, three removal efficiencies are indicated: min, average, and max, referring to minimal, average, or maximal performance of unit processes.

Most data are from WASWARPLAMO (Adewumi, 2011), based on WTRNet (Joksimović, 2006). The data have been reviewed and updated in the frame of an expert workshop that took place at FHNW, on 6.11.2013 in Muttenz, Switzerland. Experts included Prof. Thomas Wintgens, Dr. Christian Kazner, Dr. Rita Hochstrat, Thomas Gross, and Emmanuel Oertlé. Additional data input and estimations from (Asano et al., 2007; Hammer & Hammer, 2012a; Salgot & Huertas, 2006).

Table 8-5: Unit Process Data for the First Six Parameters

Name	**Turb**			**TSS**			**BOD**			**COD**			**TN**			**TP**		
	min	% av.	max	min	% av.	max	min	% av.	max	min	% av.	max	min	% av.	max	min	% av.	max
Bar screen	0	0	0	0	2	5	0	2	2.50	0	1.30	1.50	0	0	0	0	0	0
Coarse screen	0	0	0	0	5	15	2	4	6	1	2	3	0	0	0	0	0	0
Grit Chamber	1	2	3	1	2	3	0	2	5	0	2	5	0	0	0	0	0	0
Equalization Basin	0	0	0	0	0	0	4	12	15	4	12	15	0	0	0	0	0	0
Sedimentation without coagulant	0	0	0	30	50	60	20	25	30	20	25	30	5	7	9	5	7	9
Sedimentation with coagulant	50	70	80	60	70	80	40	50	60	40	50	60	0	15	30	40	50	60
Anaerobic stabilization ponds	15	70	75	30	45	60	40	65	90	30	58	85	25	48	70	5	7	10
Activated sludge	80	90	99	50	70	99	50	70	99	60	80	94	10	30	96	10	23	45

Name	**Turb**			**TSS**			**BOD**			**COD**			**TN**			**TP**		
	min	% av.	max	min	% av.	max	min	% av.	max	min	% av.	max	min	% av.	max	min	% av.	max
Low Loaded Activated Sludge w/o de-N + Sec Sedim.	89	98	99	90	97	98	95	97	98	87	90	94	10	30	50	10	22.50	45
Low Loaded Activated Sludge w de-N + sec. Sedim.	93	98	99	90	97	99	93	98	99	87	90	94	68	87	96	10	27.50	45
High Loaded Activated Sludge + Sec. Sedim.	89	97	99	86	96	98	89	95	99	85	90	94	10	20	30	10	17.50	25
Extended aeration	90	99	99	82	88	79	85	90	95	89	90	95	50	72	90	90	99.90	99.90
Trickling filter with secondary sedimentation	20	30	45	50	70	85	50	70	85	65	80	90	20	30	40	20	30	40
Rotating biological contactor (RBC)	50	70	85	35	60	70	35	60	70	65	70	85	20	30	35	20	30	40

Name	Turb			TSS			BOD			COD			TN			TP		
	min	% av.	max	min	% av.	max	min	% av.	max	min	% av.	max	min	% av.	max	min	% av.	max
Stabilization ponds: Aerobic	50	60	75	30	45	60	40	60	80	35	40	60	25	45	60	20	40	50
Stabilization ponds: Facultative	40	50	60	50	70	85	50	70	85	60	80	90	20	40	60	25	50	70
Membrane bioreactor (MBR)	90	92	95	90	92	100	90	92	95	75	80	85	30	40	50	60	70	80
Constructed wetland	10	15	40	60	75	85	25	35	50	10	15	20	50	60	80	50	60	80
Enhanced biological phosphorus removal (EBPR)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	50	95	98
P-Precipitation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	70	95	98
Denitrification	0	0	0	0	0	0	0	0	0	0	0	0	50	95	98	0	0	0
Dual media filter	80	90	95	80	90	95	65	75	80	60	70	75	5	10	12	6	10	12

Name	**Turb**			**TSS**			**BOD**			**COD**			**TN**			**TP**		
	min	% av.	max	min	% av.	max	min	% av.	max	min	% av.	max	min	% av.	max	min	% av.	max
Microfiltration	85	90	95	80	90	95	65	75	80	60	70	75	5	10	12	6	10	12
Ultrafiltration	80	90	95	80	90	95	65	75	80	60	70	75	5	10	12	6	10	12
Nanofiltration	30	50	70	99	99.95	99.90	80	90	95	80	90	95	40	40	40	90	95	99
Reverse osmosis	30	50	70	80	90	95	20	35	50	60	70	75	40	40	40	80	90	95
Activated Carbon	20	40	60	40	45	50	40	45	50	20	30	40	0	0	0	8	15	25
Ion exchange	10	20	30	40	45	50	10	20	30	0	0	0	60	70	80	70	80	90
Advanced oxidation process	70	80	90	0	0	0	70	80	90	70	80	90	0	0	0	0	0	0
Soil-aquifer treatment	85	85	85	80	90	95	85	85	85	85	85	85	85	85	85	80	90	95
Maturation pond	30	45	60	15	25	40	8	13	20	10	20	30	30	40	45	20	30	40
Flocculation	20	30	50	40	60	80	20	30	40	15	35	50	5	8	13	10	15	30
Electrodialysis	70	80	90	0	0	0	0	0	0	0	0	0	40	50	60	40	50	60

Name	Turb			TSS			BOD			COD			TN			TP		
	min	% av.	max	min	% av.	max	min	% av.	max	min	% av.	max	min	% av.	max	min	% av.	max
Ozonation	0	0	0	0	0	0	10	15	20	10	15	20	0	0	0	0	0	0
Chlorine gas	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Chlorine dioxide	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ultraviolet disinfection	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Notes: "Turb" stands for "Turbidity", "TSS" stands for "Total suspended solids", "BOD" stands for "Biological oxygen demand", "COD" stands for "Chemical oxygen demand", "TN" stands for "Total nitrogen", "TP" stands for "Total phosphorous".

Section VII.II: Table for the Last Six Parameters

This table presents the removal efficiency of every unit process for every parameters in percentage. For each parameter, three removal efficiencies are indicated: min, average and max, referring to minimal, average or maximal performance of unit processes.

Most data are from WASWARPLAMO (Adewumi, 2011), based on WTRNet (Joksimović, 2006). The data have been reviewed and updated in the frame of an expert workshop that took place at FHNW, on 6 November 2013 in Muttenz, Switzerland. Experts included Prof. Thomas Wintgens, Dr. Christian Kazner, Dr. Rita Hochstrat, Thomas Gross and Emmanuel Oertlé. Additional data input from (Asano et al., 2007; Hammer & Hammer, 2012a; Salgot & Huertas, 2006) and estimations.

Table 8-6: Unit Process Data for the Last Six Parameters

Name	FC			TC			Conductivity			Nitrate			Virus			Virus (log removed)		
	min	% av.	max	min	% av.	max	min	% av.	max	min	% av.	max	min	% av.	max	min	av	max
Bar screen	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Coarse screen	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Grit chamber	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Equalization basin	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sedimentation without coagulant	0	0	0	0	0	0	0	0	0	0	0	0	0	68.38	90	0	0.50	1

Name	FC			TC			Conductivity			Nitrate			Virus			Virus (log removed)		
	min	% av.	max	min	% av.	max	min	% av.	max	min	% av.	max	min	% av.	max	min	av	max
Sedimentation with coagulant	10	15	30	5	10	20	−10	−5	0	0	0	0	0	68.38	90	0	0.50	1
Anaerobic stabilization ponds	30	50	60	20	35	45	0	0	0	90	95	100	90	99.68	99.99	1	2.50	4
Activated sludge	50	90	99.90	90	95	99.90	0	0	0	−20	0	20	0	90	99	0	1	2
Low Loaded Activated Sludge w/o de-N + Sec Sedim.	99.50	99.80	99.92	99.90	99.95	99.99	0	0	0	−20	0	20	0	90	90	0	1	1
Low Loaded Activated Sludge w de-N + sec. Sedim.	99.50	99.80	99.92	99.90	99.95	99.99	0	0	0	−20	0	20	0	90	90	0	1	1
High Loaded Activated Sludge + Sec. Sedim.	50	90	98	90	95	99.90	0	0	0	−20	0	20	0	90	68.38	0	1	0.50
Extended aeration	90	94.95	99.90	90	94.95	99.90	0	0	0	−20	0	20	0	90	99	0	1	2
Trickling filter with secondary sedimentation	60	80	90	50	60	75	0	0	0	0	0	0	0	90	99	0	1	2
Rotating biological contactor (RBC)	60	80	90	50	60	75	0	0	0	0	0	0	0	43.77	68.38	0	0.25	0.50
Stabilization ponds: Aerobic	10	15	30	5	10	20	0	0	0	−10	−5	0	90	96.84	99	1	1.50	2

Name	FC			TC			Conductivity			Nitrate			Virus			Virus (log removed)		
	min	% av.	max	min	% av.	max	min	% av.	max	min	% av.	max	min	% av.	max	min	av	max
Stabilization ponds: Facultative	10	15	30	10	20	30	0	0	0	−10	−5	0	90	99.68	99.99	1	2.50	4
Membrane bioreactor (MBR)	80	85	90	70	75	80	0	0	0	0	50	90	99.68	99.99	100	2.50	4.25	6
Constructed wetland	0	50	99	0	0	0	0	0	0	0	50	90	90	96.84	99	1	1.50	2
Enhanced biological phosphorus removal (EBPR)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P-Precipitation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Denitrification	0	0	0	0	0	0	0	0	0	70	90	100	0	0	0	0	0	0
Dual media filter	80	85	90	80	85	90	0	0	0	5	10	12	90	99	99.90	1	2	3
Microfiltration	90	93	99	80	85	90	0	0	0	0	0	0	0	90	99	0	1	2
Ultrafiltration	99	99.90	99.99	80	85	90	0	0	0	0	0	0	99	100	100	2	4.50	7
Nanofiltration	99	100	100	90	93	95	20	60	90	20	50	80	99.90	99.99	100	3	4	5
Reverse osmosis	90	95	98	90	93	95	80	90	99	65	75	80	99.99	100	100	4	5.50	7
Activated Carbon	15	30	40	10	20	30	0	0	0	0	0	0	0	43.77	68.38	0	0.25	0.50
Ion exchange	0	0	0	0	0	0							0	0	0	0	0	0

Name	FC			TC			Conductivity			Nitrate			Virus			Virus (log removed)		
	min	% av.	max	min	% av.	max	min	% av.	max	min	% av.	max	min	% av.	max	min	av	max
Advanced oxidation process	90	92.50	95	55	65	75	0	0	0	0	0	0	90	96.84	99	1	1.50	2
Soil-aquifer treatment	70	90	100	65	70	75	0	0	0	80	90	100	29.21	91.59	99	0.15	1.08	2
Maturation pond	30	50	70	20	35	50	0	0	0	−20	−10	0	99.90	99.97	99.99	3	3.50	4
Flocculation	10	20	40	5	15	20	0	0	0	0	0	0	90	99	99.90	1	2	3
Electrodialysis	0	0	0	0	0	0	60	75	90	20	40	50	0	0	0	0	0	0
Ozonation	90	95	98	90	92	95	0	0	0	0	0	0	99.90	100	100	3	4.50	6
Chlorine gas	90	95	100	100	100	100	0	0	0	0	0	0	99	99.90	100	2	3	6
Chlorine dioxide	90	95	100	100	100	100	0	0	0	0	0	0	99	99.90	100	2	3	6
Ultraviolet disinfection	90	95	100	55	65	80	0	0	0	0	0	0	99	99.90	100	2	3	6

Notes: "FC" stands for "Fecal coliform", "TC" stands for "Total coliform".

Section VII.III: Table for Other Information and Assessment Criteria

These qualitative assessment criteria are reported in (Adewumi, 2011). In addition, several expert workshops have been conducted, and additional references have been added, to fill the missing information.

Table 8-7: Unit Process Data for Other Information and Assessment Criteria

Name	Recovery [%]	Reliability	Ease to upgrade	Adaptability to varying	Adaptability to varying	Ease of O & M	Ease of construction	Ease of demonstratio	Power demand	Chemical demand	Odor generation	Impact on ground water	Land requirement	Cost of treatment	Waste (sludge production)	Useful life [years]
Bar screen	100	3	1	3	3	3	3	3	1	0	3	0	1	1	2	30
Coarse screen	100	3	1	1	1	1	1	3	1	0	2	0	1	1	2	30
Grit Chamber	100	3	1	3	2	1	1	3	1	0	3	0	1	1	2	30
Equalization Basin	100	3	1	3	3	3	3	2	1	0	2	0	2	1	1	30
Sedimentation without coagulant	99	3	1	2	1	2	2	3	1	0	2	0	3	1	1	30
Sedimentation with coagulant	99	2	1	2	3	1	2	3	3	2	2	0	2	2	2	30
Anaerobic stabilization	100	1	1	2	2	3	3	2	1	0	3	0	3	1	1	15

Name	Recovery [%]	Reliability	Ease to upgrade	Adaptability to varying	Adaptability to varying	Ease of O & M	Ease of construction	Ease of demonstratio	Power demand	Chemical demand	Odor generation	Impact on ground water	Land requirement	Cost of treatment	Waste (sludge production)	Useful life [years]
ponds																
Activated sludge	99	3	3	3	3	2	2	2	3	1	1	0	2	2	3	30
Low Loaded Activated Sludge w/o de-N + Sec Sedim.	99	3	3	3	3	2	2	2	3	1	1	0	2	2	3	30
Low Loaded Activated Sludge w de-N + sec. Sedim.	99	3	3	3	3	2	2	2	3	1	1	0	2	2	3	30
High Loaded Activated Sludge + Sec. Sedim.	99	3	3	3	3	2	2	2	3	1	1	0	2	2	3	30
Extended aeration	99	3	3	3	3	2	2	2	3	1	1	0	2	2	3	30
Trickling filter with	99	2	2	2	2	2	2	2	2	1	2	0	3	2	3	30

Name	Recovery [%]	Reliability	Ease to upgrade	Adaptability to varying	Adaptability to varying	Ease of O & M	Ease of construction	Ease of demonstratio	Power demand	Chemical demand	Odor generation	Impact on ground water	Land requirement	Cost of treatment	Waste (sludge production)	Useful life [years]
secondary sedimentation																
Rotating biological contactor (RBC)	99	3	3	2	3	2	2	2	3	0	1	0	2	1	3	30
Stabilization ponds: Aerobic	99	1	1	2	2	3	3	2	1	0	3	0	3	1	1	30
Stabilization ponds: Facultative	99	1	1	2	2	3	3	2	1	0	3	0	3	1	1	30
Membrane bioreactor (MBR)	99	3	3	2	3	1	1	2	3	1.50	2	1	1	3	2	30
Constructed wetland	100	2	1	2	2	3	3	2	0	0	1	0	3	2	1	30
Enhanced biological phosphorus removal	100	2	3	2	2	3	3	1	1	0	2	0	3	2	2	30

Name	Recovery [%]	Reliability	Ease to upgrade	Adaptability to varying	Adaptability to varying	Ease of O & M	Ease of construction	Ease of demonstratio	Power demand	Chemical demand	Odor generation	Impact on ground water	Land requirement	Cost of treatment	Waste (sludge production)	Useful life [years]
(EBPR)																
P-Precipitation	100	3	3	3	3	3	3	3	1	2	0	0	1	1	2	30
Denitrification	100	2	3	2	2	3	3	2	1	0	1	0	2	2	1	30
Dual media filter	100	3	3	2	2	1	2	3	2	1	0	0	2	2	1	20
Microfiltration	90	3	3	2	2	1	2	3	3	1	0	0	1	3	1	20
Ultrafiltration	85	3	3	2	2	1	2	3	3	1	0	0	1	3	1	20
Nanofiltration	83	3	3	2	2	1	2	1	3	1	0	0	1	3	1	20
Reverse osmosis	80	3	3	2	2	1	2	3	3	1	0	0	1	3	0	20
Activated Carbon	100	3	1	1	1	1	1	3	3	1	2	0	1	2	1	20
Ion exchange	90	1	2	1	1	1	2	2	3	3	0	1	1	2	3	30
Advanced oxidation process	100	2	2	3	2	2	3	3	3	3	0	0	1	3	1	30

Name	Recovery [%]	Reliability	Ease to upgrade	Adaptability to varying	Adaptability to varying	Ease of O & M	Ease of construction	Ease of demonstratio	Power demand	Chemical demand	Odor generation	Impact on ground water	Land requirement	Cost of treatment	Waste (sludge production)	Useful life [years]
Soil-aquifer treatment	100	3	2	3	2	3	3	3	1	0	1	2	3	1	0	40
Maturation pond	100	2	1	2	2	3	3	1	1	0	1	0	3	1	1	15
Flocculation	100	3	3	2	2	3	3	3	2	3	0	0	1	1	1	30
Electrodialysis	100	2	2	1	2	2	3	2	3	3	0	0	1	3	0	30
Ozonation	100	3	3	3	3	1	2	2	3	0	0	0	1	3	1	15
Chlorine gas	100	3	2	3	3	2	1	2	1	3	0	1	1	3	1	15
Chlorine dioxide	100	3	2	3	3	2	1	2	1	2	1	1	1	3	1	15
Ultraviolet disinfection	100	3	2	2	1	1	1	2	3	0	0	0	1	3	1	15

APPENDIX VIII POSEIDON – TREATMENT TRAINS TABLES

The content of this appendix has been published as supplementary material to the publication presented in Appendix I (Emmanuel Oertlé et al., 2019), publicly available on the Zenodo repository: Oertlé, Emmanuel. (2018). Treatment Trains for Water Reclamation (Dataset) (Version 1.0.0) [Data set]. Zenodo. http://doi.org/10.5281/zenodo.1972627

This dataset lists typical treatment trains (combination of unit processes) from global water-reuse and reclamation practices (as a PDF),

Treatment trains provided are examples from global water-reuse and reclamation practices. The examples displayed are categorized in typical basic treatment schemes according to Graaf (2005). Single unit processes of the treatment trains are documented on the basis of the included unit processes in Poseidon and specified (*) in case of additional information on the unit process. Unit processes not yet included in Poseidon have been replaced by a similar existent unit process (or left out in one case: High-quality Windhoek).

Table 8-8: Benchmark technologies (Graaf, 2005)

1) Title 22:	Conventional wastewater treatment: **Phosphorous (P)- and Nitrogen (N)-removal - dual-media filtration - disinfection by Ultraviolet (UV) or chlorine.** The reuse varies from urban applications, green landscaping to industrial usage.
2) Soil treatment:	Conventional wastewater treatment: **P- and N-removal - infiltration through large ground areas**. The final water can be reused for unrestricted irrigation.
3) Wetlands:	Conventional wastewater treatment: **P- and N-removal - constructed wetlands as a natural polishing step**. Reuse can be done in nature conservation or agriculture.
4) Lagooning:	Treatment of wastewater by **lagooning (several types in series) - occasionally followed by chlorination.** Reuse of the effluent by (very) restricted irrigation.

5) Only disinfection:	Conventional wastewater treatment followed by **chlorination**. Treated water can be reused for irrigation under restricted conditions.
6) Direct membrane filtration:	**Micro- or Ultrafiltration** of raw wastewater followed by agricultural applications. New concept.
7) Local MBR:	Small scale treatment of (part of the) wastewater by a package **membrane bioreactor (MBR) system**. Reuse of the water in the direct neighborhood (as toilet flush water).
8) High quality:	Conventional wastewater treatment: **P- and N-removal - double membrane filtration (microfiltration/ultrafiltration followed by reverse osmosis) - final disinfection by UV.** Eventually also other processes can be applied. The treated water is of so high quality that many applications (industrial, households, etc.) are possible.

Table 8-9: Poseidon – Treatment Trains Tables

No	Case study (Reference)	Name	Process description	Unit Processes										
				1	2	3	4	5	6	7	8	9	10	11
1	This concept exists as standard in the USA (Graaf, 2005).	**Title 22 Benchmark Technology**	Conventional wastewater treatment, including P and N removal, followed by dual media filtration and disinfection by UV or chlorine. The reuse varies from urban applications, green landscaping to industrial usage. **Several examples of agricultural and environmental water re-use after treatment with variations of the Title 22 treatment train exist in Europe and Australia.**	**Bar screen**	**Grit Chamber**	**Sedimentation with coagulant**	**Activated sludge**	**P-Precipitation**	**Denitrification**	**Dual media filter**	**Chlorine gas**			
Examples for Title 22 treatment trains:														
1a	Water reclamation scheme Is Arenas, Sardinia for irrigation (AQUAREC; 2006; Vacca et al., 2005).	**Title 22-Italy**	Conventionally treated wastewater from Is Arenas wastewater treatment plant (WWTP) (screening, grit removal, primary settling, activated sludge + sec. sedimentation, NaOCl disinfection) is further treated by a tertiary treatment step and then discharged to Simbirizzi reservoir. It is re-used directly or after storage in the reservoir for irrigational purposes (Vacca et al., 2005).	Bar screen	Grit chamber	Sedimentation without coagulant	Activated sludge	Chlorine dioxide* **Sodium hypochlorite*	Flocculation	Dual media filter	Ultraviolet disinfection			
1b	The Callala water reclamation scheme in New South Wales is designed for irrigation of dairy farm pastures, golf courses and recreational areas (AQUAREC, 2006; Shoalhaven Water: http://shoalwater.nsw.gov.au/educa-tion/pdfs/The%20Wastewater%20Process.pdf).	**Title 22-Australia**	The treatment train of the water reclamation facility consists of preliminary treatment, biological treatment, phosphor removal, sludge treatment, intermediate storage, tertiary treatment and disinfection. The Callala water reclamation scheme is part of the Northern Shoalhaven Reclaimed Water management Scheme (REMS): http://shoalhavenwater.com/projects/rems.htm	Bar screen* ** Fine screen*	Grit chamber	Equalization Basin	Extended aeration* **Intermittently Decanted Extended Aeration Tank*	Stabilization pond: facultative* **Lagoons for storage*	Dual media filter* **Pressure sand filters*	Chlorine gas				
1c	The tertiary treated effluent of Limassol WWTP in Cyprus is distributed and sold for many purposes such as groundwater recharge and irrigation of golf courses, hotel gardens, olives, deciduous trees and some vegetables (AQUAREC, 2006).	**Title 22-Cyprus**	The primary treatment includes a pre-treatment unit to remove larger sized particles and to degrade the organic load of the sewage. Additionally, screen, sand and grease collectors before the biological treatment ensure a good degradation in the secondary treatment process which consists of a conventional activated sludge treatment. The tertiary treatment includes sand filtration and disinfection step performed using chlorine gas (only tertiary system is displayed).	Bar screen	Grit chamber	Sedimentation with coagulant	Activated sludge	Dual media filter	Chlorine gas					

No	Case study (Reference)	Name	Process description	Unit Processes										
				1	2	3	4	5	6	7	8	9	10	11
1d	After tertiary treatment, the effluent of Hersonissos WWTP is re-used mainly for agricultural irrigation (and to a minor extent fire protection and landscape irrigation) (AQUAREC, 2006).	**Title 22-Greece**	The WWTP of Hersonissos has been designed to treat both municipal wastewater from the Hersonissos Municipality and septage from the wider area. The WWTP-effluent passes a sand filtration unit followed by a chlorination step.	Bar screen	Grit chamber	Sedimentation without coagulant	Low loaded activated sludge with de-N and sec. Sedimentation.	Dual media filter	Chlorine dioxide* ** Sodium hypochlorite*					
1e	Example from Spain of a water reclamation scheme for park irrigation based on sewage treated in La China WWTP in Madrid (AQUAREC, 2006).	**Title 22-Spain**	The secondary effluent from WWTP La China in Madrid is reclaimed in a tertiary treatment that includes sand filtration and disinfection. After UV disinfection, the reclaimed water is sent to the main reservoirs and then delivered by for park irrigation. The main reservoirs receive chlorination (Chlorine dioxide is used as the secondary disinfectant). (Only tertiary treatment step is displayed here)	Dual media filter* **Sand filters*	Ultraviolet disinfection	Chlorine dioxide								
1f	The Santee recreational lakes project developed initially as an economic alternative to wastewater disposal in the Pacific Ocean. The series of lakes are supplied with reclaimed water and used for various recreational activities like fishing, boating, and camping. (Asano et al., 2006)	**Title 22-USA I**	Primary sedimentation system with sludge digestion and pond treatment with effluent placed in two constructed lakes. Activated sludge plant with denitrification capability is available. Effluent is then discharged to infiltration basins. The tertiary plant is consisting of a coagulation and flocculation system using alum and a lamella settler for turbidity and excess phosphorous removal followed by a denitrification filter using methanol as a carbon source. Chlorine disinfection is applied to all effluent. Effluent to be used in the lake system is de-chlorinated with Sulphur dioxide.	Sedimentation without coagulation	Low loaded activated sludge with de-N and secondary sedimentation	Dual media filter* **Infiltration basins*	P-Precipitation	De-nitrification	Chlorine dioxide* ** Chlorine not further specified*					
1g	Example for Water Reuse for industries in Brazil. This reuse scheme is used by SABESP to supply re-used water (from two wastewater treatment plants [WWTPs], Jesus Neto and Parque Novo Mundo) for industrial purposes in Sao Paulo, Brazil. (Mierzwa, 2014)	**Title 22-Brazil I**	The presented scheme is a basic treatment process train for water reuse. The main issue is the effluent final ammonia concentration, because the proposed system did not perform the nitrification step. The main consequence is the higher chlorine dosage to reach the breakpoint.	Coarse screen	Grit Chamber	Sedimentation without coagulant	High Loaded Activated Sludge + Sec. Sedimentation	Dual media filtration **Cartridge filtration (with previous coagulation)*	Chlorine dioxide* **Sodium hypochlorite*					
1h	Example from Belgium re-using water to produce cooling water for industrial purposes (AQUAREC, 2006)	**Title 22-Belgium**	A pharmaceutical company (Tienen) makes use of treated municipal wastewater for cooling water. Secondary treated effluent is ozonized for disinfection. If the amount of reclaimed wastewater is too low or temperature too high, it is mixed with groundwater before usage. The WWTP consists of low loaded activated sludge system with enhanced biological phosphorus removal.	Low loaded activated sludge with de-N and secondary sedimentation	Enhanced biological phosphorus removal	Ozonation								

No	Case study (Reference)	Name	Process description	Unit Processes										
				1	2	3	4	5	6	7	8	9	10	11
1i	This is a reuse scheme in the SPMR for **urban water reuse** (Mierzwa, 2014)	**Title 22-Brazil II**	This is the first water-reuse scheme in Brazil with a distribution network specific for reuse water. It was implemented in a residential condominium. The reuse water is applied for non-potable applications, such as toilet flush, irrigation, and floor cleaning. In this water-reuse scheme, there is the addition of a colorant to the final water in order to avoid the undue use.	Bar screen	Grit chamber	Anaerobic stabilization pond* *UASB	Trickling filter with secondary sedimentation	P-Precipitation	Dual media filter	Ultraviolet disinfection	Chlorine dioxide* **Sodium hypochlorite*			
1j	Example of water reuse for industrial purpose from San Luis Potosi, Mexico (US EPA 2012; Lazarova, 2014)	**Title 22-Mexico**	The Tenorio WWTP was designed for a total capacity of 1,050 L/s (90,720 m^3/d). and it uses the following treatment steps: Screening, grit and grease removal and advanced primary treatment in lamellar clarifiers enhanced with chemicals for the total capacity. Secondary treatment for up to 38,880 m^3/d by activated sludge with nitrogen removal, followed by tertiary treatment with lime, sand filtration, ion exchange softening and chlorine disinfection for industrial reuse. Water is re-used in cooling towers of a power plant (Lazarova, 2014).	Bar screen	Grit chamber	Sedimentation with coagulant	High loaded activated sludge & secondary sedimentation	Dual media filter	Ion exchange	Chlorine dioxide* Chlorine				
1k	Example of water reuse for industrial purpose from Durban, South Africa (US EPA, 2012)	**Title 22-South Africa**	Durban water recycling project. The preliminary and primary wastewater treatment process is comprised of screening, degritting and primary settling operations; performed by Ethekweni Metro Water Services (EMWS). Meanwhile, the effluent from the primary settling tank is fed to the activated sludge plant. Poly Aluminum Chloride (PAC) is placed followed by a dual media filtration step. The final step is ozonation. The water recycling facility produces effluents (47 mega liters/d) for reuse in industrial application. The company Mondi uses the reclaimed water for the production of fine paper and is extremely sensitive to processed water quality and its impact on paper brightness (US EPA, 2012; E-104)	Bar screen	Grit chamber	Sedimentation with coagulant	High loaded activated sludge & secondary sedimentation	*Poly aluminum chloride (PAC) (has been left out in Poseidon v3)*	Dual media filter	Ozonation				
2	Examples are present in the Mediterranean area (Israel). (Graaf, 2005)	**Soil treatment Benchmark Technology**	Conventional wastewater treatment, including P and N removal, followed by infiltration through large ground areas; the final water can be reused for unrestricted irrigation.	**Bar screen**	**Grit Chamber**	**Sedimentation with coagulant**	**Activated sludge**	**-P-Precipitation**	**Denitrification**	**Soil-aquifer treatment (SAT)**				

Examples for <u>Soil treatment</u> treatment trains:

No	Case study (Reference)	Name	Process description	Unit Processes										
				1	2	3	4	5	6	7	8	9	10	11
2a	The Dan region (Israel) infiltrates treated wastewater in the soil (SAT). Water is stored in local reservoirs and post chlorinated before usage for agricultural irrigation (AQ-UAREC, 2006)	**Soil treatment- Israel**	Effluent from the Dan region WWTP is conveyed to four recharge basins covering a total area of 80 ha. The infiltration into the groundwater is carried out by alternate flooding and drying. After the SAT system the reclaimed water has to be chlorinated to maintain bacteriological quality the long distribution lines. Approx. 200 recovery wells, located 300–1,500 m from the recharge basins, pump the recharged water from a depth of 100–200 m. Water recovered from the SAT system is of extremely high quality and can be used for unrestricted agricultural irrigation.	Bar screen* ** Fine screen*	Grit chamber	Low loaded active sludge with de-N and Sec. Sedim.* ** Activated sludge, nitrification-denitrification*	Soil Aquifer treatment	Chlorine gas						
2b	Mesa city (Arizona, USA) has two reclamation plants. Both plants reclaim water for re-use on golf courses, crop irrigation, industrial uses, freeway landscape watering, and for groundwater recharge (Asano et al., 2006), p. 1281	**Soil treatment- USA**	Northwest Water Reclamation plant has treatment that includes secondary treatment with nutrient removal, filtration, clarification, and disinfection. Reclaimed water is discharged to two recharge sites and to the Salt river, which also recharges the aquifer.	Bar screen	Grit chamber	Sedimentation without coagulant	Activated sludge	Dual media filter* **Filtration: not specified*	Chlorine dioxide* *Disinfection: not specified	Soil-Aquifer treatment				
3	Applications are present in Europe and the USA (Graaf, 2005). There are also examples in Latin America (Gauss, 2008; http://www.wsp.org/sites/wsp.org/files/publications/ConstructedWetlands.pdf)	**Wetlands Benchmark Technology**	Wetlands are used as secondary or tertiary treatment units—that is wastewater is generally treated first in primary treatment units such as settling tanks or technical treatment plants (Gauss, 2008). **Examples from Central and South America rather use low-tech solutions as primary treatments whereas applications in Europa and the USA use conventional primary wastewater treatment methods, including P and N removal.** Reuse can be done in nature conservation or agriculture.	**Bar screen**	**Grit Chamber**	**Sedimentation with coagulant**	**Activated sludge**	**P-Precipitation**	**Denitrification**	**Constructed wetland**				
Examples for <u>Wetland</u> treatment trains:														
3a	Constructed Wetland in Masaya Pilot Plant Nicaragua (Gauss, 2008)	**Wetland- Nicaragua**	The system is treating the domestic wastewater (100 cubic meters per day) generated by some 1,000 people living in the city of Masaya, Nicaragua. The scheme comprises pre-treatment (screen and grit tank) and four constructed wetland beds fed in parallel. The area of each wetland bed is about 350 square meters, totaling 1,400 square meters. Effluent from the pilot plant in Masaya can be used for restricted irrigation.	Bar screen	Grit Chamber	Constructed wetland								

No	Case study (Reference)	Name	Process description	Unit Processes 1	2	3	4	5	6	7	8	9	10	11
3b	Constructed Wetland schemes in the arid outskirts of Peru's capital Lima (Gauss, 2008)	**Wetland-Peru**	Three wetlands were constructed. Each constructed wetland scheme serves about 2,500 people and includes a manual screen, grit separators, and sedimentation tanks as pre-treatment steps for the domestic wastewater before it enters the wetland, which is composed of two units of the subsurface horizontal flow type. Treated water will be reused for reforestation purposes.	Bar screen* ** Manual screen*	Grit Chamber	Sedimentation without coagulant	Constructed wetland							
3c	Several small constructed wetland projects have been implemented since 1990 in the state of Santa Catarina in south-eastern Brazil (Gauss, 2008)	**Wetland-Brazil**	The constructed wetland treatment schemes (Agronômica, Videira, Tubarão, and São Joaquim), which use septic tanks as primary treatment, were designed for a population of 50–150 persons. Coarse sand is used as filter media, and the wetlands are planted with a local wetland plants. The effluent of some of the systems receives further treatment in stabilization ponds and is used for aquaculture (fish farming).	Sedimentation without coagulant	Constructed wetland									
3d	Treated effluent from Arcata WWTP (California, USA), is discharged into 'enhancement wetlands', which are part of the Arcata Marsh and Wildlife Sanctuary (AQUAREC, 2006)	**Wetlands-USA**	The first treatment steps at the Arcata WWTP consist of bar screens, a grit chamber and 2 settling tanks for primary treatment. Secondary and partial tertiary treatment is accomplished by 2 oxidation ponds followed by 3 parallel FWS (Free water surface) wetlands that were constructed in 1985. (After chlorination and de-chlorination, part of the wastewater is released while another part flows into three so-called 'enhancement FWS wetlands'). The 'enhancement wetlands' together with some additional landscape features, are referred to as the Arcata Marsh and Wildlife Sanctuary	Bar screen	Grit chamber	Sedimentation without coagulant	Anaerobic stabilization ponds	Chlorine dioxide* * Chlorination and de-chlorination	Constructed wetlands					
3e	Example from Spain with the goals to feed water of sufficient quality to the Cortalet lagoon in a Natural Reserve and to stimulate the recovery and establishment of local flora and fauna (AQUAREC, 2006; Sala, et al., 2004).	**Wetlands-Spain**	Empuriabrave WWTP (Costa Brava, Spain) is of the extended aeration type and consists in its current form o f a mechanical pre-treatment step and then two parallel treatment lines each comprising a biological reactor, a clarifier and three effluent polishing ponds. A chemical treatment for phosphorus removal has recently been added. Further treatment is then achieved by means of a wetland system (3 parallel cells) that started operation in 1998.	Bar screen	Grit chamber	Extended aeration	P-precipitation* ** P-removal: not further specified*	Maturation pond	Constructed wetland					
3f	Example of water reuse for agricultural purpose from San Luis Potosi, Mexico (US EPA 2012; Lazarova, 2014)	**Wetlands-Mexico**	The Tenorio WWTP was designed for a total capacity of 1,050 L/s (90,720 m^3/d). and it uses the following treatment steps: Screening, grit and grease removal and advanced primary treatment in lamellar clarifiers enhanced with chemicals for the total capacity. Natural engineered treatment and polishing for at least 51,840 m^3/d in a constructed wetland, with a semi rectangular shape, a total surface of 179 ha and a storage capacity of 2.65 M m^3, named Tenorio Reservoir, for agricultural reuse (Lazarova, 2014).	Bar screen	Grit chamber	Sedimentation with coagulant	Constructed wetland							

No	Case study (Reference)	Name	Process description	Unit Processes 1	2	3	4	5	6	7	8	9	10	11
3g	Example of water reuse for agricultural purpose from Dakar, Senegal (US EPA, 2012)	**Wetlands-Senegal**	The main wastewater-reuse site in urban agriculture in Dakar is Pikine. Of Pikine's total cultivated area of approximately 120 acres (50 ha), about 40 acres (16 ha) makes use of raw wastewater for irrigation. Usually, farmers divert wastewater from the sewage using pipes to load narrow wells located in their plot. From that well, they use water cans to irrigate crops such as lettuce, which grow rapidly. Wastewater treatment using wetlands has been introduced which showed good removals of E.coli and helminth eggs. The treatment lines tested used combinations of four ponds (each 2 m^3) in series: One waste stabilization pond followed by three reed or Vetivera sp.-planted ponds with free water surface and surface water flow (US EPA; pp. 97)	Stabilization pond: facultative	Constructed wetland	Constructed wetland	Constructed wetland							
4	Typical application for Mediterranean countries with moderate treatment facilities (Graaf, 2005)	**Lagooning Benchmark Technology**	Treatment of wastewater by lagooning (several types in series), occasionally followed by chlorination; reuse of the effluent by (very) restricted irrigation.	**Maturation pond**	**Maturation pond**	**Maturation pond**	**Maturation pond**	**Chlorine dioxide**						
Examples for <u>Lagooning</u> treatment trains:														
4a	The chlorinated effluents from two WWTPs in Haifa, Israel are purified in retention reservoirs from where water is filtered and chlorinated and either sent to irrigation or to peripheral reservoirs (AQUAREC; 2006)	**Lagooning-Israel**	The Hakishon unrestricted irrigation effluent recovery systems is based mainly on receiving effluents from Haifa and Afula WWTPs and some flood water, long-term storage, and supplementary treatment of the effluent (by surface straining filtration and chlorination). Treatment train Haifa WWTP: Built to perform nitrification-denitrification together with organic removal (<u>this treatment train has been included, as WWTP has higher capacity)</u> Treatment train Afula WWTP: Operates on the extended aeration principle. The chlorinated effluents from the two WWTPs are purified in a main reservoir with a retention time of at least 60 days (where it is also mixed with storm water). From the reservoir, water is filtered and chlorinated and sent to irrigation or to peripheral reservoirs.	Bar screen	Grit chamber	Sedimentation with coagulant	Low loaded activated sludge with de-N & secondary sedimentation	Chlorine dioxide* ** Chlorination: not further specified*	Maturation pond	Dual media filtration* **Filtration: Not further specified*	Chlorine dioxide* ** Chlorination: not further specified*			
4b	One of the typical storage and polishing lagoons case studies. Treated water of WWTPs on the island (Noirmoutier island, France) is polished in maturation ponds and reused for potatoes growing (AQUAREC, 2006)	**Lagooning-France**	For agricultural irrigation the treated wastewater from three WWTP (main one: La Salaisière WWTP) on the island is polished in maturation ponds. La Salaisiére receives effluents of three municipalities and is composed of activated sludge systems and aerated lagoon systems. The treated effluents from all WWTP flow into a lagoon-storage system, four lagoons in series with a total volume of 196,300 m^3 which is used as tertiary treatment and storage facility before irrigation. Stored water that is not used for irrigation is disposed to the sea.	High loaded active sludge + sec. Sedimentation	Anaerobic stabilization ponds:	Anaerobic stabilization ponds::	Stabilization ponds: facultative	Stabilization ponds: facultative	Maturation pond	Maturation pond	Maturation pond	Maturation pond		

No	Case study (Reference)	Name	Process description	Unit Processes 1	2	3	4	5	6	7	8	9	10	11
4c	Example from Australia of water reclamation for horticultural (unrestricted) irrigation (AQUAREC, 2006)	**Lagooning-Australia I**	Bolivar WWTP effluents are re-used for horticultural irrigation in the Virginia area (Australia). Main crops irrigated are root and salad crops, brassicas, wine grapes and olives (=unrestricted irrigation). Sewage from the Adelaide metropolitan areas is treated in Bolivar WWTP by activated sludge process. The effluents from secondary treatment were then held in shallow aeration lagoons for a minimum of 6 weeks, before passing through a dissolved air flotation and dual media filtration process at the water reclamation plant. Here, the effluents discharge via a chlorinator into a balancing storage before being pumped into the pipeline for distribution for horticultural irrigation.	Maturation pond	Flocculation* **Flotation*	Dual media filtration	Chlorine dioxide* ** Chlorination not further specified*							
4d	Example from Australia of water reclamation for restricted irrigation (AQUAREC, 2006)	**Lagooning-Australia II**	Picton water-reuse scheme produces reclaimed water used for growing Lucerne and ryegrass/clover pastures and a woodlot. The water reclamation process includes intermittently decanted extended aeration lagoons, operated in a manner to allow nitrogen and phosphorus levels in the effluent suitable for agriculture and silviculture irrigation, followed by sand filters and UV disinfection. Treated effluent is stored in a dam where a minimum 10 day retention time achieves required water quality for crop irrigation.	Maturation pond	Dual media filter* ** Sand filters*	Ultraviolet disinfection	Maturation pond							
4e	Water reuse for irrigation of golf course and football fields from Parrow, South Africa (Adewumi, 2011).	**Lagooning-South Africa**	Parrow is a northern suburb in the city of Cape Town, Western Cape Province, South Africa. Parrow WWTW has a design capacity of 1.2Ml/d but was using 85% of its capacity in 2007.In April 2007, the Parrow WWTW treatment train included extended aeration, activated sludge, maturation pond and chlorine gas disinfection. All the effluent from the treatment plant were used for irrigation of Parrow golf course and football fields. It can be upgraded to supply treated effluent to irrigate colleges and different sport complexes (Adewumi, 2011).	Bar screen	Grit Chamber	Sedimentation with coagulant	Activated sludge	Maturation pond	Chlorine gas					
4f	Water reuse for agriculture from waste stabilization ponds in Argentina (US EPA, 2012; https://landscapearchipelago.wordpress.com/2014/07/21/campo-espejo/)	**Lagooning-Argentina**	The Campo Espejo waste stabilization ponds consists of 12 modules of three waste stabilization ponds in series (facultative, aerobic, and polishing), occupying some 790.7 ac (320 ha) in total (Idelovitch and Ringskog, 1997). Today they provide 147,000 m^3/d of effluent for direct irrigation. The effluent from the Campo Espejo treatment plant is discharged to the Moyano Canal and conveyed to a special 6,672 ac (2,700 ha) restricted irrigation area for reuse. Farmers with properties within the special area receive treated effluent free of charge and are obliged to follow the irrigation regulations established. About one quarter of the irrigated area is devoted to the production of grapes, another quarter to the cultivation of tomatoes and squash, and the remaining area to the cultivation of alfalfa, artichokes, garlic, peaches, pears, and poplar biomass. (US EPA, 2012; pp. E-5)	Bar screen	Grit Chamber	Stabilization ponds: Facultative	Stabilization ponds: Aerobic	Maturation pond						

No	Case study (Reference)	Name	Process description	Unit Processes										
				1	2	3	4	5	6	7	8	9	10	11
4g	Water reuse for environmental purposes from Abu-Dhabi, United Arab Emirates (US EPA, 2012)	**Lagooning-United Arab Emirates**	For over a decade, Abu Dhabi has implemented reuse for irrigation under the municipality's Sewerage Projects Committee, under the direction of His Highness Sheikh Zayed Bin Sultan Al Nahyan. An investment of around U.S. $149 M (547.5 M UAE Dirhams) has resulted in an irrigation system using reclaimed water from the Mafraq wastewater treatment facility to irrigate approximately a quarter of the island section of the city's area to create a green oasis in the city. This has generated fresh water savings and a series of ecological, social, and economic benefits. The greening of the city has enhanced the urban environment and offset pollution and carbon emissions (US EPA, 2012; pp. E-116; http://pdf.usaid.gov/pdf_docs/Pnadl013.pdf)	Bar screen	Grit Chamber	Sedimentation without coagulant	Low-loaded activated sludge with de-N and secondary sedimentation	Stabilization pond: Aerobic	Stabilization pond: Aerobic	Stabilization pond: Aerobic* *(has been left out in Poseidon v3)*	Stabilization pond: Facultative	Dual media filter	Maturation pond	Chlorine dioxide* *Chlorine*
5	Many examples are available all over Europe (Graaf, 2005).	**Only disinfection Benchmark technology**	Conventional wastewater treatment, followed by chlorination, enabling the reuse of the treated water for irrigation under restricted conditions.	**Bar screen**	**Grit Chamber**	**Sedimentation with coagulant**	**Activated sludge**	**Chlorine dioxide**						
5a	Western branch wastewater treatment plant (EPA, Municipal Nutrient Removal Technologies Reference Document, Volume 1, 2008)	**Only disinfection-USA**	The Western Branch Wastewater Treatment Plant (WWTP) was selected as a case study because of a unique feature—three separate activated-sludge systems operating in series to remove nutrients. The Western Branch WWTP is part of the Washington Suburban Sanitary Commission (WSSC), and it is in Upper Marlboro, Maryland. It is permitted for a flow of 30 million gallons per day (MGD); in 2006 it processed an average of 19.3 MGD. The plant is permitted to discharge to the Western Branch of the Patuxent River. No reuse.	Bar screen	Grit Chamber	High Loaded Activated Sludge + Sec. Sedim.	*Nitrification** *(has been left out in Poseidon v3)*	Denitrification	Dual media filter	Ultraviolet disinfection				
5b	Treatment train of Copiapó Wastewater Treatment Plant. Water re-use in mining industry and agriculture (Guzmán, 2015)	**Only disinfection-Chile**	The wastewater from Copiapó are directed to Copiapó WWTF, where in the first place the wastewater is subjected to a primary treatment to retain thick solids, then through a secondary treatment to carry out the oxidation of organic matter by activated sludge. The mixture goes to a separation process of solid and liquid in the clarifier, generating a sludge stream and a treated water stream. The water stream is subjected to chlorination and discharged to Copiapó river.	Bar screen	Grit Chamber	Extended aeration* *With secondary sedimentation	Chlorine gas							

No	Case study (Reference)	Name	Process description	Unit Processes 1	2	3	4	5	6	7	8	9	10	11
5c	This is a reuse scheme in the SPMR for **urban water reuse** (Mierzwa, 2014)	**Only disinfection-Brazil**	The reuse water is applied for toilet flushing, irrigation, and floor cleaning. This water-reuse scheme was installed in, at least, five apartment buildings at the SPMR. This water-reuse scheme was originally designed with a rotating biological contactor for BOD removal and a filtration system. However, the entrepreneur, based on the investment costs, decided to buy and install the specific treatment train. Because of this decision, the treated water cannot be stored for more than one day before being reused, because odors problems.	Equalization Basin	Sedimentation without coagulant	Dual media filter	Chlorine dioxide* **Sodium hypochlorite*							
6	New concept, which is investigated in several places (Netherland, China, Israel). (Graaf, 2005)	**Direct membrane filtration Benchmark Technology**	Micro- or Ultrafiltration of raw wastewater followed by agricultural applications (Graaf, 2005)	Bar screen	Grit Chamber	Ultrafiltration								
Examples for <u>Direct membrane filtration</u> treatment trains:														
6a	Landscape Irrigation with reclaimed wastewater in US (Asano et al., 2006)	**Direct membrane filtration-USA**	Water Conserv II is the first project in Florida to use reclaimed water to irrigate crops for human consumption. Primary purposes of Water Conserv II were wastewater discharge abatement, agricultural (predominantly citrus) irrigation, and groundwater recharge. Two water reclamation facilities, City of Orlando Water Conserv II Water Reclamation Facility, and Orange County South Regional Water Reclamation Facility, are providing reclaimed water in the project area. Treatment process: screenings, grit removal, primary sedimentation, activated sludge with fine bubble aeration, and secondary clarification. Effluent is filtered and chlorinated prior to being pumped to the distribution center for reuse. Agriculture and commercial customers use 60% of the reclaimed water, and the remaining 40% is recharged to groundwater through River infiltration basins. (Asano, et al, 2006)	Bar screen	Grit Chamber	Sedimentation without coagulant	Loaded Activated Sludge w/o de-N + Sec Sedim.	Microfiltration	Electrodialysis	Chlorine dioxide				
6b	Example of urban water-reuse scheme in Sydney (Australia) (AQUAREC, 2006).	**Direct membrane filtration-Australia**	The primary treatment includes a fine screen, grit removal and a primary clarifier. The activated sludge system includes nitrification, denitrification and biological phosphorous removal. The tertiary treatment includes flocculation, tertiary sedimentation and filtration. A part of the effluent is further upgraded in the recycling plant by microfiltration as well as sodium hypochlorite dosing. He water is stored in three storage tanks. The recycled water is used for gardening, car washing and toilet flushing.	Bar screen	Grit removal	Sedimentation without coagulant* *Sedimentation not further specified	Low loaded activated sludge with de-N & secondary sedimentation	Flocculation	Dual media filter* ** Filter not further specified*	Microfiltration	Chlorine dioxide* ** Sodium hypochlorite*			

No	Case study (Reference)	Name	Process description	Unit Processes										
				1	2	3	4	5	6	7	8	9	10	11
7	Typical solution for Japanese office buildings is now also introduced in some Europeans sites (Graaf, 2005).	**Local MBR Benchmark technol-ogy**	Small scale treatment of (part of the) wastewater by a package MBR system with reuse of the water in the direct neighborhood (as toilet flush water). Reclaimed wastewater and/or harvested rainwater are used for a variety of purposes. The water is most commonly used for toilet flushing, but can also be used for landscape irrigation, cooling, car cleaning and fire protection (US EPA, 2012)	**Membrane bioreactor (MBR)**										
7a	An example of an MBR system used for onsite wastewater reclamation/reuse system in a private building in New York, US (Asano, et al., 2006)	**Local MBR-USA**	The Solaire is a residential high-rise building in New York that has an onsite waste-water system for treating waste-water for toilet flushing and cooling water. The Solaire water reclamation includes the following elements: Aerated influent feed tank, Trash trap to intercept non-biodegradable solids, Three-stage membrane bioreactor (MBR) consisting of an anoxic mix tank, aerobic digestion tank, filter tank containing ultrafiltration membrane units, and recirculation of the mixed liquor to the anoxic tank, Ozone oxidation for color removal, Ultraviolet (UV) disinfection, Finished water storage tanks, Booster pumping system and reclaimed water distribution piping (Asano et al., 2006)	Bar screen	Membrane bioreactor (MBR)	Ultraviolet disinfection	Ozonation							
7b	Example for Water-Reuse System for Industrial Purposes. Aquapolo Project at the Santo Andre Wastewater Treatment Plant in the Sao Paulo Metro-politan Region, Sao Paulo (SPMR) – Brazil (Mierzwa, 2014)	**Local MBR-Brazil**	This treatment train was an adaptation for the implementation of an industrial water-reuse scheme. The main issue was to use the treated effluent from a high loaded activated sludge process as a source for the reuse scheme. Because effluent nitrification was not considered in the original project, it was necessary to implement a MBR system capable to accomplish the nitrification and denitrification processes. http://www.watertoday.org/Article%20Archieve/Koch18.pdf	Bar screen	Grit Chamber	Sedimentation without coagulant	High Loaded Activated Sludge + Sec. Sedimen-tation	MBR *(with nitrification and denitrification*	Reverse osmosis	Chlorine dioxide				
7c	Example for Water-Reuse System for landscape irrigation of Olympic Park in Beijing, China: Qinghe WWTP (US EPA, 2012; http://www.wabag.com/wp-con-tent/uploads/2012/04/Membrane_bioreactors_Article_12_2007.pdf)	**Local MBR-China**	The treated water from the Qinghe WWTP is mainly used in agricul-tural irrigation, industry, and urban landscaping. The plant basically consists of a pre-treatment system, a membrane bioreactor with a capacity of 60,000 m³/d (total membrane area is 183,000 m²) and a partial stream reverse osmosis system, which produces "high-quality reclaimed water" (3,000 m³/d). This will be reused in the central area of the Olympic Park and mainly serve the supply of a small lake with fountains. 50,000 m³/d are to be pumped into the urban recycled water network. At the household level, treated water is primarily used for flushing toilets (US EPA, 2012; pp. E-31; http://www.wabag.com/wp-con-tent/uploads/2012/04/Membrane_bioreactors_Article_12_2007.pdf; http://www.water-technology.net/projects/qinghewatertreatment/)	Bar screen	Grit Chamber	Sedimentation without coagulant	High Loaded Activated Sludge + Sec. Sedimentation	MBR						

No	Case study (Reference)	Name	Process description	Unit Processes										
				1	2	3	4	5	6	7	8	9	10	11
7d	An example of an MBR system used for onsite wastewater reclamation/reuse system in a private building in Tokyo, Japan (US EPA, 2012)	**Local MBR-Japan**	In several large cities including Tokyo, regulations require a wastewater-reuse system or a runoff harvest system to be installed in a new building if the total floor area of the building exceeds a certain size. Membrane bioreactors (MBRs are often used for onsite wastewater reclamation. The MBR system was installed in a business complex building in Tokyo in 2007. Treatment capacity of the system is 680 m^3/day and reclaimed water is used solely for the purpose of toilet flushing. Wastewater reclaimed for toilet flushing includes greywater from restaurants, greywater from offices, and blowdown from a cooling tower system. Black water from the toilet is not recycled and is prohibited by regulations. (US EPA, 2012, pp. E-66).	Bar screen	Grit Chamber	MBR	Chlorine dioxide* *Chlorine							
8	Examples of this concept are Water Factory 21, Sydney Olympic Parka and Torrele (Belgium). (Graaf, 2005)	**High Quality Benchmark Tech-nology**	Conventional wastewater treatment , including P and N removal, followed by double membrane filtration (MF/UF followed by RO) and final disinfection by UV; eventually also other processes can be applied; the treated water is of so high quality that many applications (industrial, households, etc.) are possible	**Grit Chamber**	**Sedimentation with coagulant**	**Activated sludge**	**P-Precipitation**	**Denitrification**	**Ultrafiltration**	**Reverse osmosis**	**Ultraviolet disinfection**	**Chlorine gas**		
Examples for <u>High quality</u> treatment trains:														
8a	Wulpen WWTP (Belgium), **Indirect potable re-use** of municipal wastewater (Van Houtte and Verbauwhede, 2008).	**High quality-Belgium**	Conventional WWTP for municipal wastewater with UF + RO treatment of the WWTP effluent in order to enable indirect potable reuse of the treated wastewater. The filtrations units are complement-ed by two disinfection steps: by chlorine to control the bio-growth before the UV step and final UV disinfection before the infiltration. The treated water is recharged into a sand dune aquifer, which serves as the source of drinking water for 6 communities (Van Houtte and Verbauwhede, 2008).	Bar screen	Grit chamber	Sedimentation without coagulant	Low Loaded activated Sludge w de-N + sec. Sedim.	Chlorine gas	Ultrafiltration	Chlorine dioxide * ** Chloramination*	Reverse osmosis	Ultraviolet disinfection	Soil-aquifer treatment* **Sand-dune aquifer*	
8b	NEWater Project (Singapore) was implemented to supply industries and augment fresh-water resources from re-claimed water, for a total amount of 10% of Singapore daily water consumption. (AQUAREC, 2006).	**High quality-Singapore**	The <u>reclamation process (documented here)</u> consists of a double-membrane treatment of secondary effluent with MF and RO and final disinfection by UV (AQUAREC, 2006).	Chlorine dioxide * ** Sodium hypochlorite*	Ultrafiltration	Reverse osmosis	Ultraviolet disinfection							
8c	To date, this is the only direct potable reuse project world-wide. It is operating in Wind-hoek (Namibia) since 2002. It produces potable water from a mixture of pre-treated domes-tic wastewater effluent and surface water (AQUAREC, 2006).	**High quality-Namibia**	The complex treatment train includes coagulation, dual media filtration, ozonation, multi-stage activated carbon adsorption and UF prior to chlorine disinfection. (Source water is raw surface water and pre-treated domestic wastewater) (AQUAREC, 2006).	(Activated carbon) *If required*	Ozonation	Flocculation	Flotation* *has been left out for Poseidon v3	Dual media filter* **Rapid sand filtration*	Ozonation	Activated carbon* **Biological activated carbon filtration*	Activated carbon* **Granular activated carbon filtration*	Activated carbon* **Powdered activated carbon dosage*	Ultrafiltration	Chlorine dioxide* **Cl_2*

No	Case study (Reference)	Name	Process description	Unit Processes 1	2	3	4	5	6	7	8	9	10	11
8d	Example from California re-using water to produce boiler water (steam for the power station turbines) for industrial purposes (AQUAREC, 2006).	**High quality-USA I**	The Reclamation plant in El Segundo (California, USA) treats the secondary effluent from Los Angeles Hyperion WWTP to produce four types of drought proof reclaimed water. One of the streams is ultra-pure reclaimed water produced by a double membrane system (microfiltration and reverse osmosis) for the use as boiler feed water in the petroleum industry (AQUAREC, 2006).	Bar screen	Grit removal	Sedimentation with coagulant* *Coagulation and flocculation*	Flocculation	Dual media filter* **Filtration not further specified*	Chlorine dioxide* **Chlorination not further specified*	Microfiltration	Reverse osmosis			
8e	Emmen WWTP (The Netherlands), Reuse of municipal WWTP effluent to ultrapure water for the production of steam (http://nwtr.nl/du/puurwaterfabriek.php).	**High quality-The Netherlands**	Conventional WWTP for municipal wastewater is treated in several membrane processes to produce ultra-pure water. This water is suitable for production of stream without leaving behind deposits that can damage boilers, turbines and pumps. The capacity of the plant is 10,000 m^3/day (http://nwtr.nl/du/puurwaterfabriek.php).	Bar screen	Grit chamber	Sedimentation without coagulant	Low Loaded Activated Sludge w de-N + Sec. Sedim.	Dual media filter* *Rotary filter	Ultrafiltration	Activated Carbon	Reverse osmosis	Electriodialysis		
8f	One of the largest in-building recycling schemes for reclaiming water in Europe (Greenwich, United Kingdom) for toilet and urinal flushing. Daily around 500 m^3 water is reclaimed (AQUAREC, 2006).	**High quality-United Kingdom**	The Millennium Dome reclaims water consisting of greywater (10%), rain water (19%) and groundwater (71%). Several technologies from very innovative membrane treatment to natural wetlands are utilized to reclaim the water. Rain water is treated by 2 reedbeds and a storage lagoon. In the reed bed, Phragmites auralies remove contaminants from the rainwater (filtration and biological process). Greywater is treated by a biological aerated filter (BAF) and groundwater is held in contact with hydrogen peroxide, and granular activated carbon (GAC). In the final step greywater, rainwater and groundwater are passed through an ultrafiltration and reverse osmosis membrane and are finally disinfected by chlorine (AQUAREC, 2006).	Trickling filter with secondary sedimentation* ** BAF*	Activated carbon* ** GAC*	Constructed wetland	Ultrafiltration	Reverse osmosis						
8g	Groundwater recharge with reclaimed water in Orange County, US (Asano, et al., 2006).	**High quality USA II**	Orange county water district Groundwater replenishment system: Supplemental water sources for groundwater recharge include the Colorado River and the Sacramento River, delivered to southern California. Santa Ana River water, along with the imported water, is recharged using deep recharge basins. The recharged water is subsequently pumped and serves as the water supply for a large portion of the county population. The GWR system produces approximately 1.73 × 108 m^3/yr) of advanced treated reclaimed water. The GWR system consists of three major components: the Advanced Water Treatment Facility (AWTF) and pumping stations, a 21 km pipeline connecting the AWTF to existing groundwater recharge basins, and the expansion of the existing seawater intrusion barriers with additional injection and monitoring wells. The AWTF process includes microfiltration, cartridge filtration, RO, lime addition, and UV/H2O2 advanced oxidation treatment. The product water will then be introduced into the existing surface spreading basins along with water from other sources. The blended water will be percolated into the groundwater aquifers, where it eventually becomes part of Orange County's drinking water supply (Asano et al., 2006).	Bar screen	Grit Chamber	Sedimentation without coagulant	Low Loaded Activated Sludge w/o de-N + Sec Sedim.	Microfiltration	Reverse osmosis	Advanced oxidation process	Soil-aquifer treatment			

APPENDIX IX POSEIDON – COST ESTIMATION TABLES

The content of this appendix has been published as supplementary material to the publication presented in Appendix I (Emmanuel Oertlé et al., 2019), publicly available on the Zenodo repository: Oertlé, Emmanuel. (2018). Wastewater Treatment Unit Processes Datasets: Pollutant removal efficiencies, assessment criteria and cost estimations (Version 1.0.0) [Data set]. Zenodo. http://doi.org/10.5281/zenodo.1247434.

This dataset provides data on typical pollutant-removal efficiencies, assessment criteria and cost estimation for 37 common wastewater treatment unit processes. The data is based on literature research, expert workshops, and estimations. The following files are available:

- cost estimations for wastewater treatment unit processes (dataset) (Microsoft Excel file), and
- cost estimation for wastewater treatment unit processes (dataset) (as a PDF).

The data in the table below are based on the simulations and regressions performed with WTRNet (Joksimović, 2006) and additional work as described in Section 3.2.8. Each cost factor can be calculated with the equation $\boldsymbol{y = C \cdot Q^B}$, where $\boldsymbol{Q}$ = average flow [m^3/day], $\boldsymbol{y}$ = any cost component calculated (construction cost [1,000 USD2006], land requirements [ha], energy requirements [kWh/y], labor requirements [person-hour/month], other operation and maintenance [1,000 USD2006/y], and $\boldsymbol{C}$ and $\boldsymbol{B}$ are the coefficients in the table below.

Table 8-10: Poseidon – Cost Estimation Tables

Unit process	**Regression coefficient**	**Bar screen**	**Coarse screen**	**Grit Chamber**	**Equalization Basin**	**Sedimentation without coagulant**	**Sedimentation with coagulant**	**Anaerobic stabilization ponds**	**Activated sludge**	**Low Loaded Activated Sludge w/o de-N + Sec Sedim.**	**Low Loaded Activated Sludge w de-N + sec. Sedim.**	**High Loaded Activated Sludge + Sec. Sedim.**	**Extended aeration**	**Trickling filter with secondary sedimentation**	**Rotating biological contactor (RBC)**	**Stabilization ponds: Aerobic**	**Stabilization ponds: Facultative**	**Membrane bioreactor (MBR)**	**Constructed wetland**	**Enhanced biological phosphorus removal (EBPR)**
Constructi	**B**	0.512377	0.5138	0.446445	0	0.5146	0.468	0.896305	0	0.7209	0.7205	0.75104	0.75104	0.7361	0.7135	0.813302	0.844919	0.75	0.392608	0.522899

on cost	**C**	4.044137	6.40085	9.13003	0	16.16125	29.05172	0.301345	0	7.787028	8.217256	4.859582	4.859582	5.055175	4.56597	1.108493	1.050282	8.193527	9.716189	1.700555
Land requirements	**B**	0.516602	0.357506	0.400943	0	0.947658	1.018748	1.000779	0	0.987576	1.003578	1.06568	1.06568	0.98438	0.984624	1.365297	0.903106	0.972166	0.957868	0.964509
	C	0.000108	0.00014	0.000119	0	5.17E-06	1.42E-06	0.00031	0	3.05E-05	3.21E-05	1.91E-05	1.91E-05	1.38E-05	2.09E-06	5.56E-05	0.001703	7.5E-06	0.002216	4.92E-06
Energy requirements	**B**	0	0	1.007629	0	0.998126	0.998126	0	0	0.985572	1.000008	0.999984	0.999984	1	1	0	0	1	0.999962	1.000815
	C	0	0	4.135609	0	1.303594	1.303594	0	0	181.3654	183.3218	91.67819	91.67819	55	55	0	0	219	36.678	1.821608
Labor requirements	**B**	0	0	0	0	0	0.054688	0.424123	0	0.144917	0.144917	0.190664	0.190664	0.190664	0.19172	0.416493	0.945928	0.715122	0.238406	0
	C	4	4	8	0	8	12.84873	1.400421	0	159.8641	159.8641	87.21185	87.21185	87.21185	86.87102	0.12485	0.026548	1.154627	6.142528	0
Other O&M	**B**	0.487562	0.516725	0.443285	0.78685	0.525599	0.518036	0.860822	0	0.928824	0.921522	1.204618	1.204618	0.696239	1.12612	0.839442	0.796592	0.693806	0.615594	0.58907
	C	0.46051	0.623897	0.900323	0.17251	0.288647	1.562384	0.028052	0	0.076386	0.077983	0.008541	0.008541	0.490095	0.033488	0.034076	0.033291	1.047075	0.449722	0.05249
Unit process		**P-Precipitation**	**Denitrification**	**Dual media filter**	**Microfiltration**	**Ultrafiltration**	**Nanofiltration**	**Reverse osmosis**	**Activated Carbon**	**Ion exchange**	**Advanced oxidation process**	**Soil-aquifer treatment**	**Maturation pond**	**Flocculation**	**Electrodialysis**	**Ozonation**	**Chlorine gas**	**Chlorine dioxide**	**Ultraviolet disinfection**	
Construction cost	**B**	0.145001	0.145001	0.593608	0.600001	0.600001	0.844997	0.844997	0.880302	0.999991	0.650751	0.99993	0.798678	0.196785	0.999991	0.732601	0.639202	0.639202	0.739904	
	C	12.14062	12.14062	3.096288	5.764633	5.764633	1.012361	1.012361	1.520823	0.177783	1.541952	0.024184	0.408424	29.82688	0.177783	2.481176	4.154137	4.154137	1.946311	
Land requirements	**B**	0	0	0.288012	0.584242	0.584242	0.498218	0.498218	0.981242	1.000271	1.00844	0.913122	0.999307	-2.2E-32	1.000271	0.495343	0.316981	0.316981	0.876243	
	C	0.0075	0.0075	0.019249	0.000144	0.000144	0.000151	0.000151	2.68E-06	7.27E-06	1.43E-06	6.95E-06	0.00035	0.0033	7.27E-06	6.56E-05	0.004053	0.004053	2.72E-05	
Energy requirements	**B**	0.996376	0.996376	0.99987	0.999957	1	0.999976	1	1	0.950291	0.888885	1	0	1.000063	1	0.999974	0.999787	0.999787	1	
	C	0.377218	0.377218	27.40468	91.28175	109.5	164.2818	365	182.5	147.7337	1873.141	87.6	0	5.299073	1058.5	208.0859	18.28174	18.28174	87.6	
Labor requirements	**B**	0	0	0.055642	0.184421	0.184421	0.184421	0.184421	0.342606	0.236782	0.264711	0.054727	0.305671	0	0.236782	0.264711	0.302861	0.302861	0.303461	
	C	0	0	51.1519	57.01982	57.01982	57.01982	57.01982	10.22092	17.4136	13.85992	108.4598	2.504125	24	17.4136	13.85992	4.684957	4.684957	4.68509	
Other O&M	**B**	0.999459	0.999459	0.006866	1.072667	1.076042	1.353971	1.095594	0.824784	1.097682	1.265371	1.050556	0.842496	0.401581	1.097682	1.074854	0.566581	0.566581	1.149077	
	C	0.003026	0.003026	13.02714	0.015008	0.014016	0.001879	0.009753	0.180252	0.005254	0.002112	0.024053	0.026887	0.737011	0.005254	0.001872	0.652346	0.652346	0.000657	

APPENDIX X POSEIDON – WATER QUALITY PARAMETERS FOR VIETNAM

Section X.I: Water Quality Standards and Typical Wastewater Quality Considered

Table 8-11: Poseidon – Wastewater Quality Parameters for Vietnam

Parameters	Turb	TSS	BOD	COD	TN	TP	FC	TC	TDS	Ni-trate	TOC	Note / Reference
Units	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	CFU/100 ml	CFU/100 ml	mg/L	mg N/L	mg/L	
Vietnam Water Quality Standards												
Class A - discharge with drinking water function	-	100	50	150	40	6	-	-	-	10	5,000	Discharge to water bodies with a function of drinking water supply (Class A) .QCVN 40:2011
Class B - discharge without drinking water function	-	100	50	150	40	6	-	-	-	10	5,000	Discharge to water bodies without function of drinking water supply (Class B) QCVN 40:2011
Irrigation	-	-	-	-	-	-	200	-	2,000	-	-	QCVN 39: 2011/BTNMT
International Organization for Standardization (ISO) – BS ISO 16075-2:2015												**Guidelines for treated wastewater use for irrigation projects (ISO 16075-2 2015)**
Cat A Unrestricted urban irrigation and agricultural irrigation of food crops consumed raw	5	10	10	-	-	-	-	100	-	-	-	Cat. A: Very high quality treated wastewater
Cat. B: Restricted urban irrigation and agricultural irrigation of processed food crops	-	25	20	-	-	-	-	1,000	-	-	-	Cat. B: High quality treated wastewater
Cat. C: Agricultural irrigation of non-food crops	-	50	35	-	-	-	-	10,000	-	-	-	Cat. C: Good quality treated wastewater
Cat. D: Restricted irrigation of industrial and seeded crops	-	140	100	-	-	-	-	-	-	-	-	Cat. D: Medium quality treated wastewater
Cat. E: Restricted irrigation of industrial and seeded crops	-	-	35	-	-	-	-	-	-	-	-	Cat. E: Extensively quality treated wastewater
Texas water reuse standards												**(Example indicated in US EPA guidelines, 2012)**
Texas EPA: Industrial Reuse- Recirculating Cooling Towers	-	-	20.00	-	-	-	200.00	-	-	-	-	BOD: 20 mg/L without pond; 30 mg/L with pond Add. Parameter: Enterococci: 35 CFU/100 mL (max. 89 CFU/100 mL)
Typical Municipal Wastewater Vietnam												
Typical untreated MWW Vietnam	100	86	94	189	44	-	10,00	1E+0	720	18	140	Estimated, based on (World Bank 2013) and own

Parameters	**Turb**	**TSS**	**BOD**	**COD**	**TN**	**TP**	**FC**	**TC**	**TDS**	**Ni-trate**	**TOC**	**Note / Reference**
Units	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	CFU/100 ml	CFU/100 ml	mg/L	mg N/L	mg/L	
							0	7				estimations.
Typical treated wastewater Vietnam	2	6	11	22	16	-	-	10,000	500	3	10	Estimated, based on (World Bank 2013) and own estimations.
Typical Industrial Park Wastewater Vietnam												
Typical IP Effluent – before treatment	-	200	200	400	60	8	-	3,000	-	-	-	Thuan Dao Industrial Zone, The People's Committee of Long An Province. 2011. The Preparatory Survey on Utility Management of Environment-Friendly Industrial Parks in Vietnam.
Typical IP Effluent – after treatment	-	49.5	29.7	49.5	14.85	3.96	-	3,000	-	-	-	Thuan Dao Industrial Zone, The People's Committee of Long An Province. 2011. The Preparatory Survey on Utility Management of Environment-Friendly Industrial Parks in Vietnam.
Hanoi Municipal Wastewater												
Hanoi, Influent (Best quality)	-	51	45	115	34	-	-	-	-	18	-	(World Bank 2013)
Hanoi, Influent (Worst quality)	-	91	94	189	44	-	-	-	-	28	-	(World Bank 2013)
Hanoi, Effluent (Best quality)	-	5	9	17	8	-	-	-	-	0.5	-	(World Bank 2013)
Hanoi, Effluent (Worst quality)	-	10	12	24	16	-	-	-	-	0.5	-	(World Bank 2013)
Ho Chi Minh City Municipal Wastewater												
Ho Chi Minh City, Influent (Best quality)	-	49	42	135	11	-	-	-	-	18	-	(World Bank 2013)
Ho Chi Minh City, Influent (Worst quality)	-	103	78	203	11	-	-	-	-	18	-	(World Bank 2013)
Ho Chi Minh City, Effluent(Best quality)	-	7	3	30	7	-	-	-	-	3.3	-	(World Bank 2013)
Ho Chi Minh City, Effluent(Worst quality)	-	18	10	50	7	-	-	-	-	3.3	-	(World Bank 2013)
Da Nang Municipal Wastewater												
Da Nang, Influent (Best quality)	-	28	34	64	16	-	-	-	-	-	-	(World Bank 2013)
Da Nang, Influent (Worst quality)	-	73	101	178	28	-	-	-	-	-	-	(World Bank 2013)
Da Nang, Effluent (Best quality)	-	16	26	47	13	-	-	-	-	-	-	(World Bank 2013)
Da Nang, Effluent (Worst quality)	-	23	38	76	21	-	-	-	-	-	-	(World Bank 2013)
Quang Ninh Municipal Wastewater												

Parameters	**Turb**	**TSS**	**BOD**	**COD**	**TN**	**TP**	**FC**	**TC**	**TDS**	**Ni-trate**	**TOC**	**Note / Reference**
Units	NTU	mg/L	mg/L	mg/L	mg/L	mg/L	CFU/100 ml	CFU/100 ml	mg/L	mg N/L	mg/L	
Quang Ninh, Influent (Best quality)	-	41	36	68	0.1	-	-	-	-	1.1	-	(World Bank 2013)
Quang Ninh, Influent (Worst quality)	-	195	45	80	0.1	-	-	-	-	1.3	-	(World Bank 2013)
Quang Ninh, Effluent (Best quality)	-	11	20	32	0.2	-	-	-	-	1	-	(World Bank 2013)
Quang Ninh, Effluent (Worst quality)	-	35	23	68	0.2	-	-	-	-	1	-	(World Bank 2013)

Notes: "Turb" stands for "Turbidity", "TSS" stands for "Total suspended solids", "BOD" stands for "Biological oxygen demand", "COD" stands for "Chemical oxygen demand", "TN" stands for "Total nitrogen", "TP" stands for "Total phosphorous", "FC" stands for "Fecal coliform", "TC" stands for "Total coliform", "TDS" stands for "Total dissolved solids", "TOC" stands for "Total organic carbon".

Section X.II: Wastewater Quality Compliance with Different Water Quality Standards and Regulations (+ for Compliant, - for Non-Compliant)

Table 8-12: Poseidon – Water Quality Parameters for Vietnam

	Vietnam water quality standards (WQS)			International Organization for Standardization (ISO) – BS ISO 16075-2:2015					Texas water reuse standards
	Class A - discharge with drinking water function	Class B - discharge without drinking water function	Irrigation	Cat A Unrestricted urban irrigation and agricultural irrigation of food crops consumed raw	Cat. B: Restricted urban irrigation and agricultural irrigation of processed food crops	Cat. C: Agricultural irrigation of non-food crops	Cat. D: Restricted irrigation of industrial and seeded crops	Cat. E: Restricted irrigation of industrial and seeded crops	Texas EPA: Industrial Reuse- Recirculating Cooling Towers
Typical Municipal Wastewater Vietnam (10,000 m^3/day)									
Typical untreated MWW Vietnam	-	-	-	-	-	-	+	-	-
Typical treated wastewater Vietnam	+	+	+	-	-	-	+	+	+
Typical Industrial Park Wastewater Vietnam (1,000 m^3/day)									
Typical IP Effluent – before treatment	-	-	+	-	-	-	-	-	-
Typical IP Effluent – after treatment	+	+	+	-	-	+	+	+	-
Hanoi Municipal Wastewater (2,500–200,000 m^3/day)									
Hanoi, Influent (Best quality)	-	-	+	-	-	-	+	-	-
Hanoi, Influent (Worst quality)	-	-	+	-	-	-	+	-	-
Hanoi, Effluent (Best quality)	+	+	+	+	+	+	+	+	+
Hanoi, Effluent (Worst quality)	+	+	+	-	+	+	+	+	+
Ho Chi Minh City Municipal Wastewater (10,000–140,000 m^3/day)									
Ho Chi Minh City, Influent (Best quality)	-	-	+	-	-	-	+	-	-
Ho Chi Minh City, Influent (Worst quality)	-	-	+	-	-	-	+	-	-
Ho Chi Minh City, Effluent(Best quality)	+	+	+	+	+	+	+	+	+
Ho Chi Minh City, Effluent(Worst quality)	+	+	+	-	+	+	+	+	+
Da Nang Municipal Wastewater (11,000–36,000 m^3/day									

Da Nang, Influent (Best quality)	-	+	+	-	-	+	+	+	-
Da Nang, Influent (Worst quality)	-	-	+	-	-	-	-	-	-
Da Nang, Effluent (Best quality)	+	+	+	-	-	+	+	+	-
Da Nang, Effluent (Worst quality)	-	+	+	-	-	-	+	-	-
Quang Ninh Municipal Wastewater (3,500–7,500 m^3/day)									
Quang Ninh, Influent (Best quality)	-	+	+	-	-	-	+	-	-
Quang Ninh, Influent (Worst quality)	-	-	+	-	-	-	-	-	-
Quang Ninh, Effluent (Best quality)	+	+	+	-	-	+	+	+	-
Quang Ninh, Effluent (Worst quality)	+	+	+	-	-	+	+	+	-

APPENDIX XI WATER UTILITY COMPASS - WATER UTILITY EFFICIENCY ASSESSMENT QUESTIONNAIRE

Table 8-13 is adapted from two main references (Charalambous, 2014; Malcolm Farley et al., 2010), with the addition of personal content and editing.

Table 8-13: Water Utility Compass - Water Utility Efficiency Assessment Questionnaire

Issues / Questions [Reference]	**Efficiency Level 1** (poor)	**Efficiency Level 2** (fair)	**Efficiency Level 3** (average)	**Efficiency Level 4** (good)	**Efficiency Level 5** (excellent)
1. Data & Metering					
1.1 Customer Metering (Malcolm Farley et al., 2010)	We have no customer metering.	Only large customers are metered.	We have started with universal customer meters, but at present not all customers have meters installed.	Nearly all customers are metered, except public fountains, standpipes and similar.	100% of customers are metered.
1.2 Customer Meter Replacement and Age (Malcolm Farley et al., 2010)	We have no reliable information on the age of our customer meters.	Many of our customer meters are older than 10 years. We have not yet introduced a regular replacement policy.	We only change meters if they are obviously not functioning anymore.	We have a meter replacement policy but have not been able to change all meters, hence some of the customer meters are still older than 10 years.	We strictly follow our customer meter replacement policy and replace all meters every 5–7 years.
1.3 Customer Meter Class (Malcolm Farley et al., 2010)	All customer meters are class A or B.	All customer meters are class B or C.	All customer meters are Class C.	All customer meters are Class C or D.	All customer meters are Class D.
1.4 Customer Database (Malcolm Farley et al., 2010)	Customer database has not been updated for a long time.	Customer database is sporadically updated.	The customer database is in the process of being updated.	Customer database is regularly updated by house to house surveys and checks.	Customer database is updated and linked to the GIS.
1.5 System Input Metering (Malcolm Farley et al.,	Most of our system input is not metered.	Not all, but more than 50% of our system input is	Our system input is metered but we are not sure	We use mechanical and/or magnetic flow	We use magnetic flow meters that are regularly

Issues / Questions [Reference]	**Efficiency Level 1** (poor)	**Efficiency Level 2** (fair)	**Efficiency Level 3** (average)	**Efficiency Level 4** (good)	**Efficiency Level 5** (excellent)
2010)		metered.	about the accuracy of these (partly old) meters.	meters that are rarely calibrated for the metering.	calibrated.
2. Network Documentation					
2.1 Maps/Geographic Information Systems (GIS) (Malcolm Farley et al., 2010)	We do not have maps at all.	The maps we have are not updated.	We have started to update our maps.	Our maps are updated but do not include GIS.	We use GIS based on updated maps.
2.2 Intervention Documentation	We do not report interventions.	Mostly, we do not report interventions.	We only partly report interventions.	We mostly report interventions.	We have detailed reports containing information about location, pipes characteristics, valves, pumps, service connections, meters, etc.
2.3 Failure Database	We do not apply a failure database.	Between 1 and 3	We apply a failure database but do not perform statistical analysis or link failure rate with system pressure.	Between 3 and 5	We apply a failure database, perform statistical analysis and visualization of failures and link failure rates with system pressure.
2.4 Hydraulic Model	We do not use a hydraulic network model.	We use a hydraulic network model but do not link it to the network register. Our model is not calibrated and verified and rarely updated.	We also link the hydraulic network model to the network register.	We also occasionally calibrate, verify and update our model.	We link the model to the (GIS based) network register and calibrate, verify and update it in regular intervals.
2.5 Customer Information System (CIS)	We do not have a CIS.	We have some basic customer information on our CIS.	We have good information on our CIS but do not link it to our GIS.	We have good information on our CIS and link it to our GIS.	We interconnect and link the customer information system components (e.g. customer database) to our GIS.
3. Water Balance & Performance Indicators (PI)					
3.1 Water Balance (Malcolm Farley et al.,	We do not establish a water balance.	We have tried to establish a water balance but gave	We establish a water balance following our own	We establish an annual water balance in accord-	We establish an annual water balance in accord-

Issues / Questions [Reference]	**Efficiency Level 1** (poor)	**Efficiency Level 2** (fair)	**Efficiency Level 3** (average)	**Efficiency Level 4** (good)	**Efficiency Level 5** (excellent)
2010)		up in the middle of the way.	format.	ance with the international (IWA) format.	ance with the international (IWA) format and also use the 95% confidence limits.
3.2 Data Accuracy and Reliability	We do not determine accuracy and reliability of our water balance data.	We determine accuracy and reliability of our water balance but often use recommended values instead. Data accuracy and reliability is low.	We determine accuracy and reliability of our water balance but use some recommended values. Data accuracy and reliability is moderate.	We perform lots of investigations and samples and use them in our loss computations. The accuracy and reliability of the data is modest.	We perform lots of investigations and samples and thus have specific data regarding our apparent and real losses. Data accuracy and reliability is high.
3.3 Cross Check WB with Bottom-Up Analysis	We do not establish a bottom up analysis.	We establish a bottom-up analysis but do not compare it with the top-down approach or the accordance between them is very low.	We establish a bottom up analysis based on MNF-analysis and compare it with the top-down approach. The accordance between these two methods is low.	The accordance between the bottom-up and top-down approach is acceptable.	The accordance between the two methods is good.
3.4 Performance Indicators (Malcolm Farley et al., 2010)	The only PI used is percentage NRW.	We have tried to calculate NRW performance indicators other than percentage.	We regularly calculate real losses performance indicators.	We regularly calculate real and apparent losses performance indicators. We tried to calculate the ILI but do not use it.	We regularly calculate real and apparent losses performance indicators, and publish them in our annual report. We use the ILI for benchmarking.
4. District Metered Areas (DMA)					
4.1 District Meter Areas (DMAs) (Malcolm Farley et al., 2010)	We have no DMAs and have no plans to establish DMAs.	We have some zones or sectors but those are not always well-isolated and metered.	The first DMAs are established and we already have the first results.	We have several DMAs and analyze inflow data sporadically.	We have several DMAs and we monitor flow and pressure on a regular basis.
4.2 DMA Quality	DMA Quality	Between 1 and 3	We do not check boundary valves. DMA boundaries follow not natural boundaries. Flow meters and PRVs are often not correct sized and in-	Between 3 and 5	Boundary valves are checked partly. DMA boundaries follow mainly natural boundaries. Flow meters and PRVs are partly correct sized and in-

Issues / Questions [Reference]	**Efficiency Level 1** (poor)	**Efficiency Level 2** (fair)	**Efficiency Level 3** (average)	**Efficiency Level 4** (good)	**Efficiency Level 5** (excellent)
			stalled.		stalled.
4.3 DMA Quality: Customers	The type of consumers (e.g. domestic, industrial, commercial, etc.) and their respective water supply requirements are not assessed.	Between 1 and 3	Different types of consumers and their respective requirements are partially assessed.	Between 3 and 5	We have assessments of the requirements for each type of consumer in our network.
4.4 Size of the DMAs	Most of our DMAs contain less than 500 or more than 3,000 service connections and the length of distribution pipes is often outside the range of 4km to 30km.	Many of the DMAs are outside those ranges.	Some of our DMAs do not match those numbers.	Only a few DMAs do not fit those requirements.	All our DMAs contain 500–3,000 service connections and the total length of distribution pipes is between 4 and 30km.
5. Active Leakage Control (ALC)					
5.1 Leak Repair Records (Malcolm Farley et al., 2010)	We have no records of leak repairs.	The only way to know the number of leaks repaired is to look into the customer complaints book.	We keep basic leak repair records that only tell us whether the leak was on main pipe or service connection.	We keep basic leak repair records that indicate location, pipe diameter, material and type of leaks as well as date of detection and date and duration of repair.	Additionally, we have linked all this data to our GIS.
5.2 Active Leakage Control Methods	We perform only few Active Leak Control methods.	Between 1 and 3	We perform some of ALC methods.	Between 3 and 5	We apply several modern methods for awareness (e.g. pressure monitoring), leak detection (e.g. leak noise loggers) and leak localization (e.g. leak-noise-correlation).
5.3 Active Leakage Control and Repair Material	Our active leakage control and repair equipment is outdated and thus it is difficult to maintain an effective intervention	Between 1 and 3	Our ALC equipment is partly replaced by new devices but still only partly meets the requirements.	Between 3 and 5	We use up-to-date equipment of high quality (e.g. listening sticks, ground microphones, noise loggers).

Issues / Questions [Reference]	**Efficiency Level 1** (poor)	**Efficiency Level 2** (fair)	**Efficiency Level 3** (average)	**Efficiency Level 4** (good)	**Efficiency Level 5** (excellent)
	program.				
5.4 Active Leakage Control (Malcolm Farley et al., 2010)	We only repair visible leaks.	We have leak detection equipment but we do not use it.	We do leak detection occasionally if there is a specific problem in an area.	We have started to do regular leak surveys.	We cover the network by leakage survey at least once a year.
5.5 Leak Detection Team and Training	We do not have a special leak detection team. The people we deploy for leak detection are not skilled or educated/trained.	Between 1 and 3	We established a leak detection team.	Between 3 and 5	We established a very skilled leak detection team focused solely on leak detection activities and perform regularly training programs.
5.6 Leak Repair Activities (Charalambous, 2014)	We have limited abilities & capacities for repair of water mains. It takes a long time to do and often starts leaking again.	We have the basic skills for network maintenance. Long delays and the quality of repairs are a problem.	We have good skills for network repair. It is generally done in a timely fashion.	Out staff is very skilled and committed to network repair. We only occasionally have ongoing problems.	Our staff has excellent skills in the area of network repair. Repairs are undertaken swiftly, minimizing water loss.
5.7 Repair Time: Distribution Pipes (Malcolm Farley et al., 2010)	We have no records and therefore do not know how fast leaks are repaired.	Our average repair time is more than 7 days.	Our average repair time is between 7 and 3 days.	Our average repair time is between 3 and 1.5 days.	Our average repair time is less than 1.5 days.
5.8 Repair Time: House Connections (Service Connections) (Malcolm Farley et al., 2010)	We have no records and therefore do not know how fast leaks are repaired.	Our average repair time is more than 14 days.	Our average repair time is between 14 and 7 days.	Our average repair time is between 7 and 2 days.	Our average repair time is less than 2 days.
6. Pressure Management (PM)					
6.1 Pressure Monitoring (Malcolm Farley et al., 2010)	We do not have any pressure recorders installed.	We have a few pressure recorders at pumping stations and treatment plants installed.	Additionally, we sporadically measure pressure in the distribution network with pressure gauges.	We use pressure loggers instead to check the distribution network.	We have permanently installed pressure loggers and continuously monitor pressure in the distribution network.
6.2 Pressure Management	We don't manage the pressure and are not aware of the potential for pressure management.	We are aware of the potential for pressure management but don't apply it yet.	We apply pressure management within some of the most relevant DMAs.	We apply pressure management in most our DMAs.	We have pressure management everywhere and perform intensive functional tests of the system.

Issues / Questions [Reference]	**Efficiency Level 1** (poor)	**Efficiency Level 2** (fair)	**Efficiency Level 3** (average)	**Efficiency Level 4** (good)	**Efficiency Level 5** (excellent)
6.3 Pressure Management Areas (PMAs)	We do not use hydraulic modelling for our PMAs.	Between 1 and 3	We partly use hydraulic modelling for our PMAs.	Between 3 and 5	We perform hydraulic modelling to identify optimal pressure management areas (PMAs) by running simulations.
6.4 Pressure Management Equipment Quality	Our pressure management equipment is old and does not enable the implementation of successful pressure management.	Most of our pressure management equipment is outdated and inoperable.	We are equipped with adequate pressure management equipment, but a part of the equipment is too old.	Most of our pressure management equipment is modern with high functional quality.	We use modern equipment like Pressure reducing valves, flow meters, pressure sensors, isolating valves, dismantling piece and control cabinet.
6.5 Pressure Reducing Valves (PRVs)	All our PRVs are out of date and we don't invest much time and money in their maintenance.	Most of our PRV's are out of date.	From time to time we check the function of the PRVs and also maintain them but not really consider their usage in our network.	We regularly check the function of our PRVs and maintain them but we not plan thoroughly the use of diaphragm and plunger valves.	We regularly check the function of our PRVs and maintain them. We carefully plan the use of diaphragm and plunger valves based on their advantages and disadvantages.
7. Infrastructure Management (IM)					
7.1 Estimation of Future Pipe Rehabilitation and Replacement Requirement	We do not prepare any estimates for future pipe renewal requirements and only deal with it when it becomes a problem.	In a few problematic pipelines we have undertaken investigations to prepare replacement proposals.	We have good estimates of pipeline renewal requirements based on construction dates, pipe materials, asset life (engineering estimate).	Asset live estimations of different categories of pipes are based on observed trends of leak repair records.	Based on our pipe performance and maintenance history combined with appropriate forecasting techniques, we have a detailed pipe renewal strategy.
7.2 Data Collection	We do not collect any data about our infrastructure. We only repair devices after failure.	We collect limited data about our infrastructure. The collected data represent only a minor assistance for infrastructure management.	We collect data about our infrastructure but have a limited survey about age status and functionality of our material.	We collect data about our infrastructure and have detailed information about age status and functionality of our material.	We collect a lot of data about repair history, age and size of devices, construction material, location, installation date, operating pressure and maintenance.

Issues / Questions [Reference]	Efficiency Level 1 (poor)	Efficiency Level 2 (fair)	Efficiency Level 3 (average)	Efficiency Level 4 (good)	Efficiency Level 5 (excellent)
7.3 Infrastructure Maintenance	We perform rarely maintenance of our infrastructure and do not implement pressure management.	We rarely perform maintenance of our infrastructure and started deploying pressure management.	We perform maintenance of our infrastructure from time to time and deploy pressure management only partly.	We perform maintenances fairly often of our material and deploy pressure management.	We perform the maintenance regularly. With that we can prolong lifetime and decelerate functional deterioration.
7.4 Quality Inspections	We do not perform any inspections or surveys regarding quality of our infrastructure.	We only rarely perform inspections/surveys of our infrastructure and evaluate its quality.	We perform inspections/surveys of our infrastructure and evaluate its quality regularly. However, we remedy only the largest deficiencies.	Using the results we often remove shortcomings fast.	We repair/sort any infrastructure with shortcomings.
7.5 Infrastructure Performance Indicators	We do not use performance indicators to describe the functionality and investment efficiency of our infrastructure.	We use only few PIs for our infrastructure and have incomplete information regarding functionality or financial investments.	We use several performance indicators.	Using the PIs we are mostly able to receive information about technical functionality and financial investments.	We deploy a broad set of PIs. Using them, we can discover our technical or financial weak points.
7.6 Cost-Benefit Analysis	We do not perform a cost-benefit analysis. Our maintenance activity is low and replacement is only accomplished when the material does not work anymore.	We rarely use cost-benefit analysis for our decisions regarding the realization of measures or ratio of maintenance/replacement.	For some groups of material we carry out a cost-benefit analysis and are able to determine the optimum degree of maintenance and serviced life time.	We often develop cost-benefit analyses which is a help for our action planning and to find the optimal ratio of maintenance/replacement.	We determine the expected service life and perform a life cycle cost analysis for each group of materials to compute the optimal cost-benefit relationship.
7.7 Consideration of Social Costs (e.g. health damage, water-borne diseases, property damage, etc.)	We do not care about social costs. We disagree to have financial disadvantages in order to decrease the social costs.	We care about social costs but we do not accept financial unprofitable measures in order to reduce social costs.	We care about social costs and sometimes accept financial unprofitable measures in order to reduce social costs.	We care about social costs and we try to reduce them to a minimum if possible. In financial scarcity situation, we accept social costs.	We care about social costs. In order to minimize these costs we have very strict quality standards and replace materials earlier than required, economically.
8. Operation & Maintenance					
8.1 Operation Basics	The working processes are often not clear. Working	There are misunderstandings and working process-	Information exchange and the organization structure	We have a well-functioning organization.	All working processes are clear and transparent and

Issues / Questions [Reference]	**Efficiency Level 1** (poor)	**Efficiency Level 2** (fair)	**Efficiency Level 3** (average)	**Efficiency Level 4** (good)	**Efficiency Level 5** (excellent)
	steps are often not efficient and there are a lot of call backs. The information exchange is lacking.	es are not always clear and hence are conducted inefficiently.	is only exemplary within some departments, but not in the whole utility.	Working processes are mostly clear and transparent and are discussed in advance.	are discussed in advance. Every employee knows what to do and is informed about the procedure.
8.2 Specialized Teams and Training	We do not have specialized teams and training programs.	We do not have specialized teams and the offer of training programs is small.	For some tasks we have specialized teams including training programs.	For most of our tasks we have specialized teams with regular conducted training programs.	For each task we have a specialized team and regularly training programs.
8.3 Efficient Procedure	Procedures are badly organized and the information exchange is lacking and not documented.	Between 1 and 3	Some tasks are well organized but there is improving potential regarding information exchange and documentation/communication of the procedure.	Between 3 and 5	The operational procedures are organized efficiently among all involved departments and are well documented.
8.4 Type of Intervention (Preventive or Event-Driven)	We only replace our material after failure events.	We rarely implement preventive interventions, mostly we replace our material after failure.	We only implement preventive interventions if the risk potential for larger damage after a possible failure event is too high.	We normally try to implement preventive interventions, nevertheless we cannot prevent some failure events with end-of-pipe measures.	According to our knowledge about service life time of each material group we replace preventive our equipment before failure will occur.
8.5 Prioritization of Measures	We perform leak repairs arbitrary.	There is in most cases no implemented prioritization of leaks.	We partly, before leaks are repaired a prioritization is implemented, give higher priority for larger sized leaks.	Leak repairs are often prioritized according to the size of the leaks.	Leak repairs are prioritized according to the size of the leaks and considering the security of supply throughout the whole system.
8.6 Customer Complaints	We do not react to customer complaints and change nothing.	We rarely react to customer complaints and feel not responsible to change anything.	We only react to customer complaints if it is not associated with a large time and financial effort.	We mostly react to customer complaints and take them seriously.	We monitor customer complaints and take actions against them.
8.7 Maintenance Frequency	We do not maintain our equipment. Our equip-	We rarely maintain our equipment.	In most cases the maintenance frequency of our	For most equipment groups regular mainte-	We maintain our equipment in regular intervals,

Issues / Questions [Reference]	**Efficiency Level 1** (poor)	**Efficiency Level 2** (fair)	**Efficiency Level 3** (average)	**Efficiency Level 4** (good)	**Efficiency Level 5** (excellent)
	ment is old and deteriorated.		equipment is adequate, but in some cases a more frequent maintenance is desired.	nance intervals are implemented.	at least if a rapid replacement is favored in an economic, social and ecologic point of view.
8.8 Maintenance Quality	Our equipment for maintenance is of low quality and we cannot maintain our infrastructure properly. In addition, our employees are not well skilled.	Performed maintenance is not based according to present day knowledge. Equipment is outdated and employees not special skilled.	We try to improve maintenance regarding quality, but are limited through lack of modern equipment and skilled employees.	For most equipment groups and most times, we take care about maintenance work, use modern equipment and have special skilled employees for it.	We take care about maintenance work, use modern equipment and have special skilled employees for it.
9. Apparent Losses					
9.1 Meter Installing	We do not expand our meter park. Unmetered areas remain unmetered.	We install some meters in unmetered areas but often do not calibrate and install them correctly.	We install some meters in unmetered areas and generally calibrate and install them correctly.	For most of the unmetered connections we install new water meters. Calibration and installation of the meters are mainly correct.	We install new meters at unmetered connections and take care to calibrate and install our meters correctly.
9.2 Meter Accuracy Testing	We do not perform meter quality surveys.	We only rarely perform meter quality surveys.	From time to time we undertake meter accuracy tests. We often repair/replace defected meters, if we have the financial resources.	We often check functionality of our water meters and repair/replace most of the defected meters.	We regularly check functionality of our water meters and repair/replace defected meters.
9.3 Fraud: Illegal Connections, Meter Tampering, Bypasses (Malcolm Farley et al., 2010)	No assessment is made and there is no program to deal with water theft.	Illegal connections are occasionally detected.	Illegal connections and other forms of fraud are occasionally detected.	There is thorough illegal connections detection program in place.	There is a thorough illegal connections detection program in place, and bypasses are also tried to be identified.
9.4 Meter Reading and Data Transfer (Charalambous, 2014; Malcolm Farley et al., 2010)	There is no special system of controlling meter readers (meter rotation, check for errors, etc.) and are not equipped with hand	Meter readers are rotated if we suspect inaccuracies. The readers are not equipped with hand held devices and are not regis-	We rotate the meter readers regularly. Not all of them are equipped with hand held devices and registered.	Besides being regularly rotated most readers are checked for errors. The readings are registered using hand held devices.	We rotate our meter readers regularly and they are checked for errors by the billing department. The readings are regis-

Issues / Questions [Reference]	**Efficiency Level 1** (poor)	**Efficiency Level 2** (fair)	**Efficiency Level 3** (average)	**Efficiency Level 4** (good)	**Efficiency Level 5** (excellent)
	held devices and are not registered.	tered.			tered using hand held devices.
10. Human Resources					
10.1 Qualified Personnel	Our percentage of highly qualified people is very low (< 5%).	Our percentage of highly qualified people is low (5–10%).	Our percentage of highly qualified people is moderate (10–15%).	Our percentage of highly qualified people is high (15–20%).	We have a very high fraction of highly qualified employees (>20%).
10.2 Specialized NRW-Teams	We do not have skilled and specialized teams for water-loss reduction programs.	Mainly we cannot deploy specialized teams fighting against water losses.	Sometimes we can deploy specialized NRW-teams.	For most NRW-programs we have our own specialized teams.	For different tasks fighting against NRW (e.g. Active Leakage Control, Pressure Management etc.) we have own specialized teams.
10.3 Employee Density	We have less than 10 employees per 1,000 service connections in action.	We have 10–30 employees per 1,000 service connections in action.	We have 30–60 employees per 1,000 service connections in action.	We have 60–100 employees per 1000, service connections in action.	We have more than 100 employees per 1,000 service connections in action.
10.4 Training and Incentives	We do not offer any training programs and do not reward good work.	We offer only few training programs without incentive for good work.	For some specialized teams training programs are offered but we do not have a bonus system.	Besides training programs in most categories we started a bonus system.	We offer training programs in each water-loss category. We motivate our employees for good working by offering incentives.
11. Equipment and Budget					
11.1 Budget for water-loss reduction (WLR): Quantity	Our budget for WLR is very low compared to other business in our utility.	Our budget for WLR is low compared to other business in our utility.	Our budget for WLR is moderate compared to other business in our utility.	Our budget for WLR is high compared to other business in our utility.	Our budget for WLR is very high compared to other business in our utility.
11.2 Budget for WLR: Development	Our budget for WLR has significant decreased / Our budget for WLR developed much less compared with other tasks.	Our budget for WLR has decreased / Our budget for WLR developed less compared with other tasks.	The budget for WLR developed roughly in the same proportion as for other tasks in the last years.	Compared to other tasks our budget for WLR increased in the last few years.	Compared to other tasks our budget for WLR increased very strongly in the last few years.
11.3 WLR Equipment	The equipment for our workers is outdated and	The equipment for our workers is often outdated	We provide our worker with contemporary	Usually, our workers are provided with modern	All our workers are provided with modern and

Issues / Questions [Reference]	**Efficiency Level 1** (poor)	**Efficiency Level 2** (fair)	**Efficiency Level 3** (average)	**Efficiency Level 4** (good)	**Efficiency Level 5** (excellent)
	does not fulfill functional/technical/ safety requirements.	and does not fulfill functional/ technical/safety requirements.	equipment if possible, but it sometimes does not comply with our requirements.	and complete assortment of equipment, both functional, technical as well as relating to safety.	complete assortment of equipment.
11.4 Spare Parts	We have virtually no spare parts. Defected materials are replaced very slow and inaccurate.	We have only a minor assortment of spare parts and their exchange for defected equipment is often inefficient.	We have spare parts of our equipment to some extent, exchange efficiency of defected equipment could be better.	For most of our equipment we have a broad assortment of spare parts. The exchange of defected material with such spare parts is efficient.	For all our equipment we have a broad assortment of spare parts. The exchange of defected material with such spare parts works swiftly and flawless.
11.5 Vehicles	Our fleet of vehicles is by far too small and does not enable a quick processing of our transport requirements. Vehicles are often in defective conditions.	Our fleet of vehicles is too small and generally does not enable a quick processing of our transport requirements.	In most cases, our fleet of vehicles is sufficient but sometimes there are shortages in transport resulting in supply delay.	We have a broad assortment of efficient vehicles and rarely transport/supply problems.	Our vehicles allow us to quickly enable and efficiently process our transport requirements. The vehicles are in good conditions.
12. Organisation					
12.1 Use of Standard Operating Procedure (SOP)	We do not use Standard Operating Procedure (SOP) in order to achieve uniformity of the performance of a specific function.	Between 1 and 3	We sometimes use SOP but do not update them regularly.	Between 3 and 5	We have an SOP for all high-class processes. We consider the structure of the SOP´s carefully and update them regularly.
12.2 Communication	There are often disagreements and unclear instructions resulting in misunderstandings and inefficient work.	Between 1 and 3	From time to time there are disagreements and unclear instructions resulting in misunderstandings and inefficient work.	Between 3 and 5	We have an exemplary communication system within the whole utility. There is a good information exchange within the different layers but also within the layers.
12.3 Relationship	Our employees are often in a bad temper, they are not friendly to each other and there is mistrust be-	Between 1 and 3	The relations of employees within a layer are good. There is a generally good working climate.	Between 3 and 5	The relations of employees both within and between layers are very good. There is a good

Issues / Questions [Reference]	**Efficiency Level 1** (poor)	**Efficiency Level 2** (fair)	**Efficiency Level 3** (average)	**Efficiency Level 4** (good)	**Efficiency Level 5** (excellent)
	tween them.		Relationships between layers are more problematic.		working and conversation atmosphere.
12.4 Decision Making	We do not ask for feedback from our employees. We do not take suggestions seriously. We rather enforce our own views and decisions.	We try to gather the feedback and opinion of our employees only for specific issues. We take it as information but it does only rarely influence our decisions.	Everybody can provide his opinion, but at the end only the top management decides.	We obtain feedbacks from our employees. It is important for us that also our construction workers have a right to a say in a matter and feel not dismissed.	There are several persons involved in decision processes, representing interests for each section. A broad agreement is needed to make a decision.
13. Managerial Commitment					
13.1 Demonstrated Commitment of Top Management (Charalambous, 2014)	Top management is not involved.	Top management is informed on NRW reduction progress, but does not consider this as a strategic priority.	Progress in NRW reduction is part of the management information system with selected key performance indicators.	Top management is regularly informed on NRW reduction progress, and considers this as a strategic priority; but no internal accountability.	Top management requests regular reporting on progress with NRW reduction, and holds staff accountable.
13.2 Established and Operationalized a Cross departmental non-revenue water (NRW) Unit (Charalambous, 2014)	No cross-departmental NRW unit is established.	Some ad hoc coordination between technical and commercial departments.	Systematic coordination between technical and commercial departments is being introduced in NRW reducing efforts.	A cross-departmental unit has been established, and the head of the unit reports to Director of Operations.	A cross-departmental unit has been established, and the head of the unit reports to top management.
13.3 Water Audit Published in Annual Report (Charalambous, 2014)	No water audits are carried out.	Water audits are carried out from time to time, but otherwise not used as a management tool.	Water audits are carried out on an annual basis but not validated, following own format.	Annual water audits are carried out but made available only upon request.	Annual water audits are carried out, and published in the annual report.
13.4 Continued Measurable Efforts in NRW Reduction (Charalambous, 2014)	No measurable efforts in NRW reduction.	Efforts in NRW reduction are random and not coordinated.	Efforts in NRW reduction are in place, but mostly opportunistic.	Efforts in NRW reduction are being planned, and executed systematically.	Continued measurable efforts in NRW reduction are in place.
14. Public Awareness					
14.1 WLR Awareness Concerning Population	We only communicate the problem of water loss within our utility but conduct no external commu-	Between 1 and 3	We inform our population about water losses and the methods we implement against them. How-	Between 3 and 5	We thoroughly inform population about WL. We also conduct regularly WLR-events (talks, infor-

Issues / Questions [Reference]	**Efficiency Level 1** (poor)	**Efficiency Level 2** (fair)	**Efficiency Level 3** (average)	**Efficiency Level 4** (good)	**Efficiency Level 5** (excellent)
	nication.		ever, we rarely perform special efforts like WLR events.		mation desks). We convinced people that WL is severe problem.
14.2 Behavior During Severe water-loss events	We were unconcerned about severe water-loss events so far and do not have a plan how to behave and how to inform people in such a situation, respectively.	Between 1 and 3	We have elaborated a special emergency plan (including how to behave and fight it as well as inform the population) but never experienced such a situation.	Between 3 and 5	We have elaborated a special emergency plan and have already applied such a procedure and made good experience.
14.3 Politics Take the Issue Seriously	We do not venture any effort in convincing policy about the problem of water loss.	Between 1 and 3	We make an effort to inform policy about WLR, but unfortunately the awareness for this problem and cooperation could be better.	Between 3 and 5	We are intensive contact with politicians and inform them about WLR. We achieve that policy take the issue seriously.

APPENDIX XII WATER UTILITY COMPASS – LIST OF MEASURES INCLUDED IN THE DECISION-SUPPORT SYSTEM

Table 8-14 lists all measures included in Water Utility Compass, organized in categories and with corresponding identification numbers. The list of measures is adapted from the decision-support system and a prioritized list of measures for controlling water losses, adapted to regional conditions from the European *waterloss* project: Management of water losses in a drinking water supply system (Project code: 2G-MED09-445).

Table 8-14: Water Utility Compass – List of Measures Included in the Decision-Support System

Category	Measure	ID
Active Leakage Control	Apply a few modern methods of active leakage control for leak awareness, detection, and localization.	110
	Apply several modern methods of active leakage control for leak awareness, detection, and localization.	112
	Replace the most critical active leakage equipment to achieve some level of accuracy.	287
	Keep all the active leakage control material up-to-data and at a high standard.	232
	Use leak detection equipment in rare occasions given specific problems in limited areas	332
	Start doing regular leak surveys.	298
	Cover the whole network with leakage surveys at least once a year.	131
	Buy leak detection equipment.	114
	Prioritize leak repairs according to the size of the leaks as well as considering the stability of supply of the whole system.	264
	Start running night step-testing.	301
	Use pressure variations to localize leakage and water loss.	339
	Implement a systematic leak detection planning.	182
	Perform acoustic leak detection surveys at regular intervals.	257
	Use leak location software to support leak detection.	333
	Use portable ALC equipment.	338
Auditing	Seek external auditing of your system (certification process).	292
Bottom-up assessment	Use minimum-night-flow (MNF) analysis for the bottom-up assessment of real losses.	335
Customer information system (CIS)	Store the information about your customers in a CIS.	306
	Link your CIS to your geographic information system (GIS).	245
	Monitor customer complaints and take actions accordingly.	252
Customer and metering management	Improve the communication with customers and evaluate their complaints.	193
	Update your customer database	319
	Regularly update your customer database by house to house surveys and checks	285

Category	Measure	ID
	Link your customer database to your GIS	246
	Maintain and update customer database by house to house surveys	247
	Install meters for all customers	215
	Install meters for all customers except public fountains, standpipes and similar	216
	Start installing meters for large customers	299
	Store information like age, type for all customer meters	305
	Introduce a customer meter replacement policy	221
	Strictly follow the customer meter replacement policy	309
	Upgrade meters to Class C	320
	Upgrade meters to Class D	321
	Place meters in previously unmetered areas and take care to calibrate the meters	261
	Regularly perform meter quality surveys and repair or replace defected meters	282
	Use hand held devices to register meter readings, rotate the meter readers regularly and check the readers for errors	329
	Implement a pilot project to evaluate water meter errors (e.g. under-/over registration levels)	181
	Install an automated meter reading system (AMR system)	213
	Define the water meter's optimal replacement time, age, aging factors, etc.	143
	Improve your measurements of unbilled authorized consumption	197
	Link meter readers to smart portable devices	242
	Upgrade your metrological class meters	322
	Replace non-functioning water meters	286
	Adapt the size of water meters based on the actual consumption pattern	102
Data accuracy and collection	Compute your water balance	127
	Establish an annual water balance according to the IWA standard	157
	Compute the confidence intervals for your water balance	126
	Determine accuracy and reliability of your water balance	145
	Regularly perform investigations and samples to create a highly accurate water balance	280
	Establish a bottom-up analysis	152
	Establish a bottom-up analysis and compare it with your water balance	153
	Compare your bottom-up analysis with your water balance	125
	Report origin and level of accuracy of data for further assessment	288
	Install data handling quality assurance systems	214
	Keep repairing times and other information stored in an according register	237
Distribution network	Install permanent acoustic loggers	218
	Use trace gas to detect leaks in your distribution network	345
	Develop operational guidelines for the leak repairs	146
	Define and use emergency leak repair kits	139
	Check and repair joints in the network	118
	Add cathodic protection to the network	103
	Check for bimetallic connections in the network and replace if possible	120
	Improve pipe installation practices	191

Category	**Measure**	**ID**
	Define a service connections replacement policy	137
	Introduce automatic closing valves and switches in tanks and reservoirs	223
	Observe and document actual pipe aging (e.g. on test grounds)	254
	Reduce the length of service connections where possible	268
DMA	Establish some DMAs and start analyzing the data	161
	Establish several DMAs and analyze the data	160
	Check boundary valves. Try to adapt DMA borders to natural boundaries. Use suitable meters and PRV's.	119
	Keep track of the type of customers in the DMAs and create requirement lists for each type of customer.	239
	Make sure that most DMAs have between 500 and 3,000 service connections and 4km to 30km total distribution pipeline length	249
	Adjust all DMAs to have between 500 and 3,000 service connections and 4km to 30km total distribution pipeline length	105
	Divide the distribution system into smaller areas, which are easier to manage and monitor	147
	Incorporate pressure management into the DMA planning	202
	Install meters of appropriate size to measure the DMAs inflow	217
Documentation	Document all the interventions (including location, pipe characteristics, valves, pumps, etc.)	148
	Use a failure database to store a history of failures	324
	Use a failure database, perform statistical analysis on it and visualize the data	325
	Have a customer complaints book and keep track of the leak repairs in there.	175
	Keep basic leak repair records to keep track of the leaks on the main pipes and service connections	236
	Keep basic leak repair records to keep track of all leaks (including leak, pipe and repair data)	235
	Link the repair records to the GIS	244
	Start collecting data about your infrastructure regarding age, status, functionality, material, etc.	297
	Collect more detailed data about your infrastructure and use it in decisions regarding infrastructure management.	124
	Additionally collect data like repair history, size of devices, installation dates, operating pressure etc. for your infrastructure	104
	Improve the documentation and organization of operational procedures	195
	Include the status of NRW reduction and selected KPIs into the decision making progress of the management	201
	Include and consider the current status of NRW reduction. Use selected KPIs to support the decision process.	199
	Hold the staff accountable for the results they provide	178
	Carry out regular water audits	117
	Publish the results of the water audits in an annual report	266
	Carry out annual water audits and publish them in reports	116
	Define performance targets (e.g. quality standards, repair time, etc.)	141
	Establish guidelines for Water Balance volumes calculation	159
	Keep a register for the information of all failures	231
	Keep a register containing a record of each intervention	230
	Define methodologies and tools for different pipe types	140

Category	Measure	ID
	Create and maintain a central registry of underground infrastructure	135
Equipment	Increase assortment of spare parts	203
	Define an asset management policy	138
	Acquire and use portable ALC equipment	113
	Keep an available stock of repair material available	234
Finance	Increase the budget for water-loss reduction	204
	Increase the budget for water-loss reduction	205
	Improve the billing database	192
	Strengthen and implement a legislation addressing the recovery of payments	308
	Introduce systematic controls for the billing records	226
	Restructure the tariff structure (including the fixed charge)	289
	Introduce target-oriented water pricing	227
	Introduce different tariffs for different water users	224
GIS	Start using maps to document the networks	302
	Regularly update the maps according to the changes	284
	Use GIS to maintain your maps	328
	GIS development (gradual improvement of GIS functionalities)	171
Human Resources	Give clear instructions for workers	172
	Establish a cross-departmental unit which reports to top management in regular intervals	154
	Form a team which specializes on ALC	165
	Provide a training for the ALC team	265
	Train your meter reader staff	317
	Train employees regarding the handling of the water accounting	314
	Increase the fraction of highly qualified people	208
	Gather feedback from employees and use them for improvements	167
	Reward good work with a bonus, holidays or a present	290
Hydraulic model	Use a hydraulic network model and link it to your network register	326
	Keep the hydraulic network model calibrated, verified and updated	238
	Improve the hydraulic model and continuously run it	196
	Introduce a hydraulic model of your system	222
	Link the hydraulic model to the network register	243
Infrastructure	Undertake some investigations for critical and problematic pipelines to prepare replacement proposals	318
	Generally try to get some estimates of pipeline renewal requirements based on construction dates, pipe materials, asset life, etc.	168
	Adjust asset live estimations for separate categories based on observed trends in leak repair records.	106
	Create a detailed pipe renewal strategy based on the experience in the past as well as forecasting of the future	133
	Perform maintenance of your infrastructure from time to time and deploy some pressure management	259
	Regularly perform maintenance of your infrastructure as well as pressure management	281
	Start performing inspections/surveys of your infrastructure regularly. Tackle the most important issues.	300

Category	Measure	ID
	Sort any issue, which has been found for any infrastructure.	294
	Apply preventive interventions if the risk potential for a large amount of damage exceeds a certain level.	111
	Keep all the equipment functioning using preventive interventions.	233
	Maintain the equipment in regular intervals	248
	Get modern equipment and specialized, skilled employees to take care of maintenance work.	170
	Get better equipment for your staff, both technically, modern as well as safe	169
	Stock up on spare parts and use it quickly to repair broken equipment	304
	Have a broad set of spare parts for all the equipment and replacing defect parts is done in a swift manner	174
	Invest in your car park and make sure that the vehicles are in good condition	229
Metering	Check the accuracy of the volumetric meters using a second test meter	121
	Improve handheld meter reading methods to minimize reading and transfer errors	189
	Introduce remote reading of meters directly from the command center	225
	Calibrate water meters	115
	Regularly rotate the meter readers and meter reading routes	283
Organization	Implement efficient working steps, avoid idles	185
	Facilitate acquisition and transport of equipment and people	162
	Prioritize leak repair according to the size of the leaks and consider security of supply throughout the whole system	263
Other	Include social costs in your assessment and planning of the budget and replacement strategies	200
	Detect illegal connections	144
	Identify illegal bypasses	179
	Use SOP for more high-class processes and update them regularly.	342
	Continually make efforts in NRW reduction	129
	Inform the population about water-loss and methods against them	211
	Conduct regular water-loss reduction events and try to convince people that this is a severe problem	128
	Create a special emergency plan on how to inform the population and behave during severe water-loss events	134
	Train the appliance of the special emergency plan which gets put in place during a severe water-loss event	316
	Improve the cooperation with politicians and inform them about water-loss reduction	194
Performance Indicators	Regularly calculate real losses performance indicators	276
	Regularly calculate apparent losses performance indicators	275
	Publish your performance indicator results in an annual report and use ILI for benchmarking	267
	Keep track of your repair times for distribution pipes	240
	Reduce your average repair time to less than 7 days for distribution pipes	273
	Reduce your average repair time to less than 3 days for distribution pipes	271
	Reduce your average repair time to less than 1.5 days for distribution pipes	269
	Keep track of your repair times for house connections	241
	Reduce your average repair time to less than 7 days for house connections	274
	Reduce your average repair time to less than 3 days for house connections	272

Category	**Measure**	**ID**
	Reduce your average repair time to less than 1.5 days for house connections	270
	Start using performance indicators and use them to identify the weak points of the infrastructure.	303
	Use more performance indicators and use them to identify the weak points of the infrastructure.	337
	Use a broad set of performance indicators to discover technical or financial weak points.	323
	Use the cost-benefit analysis to determine a good balance of maintenance and replacement	344
	Use the cost-benefit analysis more regularly to determine a good balance of maintenance and replacement	343
Pressure management	Install pressure recorders at pumping stations and treatment plants	219
	Regularly measure the pressure in the distribution network using pressure gauges	278
	Regularly measure the pressure in the distribution network using pressure loggers	279
	Continuously monitor the pressure in the distribution network using loggers	130
	Start applying pressure management in the most relevant DMAs	296
	Increase the coverage of DMAs using pressure management and perform intensive functional testing of the system	206
	Perform pressure management on the whole system and test it regularly and intensively	260
	Use hydraulic modelling for some of your PMAs	331
	Use hydraulic modeling for the whole network	330
	Equip yourself with adequate pressure management equipment and keep it up-to-date where necessary	151
	Use modern, up-to-date equipment like PRV, flow meters, pressure sensors, isolating valve, etc. to manage the pressure	336
	Use PRVs and maintain them	340
	Regularly check the function of your PRVs and maintain them	277
	Plan the use of diaphragm and plunger valves based on their pros and cons.	262
	Adjust the pressure in the network by using boosters and PRVs accordingly	107
	Define pressure management zones	142
	Perform intensive functional tests on the system	258
	Modulate pressure to reduce water loss	251
Public Awareness	Run a public awareness campaign	291
Reduce illegal actions	Monitor water consumption patterns	253
	Impose high fines on irregularities on metering devices	186
	Implement a water theft tracing project	183
	Start a pilot project to address meter tampering	295
	Identify water theft by remote sensing and other sensing methods	180
	Inspect water meters and their security seals at regular intervals	212
	Supervise fire hydrants for illegal water use and implement measure to counteract	310
	Analyze the consumption pattern using historical data	109
	Impose high fines on water theft and other illegal actions	187
	Take legal measures to prosecute water theft/illegal use	311
Reduce unbilled uses	Train firemen regarding an efficient usage of water	315
	Wash streets with alternative water (reclaimed water, rain, river)	346

Category	Measure	ID
	Optimize watering of parks/sports fields (method/time/duration)	256
	Implement artificial turf on sports fields	184
	Harvest rain for irrigation of city parks	173
	Set up rules for different water uses (e.g. fire fighters, transient phenomena, etc.)	293
	Optimize filter cleaning cycles	255
	Adapt the flushing duration	101
	Clean tanks whenever the water level is low	123
	Install unmetered flow reducers (UFR)	220
	Abolish as many roof tanks as possible	100
Staff	Establish a leak detection team	156
	Establish a highly skilled leak detection team and perform regular training programs	155
	Fix network issues in a fairly timely manner by good skilled workers	163
	Fix your network swiftly, done by excellently skilled people	164
	Streamline the information exchange between the workers and departments.	307
	Use appropriate organizational structures for the given tasks.	327
	Establish clean and clear working processes	158
	Have specialized teams as well as training programs for specific tasks.	177
	Have specialized teams as well as training programs for all tasks.	176
	Increase the fraction of highly qualified staff	209
	Employ specialized NRW-teams	149
	Employ specialized NRW-teams for each task (e.g. Active Leakage Control, Pressure Managements, etc.)	150
	Increase the density of employees per service connections	207
	Increase the staff to have more than 100 employees per 1,000 service connections	210
	Introduce training programs for different specialized teams	228
	Incentivize good work	198
	Improve on the communication between different layers as well as inside the layers of the organization.	190
	Improve communication between employees. Provide a good working environment and atmosphere.	188
	Gather and consider the feedback from everybody in the company and make decisions in groups	166
	Create a cross-department unit which coordinates between the technical and commercial departments	132
	The head of the cross-department unit should report to the director of operations	312
	The head of the cross-department unit should report to the top management	313
Standard Operating Procedures	Create, use and regularly update Standard Operating Procedures (SOP´s)	136
	Check the supply chain managements and verify their standards	122
System input metering	Meter the system input	250
	Use mechanical and/or magnetic flow meters which are sometimes calibrated to meter the system input	334
	Use regularly calibrated magnetic flow meters to meter the system input	341
Wastage	Advertise installation of water efficient devices in households and public buildings	108

APPENDIX XIII WATER UTILITY COMPASS – PERFORMANCE INDICATORS AND BENCHMARKING

Table 8-15: Water Utility Compass – Performance Indicators and Benchmarking

Performance Indicator (PI)	Formula	Explanation	Reference	Benchmarking / Performance Category						
Infrastructure Leakage Index (ILI)	CARL/UARL [-]	The ILI is a measure of how well a distribution network is managed (maintained, repaired, and rehabilitated) for the control of real losses, at the current operating pressure. It is the ratio of Current Annual volume of Real Losses (CARL) to Unavoidable Annual Real Losses (UARL). ILI = CARL / UARL Being a ratio, the ILI has no units and thus it facilitates comparisons between countries that use different measurement units (metric, U.S., or imperial).	Liemberger R. et al. 2006: Water Loss Performance Indicators	Developed Country Situation	A	1–2				
					B	2–4				
					C	4–8				
					D	>8				
				Developing Country Situation	A	1–4				
					B	4–8				
					C	8–16				
					D	>16				
Real Losses per service conn. (w.s.p.) [Liters/Connection/Day (when system is pressurized)]	(CARL in liter/365)/(Supply time/24) /Num. connections [l/conn/day]	Real water losses per service connection. In general, the higher the number of service connections the higher the absolute water losses but the lower the losses related to service connections.	Liemberger R. et al. 2006: Water Loss Performance Indicators	Average pressure:		10 m	20 m	30 m	40 m	50 m
				Developed Country Situation	A		<50	<75	<100	<125
					B		50–100	75–150	100–200	125–250
					C		100–200	150–300	200–400	250–500
					D		>200	>300	>400	>500
				Developing Country Situation	A	<50	<100	<150	<200	<250
					B	50–100	100–200	150–300	200–400	250–500
					C	100–200	200–400	300–600	400–800	500–1,000
					D	>200	>400	>600	>800	>1,000
Real Losses per service conn. per m pressure (w.s.p.) [Liters/Connecti	Real Losses p.s.c./Avg operating pressure [l/conn/day/m pressure]	Determine the real losses per service connection normalized to pressure, meaning that this PI is independent of the operating pressure.	Derived from: Liemberger R. et al. 2006: Water Loss Performance Indicators	Developed Country Situation	A	<2.5				
					B	2.5–5				
					C	5–10				
					D	>10				

Performance Indicator (PI)	Formula	Explanation	Reference	Benchmarking / Performance Category		
on/Day/m pressure (when system is pressur-ized)]						
				Developing Coun-try Situation	A	<5
					B	5–10
					C	10–20
					D	>20
Losses per main	(CARL in li-ter/365)/(Suppl y time/ 24)/Length of mains [l/km/day]	Losses related to main. Only relevant if Density of service connections is below 20 per km of mains.	Sharma S. 2008: Performance Indicators of Water Losses in Distribution Systems	good		<10,000
				average		10,000–18,000
				low		>18,000
Percentage of non-revenue water (NRW)	NRW/System input volume * 100 [%]	Those components of System Input which are not billed and do not produce revenue. Equal to Un-billed Authorized Consumption plus Physical and Commercial Water Losses. Easy to determine, the lower the value the better. However, this PI is often not recommended to use.	-	Developed Coun-try Situation	A1	<5
					A2	5–10
					B	10–20
					C	20–30
					D	>30
				Developing Coun-try Situation	A1	<10
					A2	10–25
					B	25–40
					C	40–65
					D	>65
Pressure	PA/(Pmin+Psafe	Pressure Performance Indicator. Potential to	-	high		<1.25

Performance Indicator (PI)	Formula	Explanation	Reference	Benchmarking / Performance Category		
management index (PMI)	ty) [-]	reduce water losses with a lowered operating pressure. Note that for the safety margin usually 3–5 m are taken.				
				average		1.25–3
				low		>3
Apparent losses per service conn. (w.s.p.) [Liters/Connection/Day]	App. losses per day in liter/ (Supply time/24)/Num. connections [l/conn/day]	Apparent water losses per service connection. In general, the higher the number of service connections the higher the absolute water losses but the lower the losses related to service connections.	Liemberger R., IWA Water Loss 2010: Recommendations for Initial Non-Revenue Water Assessment	Developed Country Situation	A	<50
					B	50–100
					C	100–150
					D	> 150
				Developing Country Situation	A	<60
					B	60–120
					C	120–200
					D	>200
Apparent losses relative to billed consumption (% of billed consumption)	App. losses / Billed consumption *100 [%]	Apparent water losses referred to billed consumption	Liemberger R., IWA Water Loss 2010: Recommendations for Initial Non-Revenue Water Assessment	Developed Country Situation	A	<5
					B	5–10
					C	10–15
					D	>15
				Developing Country Situation	A	<6
					B	6–12
					C	12–20
					D	>20
Apparent leakage index (ALI) [App. Losses / 5%	App. Losses / 5% of Billed water consumption [-]	Apparent water losses based on water sales. The higher the apparent losses the less water can be sold by sales price the higher the PI should be.	AWWA Free Audit tool	very high	A	1
				high	B	2

Performance Indicator (PI)	Formula	Explanation	Reference	Benchmarking / Performance Category				
of billed water]				medium	C	3		
				low	D	4		
				very low	E	5		
Illegal Connections [% of Illegal Connections]	Num. illegal connections / Num. connections * 100 [%]	% (compared to total service connections)	Sharma S. 2008: Performance Indicators of Water Losses in Distribution Systems	very high		2		
				high		4		
				average		6		
				poor		8		
				very poor		10		
Customer Meter Inaccuracies [% of Metered Consumption]	Cust. meter inacc. / Metered Consum. * 100 [%]		Charalambous B. 2014	Developed Country Situation		2		
				Developing Country Situation		5		
Data Handling Errors [% of Authorized Consumption]	Data handling error / Metered Consum. * 100 [%]		Sharma S. 2008: Performance Indicators of Water Losses in Distribution Systems	average		0.25		
Unbilled Authorized Consumption [% of System Input Volume]	Unbilled water consum. / System input vol. * 100 [%]	Water that is not lost, but unbilled and therefore not revenue	AWWA Free Audit tool	very high	A	<1.25		
				high	B	1.25		
				medium	C	1.5		
				low	D	1.75		
				very low	E	2		
Average age of mains, service connections	Avg. age [y]					mains	service connections	customer meters

Performance Indicator (PI)	Formula	Explanation	Reference	Benchmarking / Performance Category						
and customer meters [y]				very high		<20		<20		<3
				high		20–30		20–30		3–5
				average		30–45		30–45		5–10
				low		45–60		45–60		10–12
				very low		>60		>60		>12
Non-Revenue-Water per Connection per Day [Liters/Connection/Day (when system is pressurized)]	NRW per day in liter / Num. conn. [l/conn/day]		Liemberger R., IWA Water Loss 2010: Recommendations for Initial Non-Revenue Water Assessment			10 m	20 m	30 m	40 m	50 m
				Developed Country Situation	A1		<50	65	<75	<85
					A2		50–100	65–125	75–150	85 p-175
					B		100–200	125–250	150–300	175–350
					C		200–350	250–450	300–550	350–650
					D		>350	>450	>550	>650
				Developing Country Situation	A1	<55	<80	<105	<130	<155
					A2	55–110	80–160	105–210	130–260	155–310
					B	110–220	160–320	210–420	260–520	310–620
					C	220–400	320–600	420–800	520–1,000	620–1,200
					D	>400	>600	>800	>1,000	>1,200