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Development of an integrated simulation model for treatment and distribution of reclaimed water

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Abstract

Research is currently being conducted as part of the AQUAREC project, with the objective being the development and validation of design principles for water reuse systems. To achieve the project objective, simulation and optimisation software for integrated water reuse systems need to be developed. 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. A hydraulic/process simulation model has been developed and is described, which will be used in combination with an integrated optimisation engine to allow a range of design possibilities to be explored. The model includes a computational module for wastewater treatment trains, a computational/optimisation module for reclaimed water distribution system, and a knowledge base. The computational modules are used to calculate the performance of user-defined reuse system alternatives, utilizing the information contained in the knowledge base that includes rules for generation of treatment trains, design, cost and evaluation criteria information.

Keywords: Decision support; Simulation; Optimisation; Water reuse

1. 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

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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. The complexity associated with planning of water reuse schemes is therefore very high due to a very large number of design combinations possible, and establishes the need for use of a decision support systems (DSS) to aid in the planning process.

A DSS for Water Treatment for Reuse with Network Distribution (WTRNet) is currently being 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 for evaluation and optimisation of treatment and distribution aspects of water reuse, and will be used to achieve the ultimate project aim of the development the design principles for water reuse systems. This paper describes the current progress on the development of the DSS — the simulation and optimisation models for water reuse systems — and discusses the direction in which the development is heading. This is preceded by a brief summary of a literature review of DSS in water reuse, covering the treatment and distribution aspects of reclaimed water.

2. Review of DSS for water reuse

2.1. Generation and screening of treatment trains

The number of treatment processes used to treat wastewater has been steadily growing. This is particularly true for advanced treatment technologies capable of treating wastewater to a degree of quality appropriate for reuse, making the selection of the most suitable sequence of processes (treatment train) for any potential reuse situation more complex. The challenges experienced by planners and designers of water reuse systems include deciding on suitable treatment trains from a large number of unit process combinations [1] as well as handling of multiple objectives that treatment systems need to satisfy [2].

The selection and design of appropriate treatment alternatives for water reclamation can be considered in a three-stage process involving the selection of alternatives, pilot-plant studies and selection of a preferred alternative for detailed design [3]. The focus here is on the first stage, the evaluation of performance and cost of a number of treatment alternatives to select the most appropriate ones for more detailed evaluation. The tasks involved in this stage can further be divided into: selection of unit processes, synthesis of treatment trains, evaluation and screening of synthesised treatment trains, and selection of an optimal (or near optimal) treatment train [4]. The development of the simulation model focused on the first three of these tasks, while the integrated optimisation component is currently under development and will be added to WTRNet in the future.

Models developed in the past for synthesis of treatment trains 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 [5,6], Monte Carlo simulation [1], heuristic search [7,8], and modelling to generate alternatives [9]. A detailed overview of these methodologies is presented by Dinesh [4]. The same author presented a comprehensive approach for evaluating and optimising 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, WAWTTAR, described by Finney and Gerheart [10], is intended primarily for developing countries, and it does not include an optimisation routine. 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.

The cost of wastewater reclamation is often cited as the key criterion for evaluation of treatment trains; however, there are a number of other criteria that have been used in the past. Metcalf and Eddy [11], for example, point out 23 important factors that should be considered when evaluating and selecting unit processes for wastewater treatment, in addition to the economic life-cycle analysis. The criteria used by other researchers varied depending on the methodology used in the selection of preferred alternatives, as well as the intended purpose of the model. For example, Rossman [5] used cost, energy and land requirements and subjective ratings of processes in an implicit enumeration approach, while Loetscher [12] used 50 criteria and a multi-level amalgamation technique to select an appropriate sanitation alternative for developing countries. Balkema et al. [2] provide a critical overview of methodologies used for comparisons of a large number of treatment alternatives, and suggest a set of multidisciplinary sustainability indicators including functional, economic, environmental and socio-cultural aspects.

2.2. Distribution of reclaimed water

In the context of optimal distribution system design, simulation models are typically used in conjunction with mathematical optimisation. The design problem is often viewed as a least-cost optimisation problem with pipe diameters acting as the primary decision variables, assuming a predetermined pipe layout [13]. A number of methodologies have been developed 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 [14], reliability and redundancy of designs, uncertainty, and sizing decisions influencing future development and demands. An overview of optimisation techniques and objectives in the water distribution system design can be found in Walski et al. [15].

Treatment of storage facilities in the optimisation of distribution systems is of key importance, given that most water reclamation schemes include significant reservoirs. The sizing and operation of reservoirs in reclaimed water systems differ from the design considerations in potable water systems, as they are focused on the annual water balances in addition to the daily operation. Therefore, the literature review also extended into the area of design and operation of regional reservoir systems. A large number of optimisation techniques have been used for optimal design and operation of reservoir systems, and a comprehensive review can be found in Labadie [16]. Some researchers addressed aspects particularly relevant to reclaimed water distribution systems, including a multi-period optimisation model for sizing of reservoirs serving multiple demand areas [17]; an optimisation model for a multi-source, multi-quality regional water distribution system [18]; and a management model for optimal operation and control of a regional water system with numerous water sources of various qualities and consumers with differing flow rates and quality requirements [19].

The water distribution aspect of water reuse systems has also been addressed in several integrative approaches to evaluating water reuse schemes. Linear programming in combination with GIS was used by Nobel [20] to calculate and display feasible and optimal water exchange scenarios in a region. The model, however, calculates the optimal allocation of water for a given scenario by assuming the distribution networks as straight, constant diameter pipes between sources and sinks (users). Oron [21] 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 optimise the comprehensive system, and the optimal solution to a sample problem of wastewater reuse in agricultural irrigation was found using linear programming. Economopoulou and Economopoulos [22] presented a methodology that uses a knowledge base and inference procedures for developing rational wastewater management schemes for small- to medium-size communities, with emphasis on the use of natural treatment systems and reuse of treated wastewater.

3. Model development

The literature review summarised above reveals that the existing DSS for synthesis of treatment trains for water reuse allow the user to evaluate only the treatment aspects of overall reuse schemes, 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" [23]. The models that include the distribution aspects of reuse schemes, on the other hand, do not incorporate provisions for the assembly of treatment trains from individual unit processes, and consider the treatment component in a simplified manner. In the development of process synthesis models it is assumed that the cost of providing the distribution of reclaimed water is the same for all treatment alternatives, which is true only if a single treatment facility is considered providing reclaimed water that meets a water quality and/or reclamation standard for a particular end-use. In addition, neither of the existing programs provides suggestions for default treatment trains that may be most applicable based on current experience with water reuse for a specific influent quality/water quality standards combination.

The two reviewed programs developed for synthesis of treatment trains for water reuse include respective knowledge bases which contain information (performance, cost, etc.) for a limited number of unit processes. While new processes can be added in WAWTTAR, the number of unit processes included in MOSTWATER is fixed. MOSTWATER also includes a finite number of rules that describe the acceptable combinations of unit processes in a treatment train, which are absent in WAWTTAR. Therefore, none of these tools offers a complete flexibility to the user in terms of the unit processes that can be joined to form a treatment train and the way in which they can be combined. In addition, both the unit process design information and the evaluation criteria for treatment trains included in the MOSTWATER knowledge base are fixed.

The main goal of the development of WTRNet is to incorporate both the process synthesis and water distribution aspects of reuse schemes in an integrated DSS. The development of WTRNet is aimed at providing a DSS that will overcome some of the limitations that appear in currently available decision support tools, by including the following features:

- The ability to include multiple treatment facilities within a wider water reuse scheme in the evaluation where the treated wastewater could be upgraded at several sites to meet the specific quality requirements of multiple users (distributed treatment).
- Provide a completely open modelling environment that will allow users the flexibility in terms of editing the information contained in the model knowledge base and adding information to the 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 layout and locations of pumping, transmission and storage facilities and providing a least-cost preliminary sizing of the distribution system that meets all operational requirements.

The following section describes the combined hydraulic/process simulation component of WTRNet. The simulation model allows planners of reuse schemes to explore a large number of design alternatives (treatment and distribution) in an efficient manner for the purpose of identifying the most promising schemes. The simulation model will be used at a later stage in an optimisation framework for synthesis of treatment trains and the topology of the distribution network, which will form a complete DSS for integrated water reuse schemes.

4. Model description

The simulation model was developed using Visual Basic^{TM} and provides a user-friendly graphical interface consisting of a main form that is used to display the locations of facilities comprising a water reuse scheme and a series of forms used for editing the input data and the display of results. The model uses project files to store the knowledge base and user-entered information. The developed simulation model includes a default knowledge base, as well as separate computational modules for wastewater treatment schemes and the reclaimed water distribution system.

4.1. Model knowledge base

The model 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 on the distribution system components. The information contained in the knowledge base has been assembled by several AQUAREC project partners through a combination of literature survey and experience in designing and operating wastewater treatment and reuse schemes. A brief description of the information contained in the knowledge base is provided below.

The end users of reclaimed water are currently classified in eight different groups, shown in Table 1. The preliminary classification of types of end users currently included in the model knowledge base has been proposed by partners in the AQUAREC project, who are also developing the guidelines for the quality requirements for each type of end use based on existing guidelines around the world.

The key steps in the development of the knowledge base were identification and collection of information on individual unit processes that could be used to form treatment schemes to be evaluated. For each unit process currently included in the knowledge base and shown in Table 2, the following information was assembled: allowable influent quality 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 them to review all the information and alter the expressions used in the calculation to suit local conditions.

Several approaches were considered for inclusion in WTRNet to guide the user through the generation of treatment trains, and two methodologies were developed with the intention of allowing as much flexibility as possible in generating treatment trains and at the same time providing some useful guidance. The methodologies currently included in WTRNet include are the Expert approach and the Step-

Table 1
Reclaimed water end uses included in the model knowledge base

End-use type	Description/examples
Residential	Residential uses: private garden irrigation, toilet flushing, home air conditioning systems, car washing; Aquifer recharge by direct injection
Urban	Urban uses and facilities: irrigation of open access landscape areas (parks, golf courses, sport fields, etc.); Street cleaning, fire-fighting, ornamental impoundments and decorative fountains; Greenhouse crops irrigation; Irrigation of raw consumed food crops; Fruit trees sprinkler irrigated
Irrigation (restricted)	Irrigation of pasture for milking or meat animals; Irrigation of industrial crops for canning industry and crops not raw-consumed; irrigation of fruit trees except by sprinkling; Irrigation of industrial crops, nurseries, fodder, cereals and oleaginous seeds; Impoundments, water bodies and streams for recreational use in which the public's contact with the water is permitted (except bathing)
Impoundments	Impoundments, water bodies and streams for recreational use where public's contact with water is not permitted Irrigation of forested areas, landscape areas and restricted access areas; Forestry; Aquiculture (plant or animal biomass); Aquifer recharge by localized percolation through the soil
Industrial	Industrial cooling, except for the food industry
Surface	Surface water quality (potable water)
Bathing	Bathing water
Irrigation (unrestricted)	Unrestricted irrigation

Wise approach. For the Expert approach, suggestions regarding the possible treatment trains that could be used for influent quality/end-use combinations were compiled based on an extensive review of reuse schemes around the world conducted by a number of AQUAREC project partners. The influent quality is broadly differentiated between raw wastewater, primary effluent and secondary effluent. For each combination of the influent quality and intended end use, a list of "typical" treatment trains has been assembled, which can be used by a software user as staring points in the investigation of treatment alternatives. In the Step-Wise approach, the user begins the treatment train assembly process by first selecting the end influent quality and the end use of reclaimed water, and then by inserting unit processes The rules that guide the user in the selection of unit processes are kept simple, and identify logical pre- and post-cursors for each unit process that are combined for processes contained in the treatment train when a new process is to be added.

The distribution system information contained in the knowledge base includes expressions for calculating costs of pipes, pumping, and storage facilities. Calculation of pipe unit costs is conducted separately depending on land-use in the areas of installation (rural, suburban and urban). The pumping cost expression is based on the capacity in terms of the flow and head required. Costing of storage facilities includes four types of storage elements: reservoirs, covered concrete tanks, concrete tanks and earthen basins.

Table 2
Unit processes included in the model knowledge base

Category	Unit processes
Primary	Fine screen Sedimentation w/o coagulant Sedimentation w/ coagulant DAF w/ coagulant Membrane filtration Actiflo®
Secondary	High loaded activated sludge + secondary sedimentation Low loaded activated sludge w/o de-N + secondary sedimentation Low loaded activated sludge w/ de-N + secondary sedimentation Trickling filter + secondary sedimentation RBC Submerged aerated filter Stabilization pond Constructed wetland Membrane bioreactor EBPR P-Precipitation
Tertiary	Filtration over fine porous media Surface filtration Microfiltration Ultrafiltration Nanofiltration Reverse osmosis GAC PAC Ion exchange Advanced oxidation SAT Maturation pond Constructed wetland — polishing Flocculation
Disinfection	Ozone Paracetic acid Chlorine dioxide Chlorine gas UV radiation

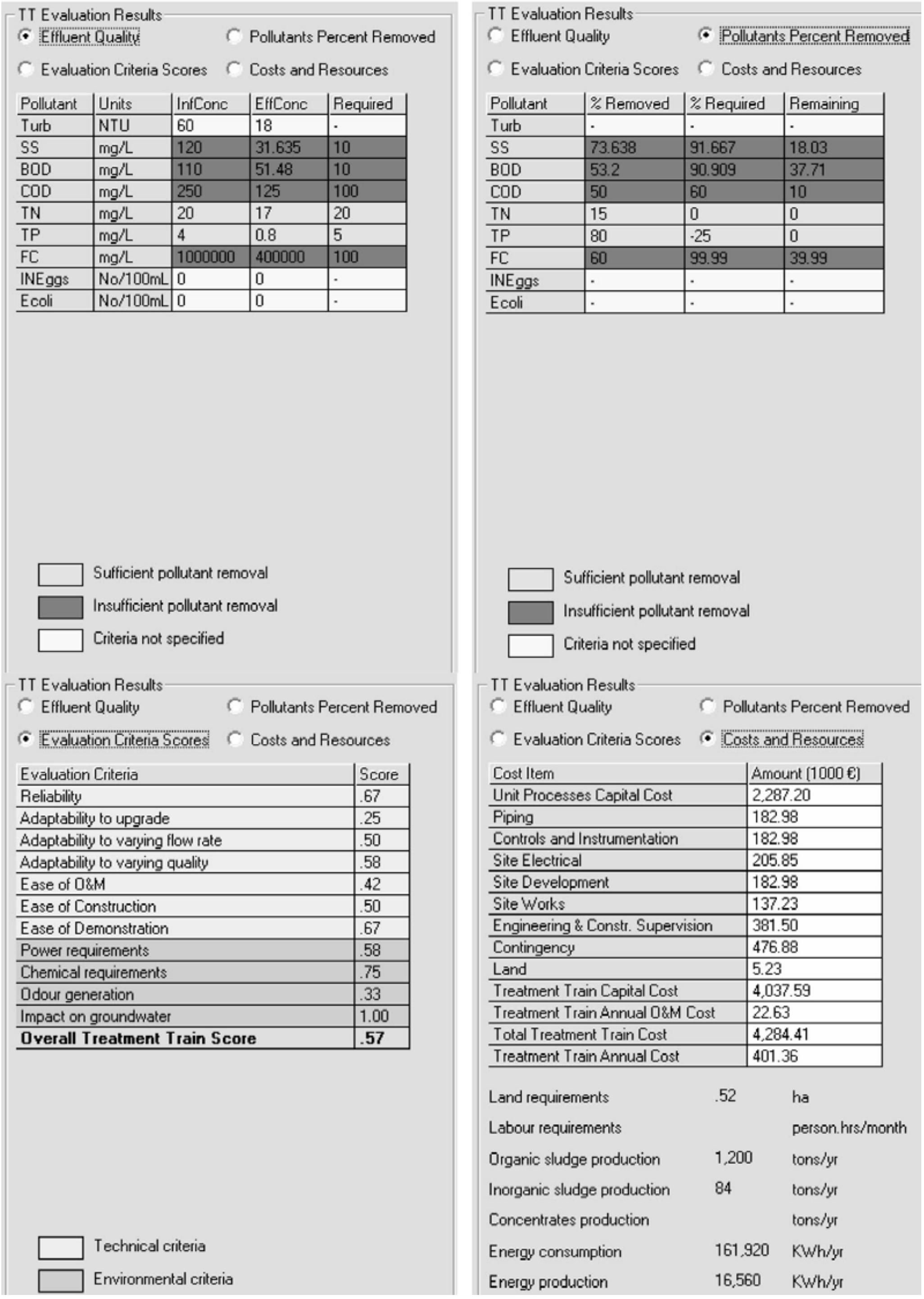
4.2. Treatment performance module

The treatment performance module was developed with functionality to perform the evaluation of user-selected combination of unit processes in a treatment train. The evaluation of alternative treatment trains includes sizing the unit process, calculating the effluent quality achieved by the current treatment train, evaluation criteria scores, costs and resources. Details of the last three results contained in the output of the treatment train evaluation are shown in Table 3.

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 are displayed through four separate frames on the form: effluent quality, pollutant percent removed, evaluation criteria scores and costs and resources. This is

Table 3
Treatment train evaluation criteria

Type of criteria	Name of criteria
Quantitative	Effluent quality Cost Land required Sludge and concentrate produced Energy balance
Qualitative: technical	Reliability Adaptability to upgrade Adaptability to varying flow rate Adaptability to changes in water quality Ease of O&M Ease of construction Ease of demonstration
Qualitative: environmental	Power requirements Chemical requirements Odour generation Impact on groundwater



TT Evaluation Results

● Effluent Quality ○ Pollutants Percent Removed

○ Evaluation Criteria Scores ○ Costs and Resources

Pollutant	Units	InfConc	EffConc	Required
Turb	NTU	60	18	-
SS	mg/L	120	31.635	10
BOD	mg/L	110	51.48	10
COD	mg/L	250	125	100
TN	mg/L	20	17	20
TP	mg/L	4	0.8	5
FC	mg/L	1000000	400000	100
INEggs	No/100mL	0	0	-
Ecoli	No/100mL	0	0	-

▢ Sufficient pollutant removal

▨ Insufficient pollutant removal

□ Criteria not specified

TT Evaluation Results

○ Effluent Quality ● Pollutants Percent Removed

○ Evaluation Criteria Scores ○ Costs and Resources

Pollutant	% Removed	% Required	Remaining
Turb	-	-	-
SS	73.638	91.667	18.03
BOD	53.2	90.909	37.71
COD	50	60	10
TN	15	0	0
TP	80	-25	0
FC	60	99.99	39.99
INEggs	-	-	-
Ecoli	-	-	-

▢ Sufficient pollutant removal

▨ Insufficient pollutant removal

□ Criteria not specified

TT Evaluation Results

○ Effluent Quality ○ Pollutants Percent Removed

● Evaluation Criteria Scores ○ Costs and Resources

Evaluation Criteria	Score
Reliability	.67
Adaptability to upgrade	.25
Adaptability to varying flow rate	.50
Adaptability to varying quality	.58
Ease of O&M	.42
Ease of Construction	.50
Ease of Demonstration	.67
Power requirements	.58
Chemical requirements	.75
Odour generation	.33
Impact on groundwater	1.00
Overall Treatment Train Score	**.57**

▢ Technical criteria

▨ Environmental criteria

TT Evaluation Results

○ Effluent Quality ○ Pollutants Percent Removed

○ Evaluation Criteria Scores ● Costs and Resources

Cost Item	Amount (1000 €)
Unit Processes Capital Cost	2,287.20
Piping	182.98
Controls and Instrumentation	182.98
Site Electrical	205.85
Site Development	182.98
Site Works	137.23
Engineering & Constr. Supervision	381.50
Contingency	476.88
Land	5.23
Treatment Train Capital Cost	4,037.59
Treatment Train Annual O&M Cost	22.63
Total Treatment Train Cost	4,284.41
Treatment Train Annual Cost	401.36

Land requirements	.52	ha
Labour requirements		person.hrs/month
Organic sludge production	1,200	tons/yr
Inorganic sludge production	84	tons/yr
Concentrates production		tons/yr
Energy consumption	161,920	KWh/yr
Energy production	16,560	KWh/yr

Fig. 1. Treatment train evaluation results.

illustrated in Fig. 1, which shows the four screens that display the results of an evaluation of a treatment train.

In addition to displaying the evaluation results for the treatment trains selected using one of the two methodologies presented above, the user has the option to save the treatment train currently displayed. Saved treatment trains are selected for display using a separate tab, which allows the user to quickly compare the treatment trains generated during the selection process, regardless of the methodology used.

4.3. Distribution system performance module

The distribution system performance computational module is used to optimally size the distribution system elements based on a predetermined branched layout and preferences of the user for locating the pumping and storage facilities. The least-cost sizing of the distribution system facilities is ensured by incorporating 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 conceptualised as consisting of a series of segments of user-selected standard pipe sizes, where the user selects the sizes they wish to be considered for each of the network links.

Prior to formulating and solving the LP problem, a series of operations are performed to verify the data consistency and calculate the values required for LP formulation. Data consistency checks include confirming the existence of supply and demand nodes, and absence of loops in the user-defined network. If the network passes all the data consistency checks, the following three procedures are performed: (1) identification of routes from supply nodes to demand nodes, (2) calculation of peak flows in all links, and (3) calculation of unit head losses using the Hazen-Williams or Darcy-Weisbach equation (selected by the user) for standard (available) pipe sizes. The LP problem is then formulated as follows:

- Minimize:

$$\sum_{ij \in A} \sum_{m=1}^{M_{ij}} c_{ijm} l_{ijm} + \sum_{k \in B} c_k p_k$$

- Subject to:

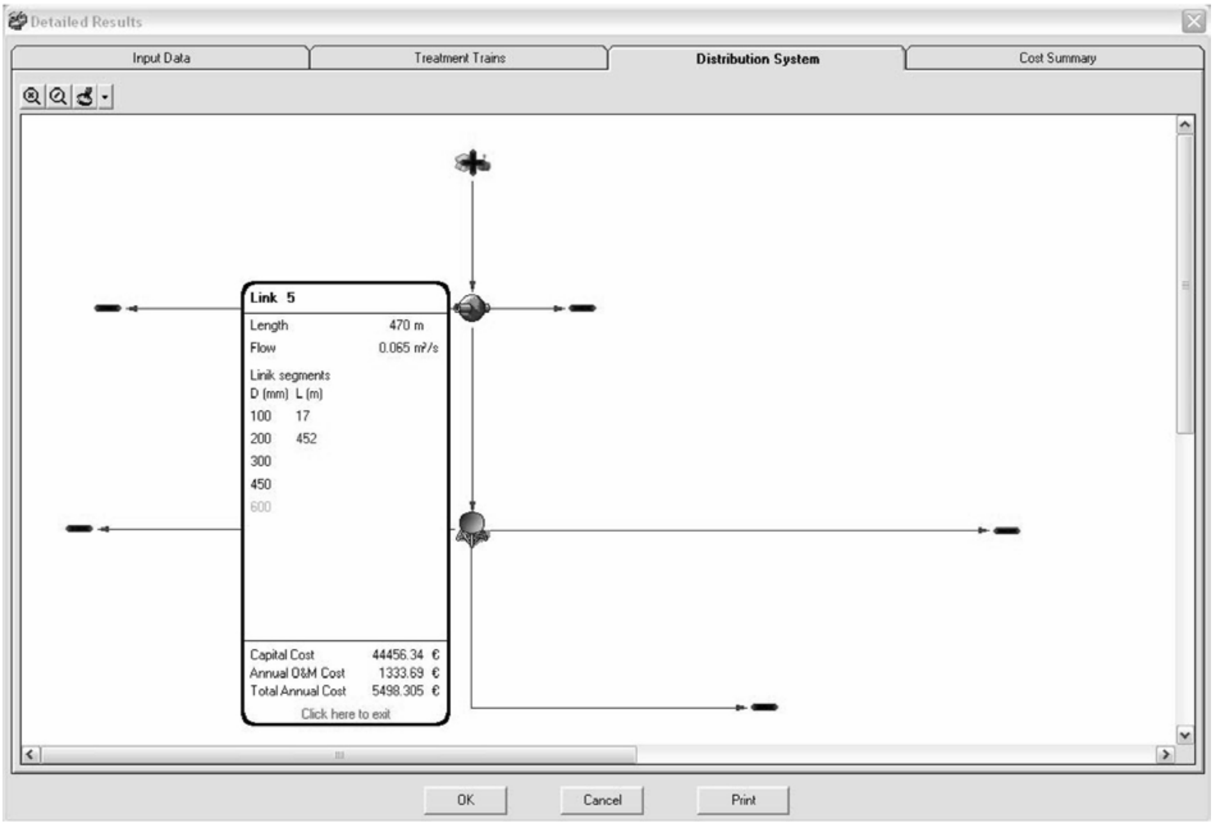
$$\sum_{k \in C} p_k - \sum_{ij \in D} \sum_{m=1}^{M_{ij}} h_{ijm} l_{ijm} \geq H_r, \ \forall_r$$

$$\sum_{m=1}^{M_{ij}} l_{ijm} = L_{ij}, \forall_{ij} \in A$$

$$l_{ijm} \geq 0, \quad \forall_{ijm}$$

were: A is the set of all network links described as ij node pairs, B the set of all network pumps, M_{ij} the number of diameter segments considered for link ij, c_{ijm} the unit cost of diameter segment m for link ij (€/m), l_{ijm} the length of pipe of diameter segment m for link ij (m), c_k the unit cost of the pumping station k (€/m), p_k the head provided by pumping station k (m), C the set of all network pumps on route r, D the set of all network links on route r, h_{ijm} the unit head loss of diameter segment m for link ij (m/m), H_r the required head for supply node of route r (m), and L_{ij} is the length of link ij (m).

The formulated LP problem is solved using the Mixed Integer Linear Programming solver lp_solve [24], integrated into WTRNet. The output of the distribution system performance module includes optimal values for pipe sizes for all node connections and capacities of pumping facilities (head and flow rate). These values are used to calculate and display the capital,



Link 5

Length 470 m
Flow 0.065 m³/s

Linik segments

D (mm)	L (m)
100	17
200	452
300	
450	
600	

Capital Cost 44456.34 €
Annual O&M Cost 1333.69 €
Total Annual Cost 5498.305 €

Click here to exit

Fig. 2. Distribution system evaluation results.

operating and maintenance, and annualized costs for each system component, as shown in Fig. 2, and for the distribution system as a whole.

5. Conclusions

The combined hydraulic/process simulation model presented here provides a comprehensive framework for analysis of infrastructural aspects of water reuse systems, including the integration of distribution and treatment elements, and assessment of feasibility of decentralised water reuse systems. The developed simulation model overcomes limitations of currently available decision support tools by: (1) providing a framework for analysing decentralised treatment schemes, (2) allowing the user as much flexibility as possible in generating and evaluating treatment trains, (3) providing some useful guidance and starting points to the user for evaluation of treatment alternatives, and (4) incorporating an optimisation routine for least-cost sizing of the treatment schemes distribution system. The simulation model forms the basis for the development of the WTRNet package that will also incorporate optimisation routines for synthesis of treatment trains and the topology of the distribution network to form a complete DSS for integrated water reuse schemes. The complete DSS will be made available, most likely as a commercial product, following the completion of the AQUAREC project in March 2006.

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