An integrated approach to least-cost planning of water reuse schemes

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Abstract Fresh water supplies throughout the world have been getting scarcer over the past few decades. Population and industrial growth leading to an immense increase in the number and intricacy of sources of water pollution, climate change, and shifts in weather patterns towards extremes are just some of the factors that are making the option to reuse water more attractive throughout the world, and necessary for some regions. While there are numerous obstacles to be overcome in planning water reuse schemes, the costs of treatment and distribution are two of the most important factors that need to be considered at the planning level. An additional factor, the selection of end users, also can have significant impact. New decision support software for integrated water reuse, called WTRNet, has been developed, which incorporates these three factors in determining the least-cost design alternatives. A brief overview of existing tools relevant to water reuse is presented, followed by a thorough description of key software features. An application of the WTRNet software on a case study involving a small number of potential industrial users of reclaimed water is presented, which demonstrates the importance of utilizing formal optimisation in determining the most promising design alternatives.

Keywords Decision support; least cost design; optimization; water reuse

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Introduction

Reclaimed water projects typically include construction of new or upgrades to a municipality's treatment systems, to treat wastewater to the required quality level, and construction of distribution systems for reclaimed water. A water reuse system is likely to have many possible design options: type and degree of treatment, number and location of treatment plants, number and location of pumps/pumping stations, number, size and location of storage tanks, layout and size of distribution pipe network. These elements are all linked to give multiple interactions and a very large number of design combinations, even for apparently small systems. In addition, a large number of potential end-users of reclaimed water may exist from which a selection needs to be made on whom to provide water to, which further complicates the decision making. The complexity associated with planning of water reuse schemes is therefore very high due to the very large number of design combinations possible, and establishes the need for use of decision support systems (DSS) to aid in the planning process.

A DSS for Water Treatment for Reuse with Network Distribution (WTRNet) has been developed within the AQUAREC project on 'Integrated Concepts for Reuse of Upgraded Wastewater', under the Fifth European Community Framework Programme. The DSS provides an integrated framework optimization of treatment and distribution aspects of water reuse and the selection of end-users, and has a broader aim of developing the design principles for water reuse systems. This paper describes the components of the DSS–simulation and optimization models for least-cost planning of water reuse systems, and introduces a case study on which WTRNet has been applied to develop least-cost

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design alternatives. This is preceded by a literature review of DSS methodologies relevant to planning of water reuse schemes.

Review of DSS for water reuse

This section summarizes the results of a comprehensive literature review of tools relevant to the development of an integrated DSS for water reuse, dealing with wastewater treatment for reuse, distribution of reclaimed water, and integrated approaches.

Models developed in the past for synthesis of treatment trains, evaluation and screening of synthesized treatment trains, and selection of the optimum (or near optimal) treatment train used a variety of methodologies to generate and screen unit process combinations. Examples of methodologies used for wastewater treatment (with and without reuse) include enumeration techniques (Rossman, 1980; Hydromantis, 2003), Monte Carlo simulation (Chen and Beck, 1997), heuristic search (Krovvidy and Wee, 1993), and modelling to generate alternatives (Chang and Liaw, 1985). A detailed overview of these methodologies is presented by Dinesh (2002). The same author presented a comprehensive approach for evaluating and optimizing treatment alternatives for wastewater reuse using genetic algorithm (GA) in a DSS called MOSTWATER. Another tool developed to assist planners in evaluating treatment trains for wastewater reclamation called WAWTTAR, described by Finney and Gerheart (1998), is intended primarily for developing countries. Both of these models aid the user in evaluation of treatment trains from unit processes contained in their respective databases, and none offer suggestions for complete treatment trains based on local conditions. In addition, the WAWTTAR model does not include any optimization routines.

The cost of wastewater reclamation is often cited as the key criterion for evaluation of treatment trains, although a number of other criteria have been used in the past. Metcalf and Eddy (2003), for example, point out 23 important factors that should be considered when evaluating and selecting unit processes for wastewater treatment, in addition to economic life-cycle analysis. The criteria used by other researchers vary depending on the methodology used in the selection of preferred alternatives, as well as the intended purpose of the model. Rossman (1980) used cost, energy and land requirements and subjective ratings of processes in an implicit enumeration approach, while Loetscher (1999) used 50 criteria and a multi-level amalgamation technique to select an appropriate sanitation alternative for developing countries.

In the context of optimal distribution system design, a number of methodologies have been developed in the past that consider not only the pipe-sizing problem, but also include other important aspects of water distribution system design such as cost data (e.g. whole-life costs) implications (Skipworth *et al.*, 2002), reliability and redundancy of designs, uncertainty, and sizing decisions influencing future development and demands. An overview of optimization techniques for water distribution system design can be found in Walski *et al.* (2003).

The water distribution aspect of water reuse systems also has been addressed in several integrative approaches to evaluating water reuse schemes. Linear programming in combination with GIS was used by Nobel (1998) to calculate and display feasible and optimal water exchange scenarios in a region. Zhang (2004) also used GIS for basic data processing and information gathering in the development of a comprehensive urban water reuse model, which used a network flow optimization model for modelling an urban water network. This approach also included a simplified modelling of multi-level waste-water treatment processes for water reuse and employed stochastic optimization methods to quantitatively model uncertainty issues in urban water reuse planning and manage-ment. Oron (1996) presented an integrative approach encompassing all relevant aspects of water reuse schemes, including the transportation and storage of reclaimed water. A linear objective function was used to optimize the comprehensive system, and the optimal solution to a sample problem of wastewater reuse in agricultural irrigation was found using linear programming.

Overview of WTRNet software

The literature review summarized in the previous section revealed that the majority of the existing decision support systems for evaluating water reuse projects focus on synthesis of treatment trains, despite the fact that 'no single factor is likely to influence the cost of water reclamation more than the conveyance and distribution of the reclaimed water from its source to its point of use' (USEPA, 2004). The models that include the distribution aspects of reuse schemes either do not incorporate provisions for the assembly of treatment trains from individual unit processes, or consider the treatment train components in a simplified manner by considering only general levels of treatment. In addition, both the layout of the distribution system and the optimal design of its components (pipes, pumping stations, and storage reservoirs) are greatly simplified.

The development of WTRNet aimed at incorporating both the process synthesis and water distribution aspects of reuse schemes in an integrated DSS, and overcoming some of the limitations that appear in currently available decision support tools. Some specific objectives set out in the development of the software were:

- Provide a completely open modelling environment that will allow users flexibility in terms of editing and adding information to the software knowledge base (e.g. unit processes and their characteristics, pollutants to be considered, use types and quality requirements, rules for combining unit processes in a treatment train, etc.);
- Provide suggestions for complete treatment trains based on the influent quality (or current level of treatment provided in the case of existing wastewater treatment facilities) and quality requirements for 'standard' end uses of reclaimed water;
- Include the distribution system in the reuse scheme evaluation by allowing users to specify the locations of pumping, transmission and storage facilities, and providing a least-cost preliminary sizing of the distribution system that meets all operational requirements.

The software includes a knowledge base, a control module that contains the graphical user interface (GUI), and three computational modules for evaluation of treatment performance, sizing of the distribution system, and optimization. Each of these components is described below.

Knowledge base

The knowledge base contains the following information: water quality requirements for different types of end uses of reclaimed water, design and costing information on unit processes, suggestions for treatment trains that could be used for influent quality/end use combinations, rules for combining unit processes, and the design and costing information for the distribution system components. There are 44 unit processes currently included in the knowledge base, ranging from preliminary treatment to disinfection. For each of the unit processes, the following information was assembled: maximum allowable influent pollutant concentrations, design criteria for sizing, process efficiencies for a series of pollutants, land and labour requirements, sludge and concentrates production, cost estimates and preference scores on qualitative evaluation criteria. All of this information is displayed to the user in a series of editable forms, which allow the user to review all the information and alter the expressions used in the calculation to suit local conditions. Further details on the information contained in the knowledge base can be found in Joksimovic *et al.* (2006).

Treatment performance module

The treatment performance has been developed with functionality to perform the evaluation of user-selected combinations of unit processes in a treatment train. The evaluation of treatment train performance and the display of treatment train evaluation results are carried out as changes to the treatment train are made. Since the evaluation results in a large output, the calculated data is displayed through four separate frames on the form: effluent quality, pollutant per cent removed, evaluation criteria scores, and costs and resources.

Distribution system sizing module

The distribution system performance computational module is used to optimally size the distribution system elements based on a pre-determined branched layout and preferences of the user for locating the pumping and storage facilities. The method used is a two-step procedure that first determines the optimal allocation of reclaimed water (along with optimal sizes of seasonal storage), followed by the sizing of pipes and pumping stations.

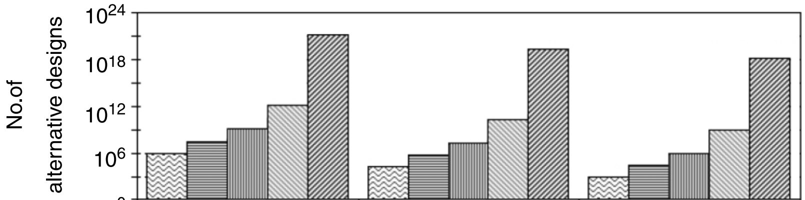
The problem of optimal allocation of reclaimed water is solved as a minimum cost flow problem following an approach similar to the one proposed by Kuczera (1989), and solved using the RELAX-IV algorithm (Bertsekas and Tseng, 1994). The solution of the minimum cost flow problem determines the flows in real parts of the network (pipes) and conceptual flows (storage carryover arcs) over twelve monthly intervals and fixed locations of storage facilities. Output from this optimization algorithm is used in three ways: (1) the optimal operating policy identifies volumes of reclaimed water transferred to each user; (2) maximum monthly flows in the real part of the network are used to calculate the pipe head losses for the optimal sizing of pipes and pumping stations; and (3) the maximum storage carryover arcs are used to size and cost the seasonal storage elements of the distribution network.

The least-cost sizing of pipes and pumping facilities is then carried out using a linear programming (LP) algorithm, which uses the information on standard pipe sizes and pumping station costs contained in the model knowledge base. The model is limited to branched distribution networks, typical in water reuse schemes and appropriate at the planning level of analysis, and uses standard representation of the network in the form of links and nodes. Each link is further conceptualized as consisting of a series of segments of standard pipe sizes, where the user selects the sizes they wish to be considered for each of the network links.

Optimization module

As indicated above, the knowledge base included in WTRNet covers 44 treatment unit processes. Evaluating all possible combinations of these unit processes (i.e. without any rules for combining them in a meaningful way) yields the number of total possible combinations as 1.76×10^{13}. However, the analyses of water reuse options can be conducted in situations where some treatment of wastewater is already provided. In addition, rules incorporated in WTRNet for assembling treatment trains further restrict the search space.

The combined effect of introducing treatment train rules and restricting the starting unit process according to the influent quality on the possible number of ways in which the unit processes could be combined to form a treatment train was analysed. The results of this analysis, shown in Figure 1, indicate that the number of possible treatment trains is drastically reduced if treatment train assembly rules are considered. The same figure has additional results showing the number of possible design alternatives for various numbers of potential end-users and influent quality. In the case of raw sewage influent, the total number of design alternatives for any number of end-users requires that



	Raw sewage	Primary effluent	Secondary effluent
1 user	1.21×10^6	19 608	1139
5 user	$3.74E \times 10^7$	607 848	35 309
10 user	$1.24E \times 10^9$	$2.01E \times 10^7$	$1.17E \times 10^6$
20 user	$1.27E \times 10^{12}$	$2.06E \times 10^{10}$	$1.19E \times 10^9$
50 user	$1.36E \times 10^{21}$	$2.21E \times 10^{19}$	$1.28E \times 10^{18}$

Figure 1 Number of design alternatives

a formalized optimization approach be applied. The situation is similar if primary effluent is used as a source in a system incorporating several potential end-users. If secondary effluent is used as a source and only several potential end-users are considered, an exhaustive search potentially could be used to identify the least-cost alternative.

In order to accommodate the wide range of the number of possible design alternatives, three algorithms are incorporated in the optimization module. If the secondary effluent is to be reclaimed and the number of potential customers is not large, exhaustive enumeration is used to determine the least-cost design alternatives for all combinations of end-users. If the secondary effluent is to be reclaimed for a (potentially) large number of end-users, a simple GA is used for optimal user selection. Finally, if the source of water is raw sewage or primary effluent, the optimization algorithm used is a GA with customized operators. The algorithm conducts a simultaneous search of least-cost design alternatives and the best selection of customers, and uses the project net present value (NPV) as the evaluation criteria.

Case study

The WTRNet software has been applied in the study of industrial water reuse options in the city of Kyjov, located in the South Moravia area of the Czech Republic. The industrial zone of Kyjov is approximately 5 ha in size, within which the majority of businesses are in the metal and glass industries. The wastewater treatment plant (WWTP) in Kyjov, which is in the immediate vicinity of the industrial zone, is sized for approximately 26 000 population equivalents (PE), and currently receives an average flow of 9 500 m^3/d. The WWTP is a mechanical-biological treatment plant with aerobic stabilization of sludge. Collected sewage is pre-treated (bar screen, mechanical fine screen, grit chamber). Another operational complex forms a biological treatment stage, which includes a circulating activation tank, secondary settling tanks, and a pumping station for re-circulated and excess sludge.

Six industries were identified as potential end-users of upgraded wastewater from the Kyjov WWTP. Table 1 displays the details of these industries, along with their estimated quantity requirements for reclaimed water. The total reclaimed water demand estimated for these users represents less than 10% of the current plant average flow. Nevertheless, an assumption was made that 10% of the effluent from the WWTP would need to receive additional treatment in order to satisfy both the quantity and quality requirements of these potential users.

Investigation of wastewater reuse opportunities in Kyjov was carried out using WTRNet. The Kyjov WWTP effluent quantity and quality was used as the source of

Table 1 Potential users of reclaimed water in Kyjov

Company	Industry type	Estimated water demand (m^3/d)
Sebesta spol. s r.o.	Manufacturing of packaged wastewater treatment plants	23
KM Beta, a.s.	Manufacturing of building and roofing products	35
Sroubarna Kyjov spol. s r.o	Manufacturing of fasteners	122
EKOR s.r.o	Waste management	9
Mlekarna Kyjov, a.s.	Dairy works	74
Vetropack Moravia Glass, a.s.	Glass manufacturer	297
Total		600

reclaimed water, and a preliminary layout of the distribution system was implemented. The distribution system modelled consists of a single pumping station and 10 000 m^3 of operational storage, both located at the WWTP, in addition to the piping required to deliver the reclaimed water to the potential end-users.

The results of applying the exhaustive enumeration optimization methodology are shown in Figure 2. The six potential end-users produced 63 different combinations. For each combination, a least-cost design was produced, comprising the treatment, distribution, and total costs indicated in Figure 2. The first remark that is made on the results of evaluation is that the variability in overall water reclamation system costs is due primarily to the varying costs of the distribution system as different sets of potential end-users were selected. The treatment costs, although not linear, are in proportion to the per cent demand satisfied (volume) and do not exhibit such variation, potentially due to the assumption that the potential end-users in this case study require the same quality of water. Nevertheless, the importance of evaluating water reuse systems in an integral manner is clearly demonstrated. Secondly, an examination of the unit processes forming each of the 63 treatment trains was conducted. In close to 75% of the cases, the least-cost treatment train consisted of micro filtration followed by ion exchange. The remaining 25% of treatment trains contained the following combination of unit processes: surface filtration, advanced oxidation (UV/H_2O_2), and SAT. Further examination of results revealed that this treatment train was chosen in cases where up to one-third of total demand was satisfied.

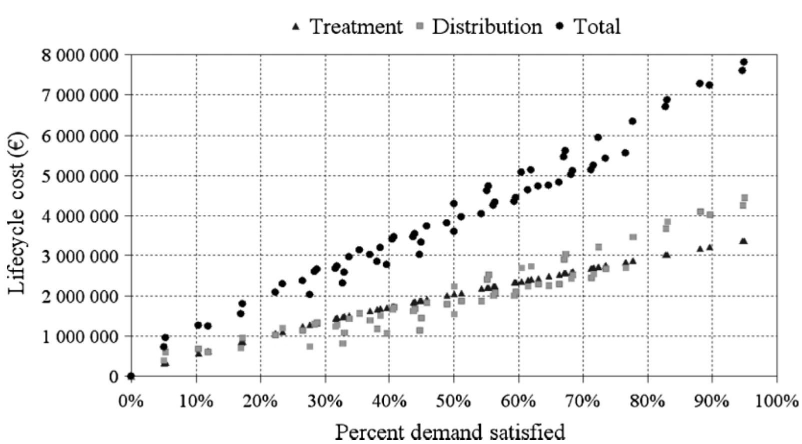


Figure 2 Results of evaluation of water reuse options in Kyjov

The results of evaluations using WTRNet provide a complete set of possible water reuse options in Kyjov for the selected potential end-users. This is in contrast to the traditional approach, where the best out of several alternatives identified *a priori* is chosen for further investigations. The importance of the approach considered in WTRNet is illustrated in the case of Kyjov, where results indicate that anywhere between 34% and 45% of the demand could be satisfied with the same lifecycle cost of €3 million, depending on the choice of end-users. By providing a full range of design alternatives, it is ensured that the decision made on the future course of action involving a more detailed study is sound.

Conclusions

Planning of integrated water reuse systems is a highly complex exercise, which needs to consider the selection of treatment processes required to achieve the desired effluent quality, the distribution system required to deliver the reclaimed water to customers, and the selection from a set of possible end-users with potentially differing quantity and quality requirements. The WTRNet decision support tool presented in this paper provides a platform that can be used to conduct the integrated assessment of water reuse options in an efficient manner. The application of WTRNet is illustrated in a case study of water reuse options in the city of Kyjov, on a relatively small scale with few potential end-users. Nevertheless, the importance of integrated least-cost planning is clearly demonstrated.

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