Optimal planning of water and wastewater management infrastructure for insular areas: the role of water reuse

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ABSTRACT

The present article estimates the financial benefits of water reuse by calculating the annualised total cost of water and wastewater management, using mixed integer linear programming. The programme is using as input: geographical data, population distribution, and groundwater availability (for a given area), to calculate the qualitative localised water needs, and to estimate the sizes and locations of water and wastewater management infrastructure, so as to minimise the relative annualised total cost (capital and operating). The programme is used to calculate the optimum water and wastewater infrastructure (and the relative annualised water and wastewater management cost), with and without the option for water reclamation and reuse. One case study is presented for the Greek islands of Santorini and Thirasia. The proposed model has showed significant computational benefit, compared with previous models. Thus, for Santorini–Thirasia Islands, the total annualised cost for optimum water and wastewater management infrastructures, with water reclamation, has been calculated as $2,153,694, while the above cost has been calculated as 19% higher, if water reclamation is not an option. It is obvious from the computational results that water reuse can reduce significantly the total water and wastewater management cost.

Key words | integrated water resources management, mixed integer linear programming, optimisation, water reuse

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INTRODUCTION

Water and wastewater management infrastructure is often planned without integrated approach, which often leads to high capital and operational costs (Sedlak *et al.* 2013). Moreover, water reclamation facilities are usually designed retrospectively, long after the commissioning of the wastewater treatment plants (Bischel *et al.* 2013). Such approach may limit the utilisation of reclaimed water and may result in high management costs (Gikas & Tchobanoglous 2009a). Islands have limited water recourses, often comprising of overexploited groundwater, and costly desalinated seawater (Solomon & Smith 2007; GSSW 2014). It is thus important to plan water and wastewater management in an integrated way, taking into account production, treatment and distribution cost. Appropriately treated wastewater can be used for non-potable applications, in place of groundwater or desalinated water as a more sustainable option and may contribute to overall water resources management cost reduction (Gikas & Angelakis 2009). The use of reclaimed water is currently promoted worldwide, and particularly in the Mediterranean basin (Kellis *et al.* 2013; Angelakis & Gikas 2014). Often, decisions about the installation of water/wastewater management infrastructure are often taken empirically if not arbitrary (Lienert *et al.* 2015). Lately, however, a number of modelling approaches have been proposed, most of which are based on mixed integer programming (Liu *et al.* 2011, 2012; Padula *et al.* 2013; Nápoles-Rivera *et al.* 2013;

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Al-Nory et al. 2014; Bocanegra-Martínez et al. 2014; Saif & Almansoori 2014).

In our previous work (Liu et al. 2011), an optimisation model was developed for water and wastewater management to assess total (capital and operating) annualised water and wastewater management cost, through mixed integer linear programming (MILP). To further enhance the computational performance especially for tackling large-scale problem instances, we aim here to develop a new efficient MILP model, under the assumption that the direction of water/wastewater flows keeps the same for all time seasons considered. Thus, the previous model (Liu et al. 2011) has been modified, by introducing a new binary variable and changing the corresponding constraints. The aim of the present paper is in two directions: on one hand the paper aims to develope a new approach for efficient optimisation for integrated water and wastewater management infrastructure, through MILP. On the other hand the paper aims to calculate the contribution of water reuse to the reduction of the total (capital and operating) annualised water and wastewater management cost. For the second aim, a case study for the Greek islands of Santorini and Thirasia is examined.

The structure of this paper is organised as follows: initially the problem statement, followed by the mathematical model is presented. Then, calculations are performed for the islands of Santorini and Thirasia and the computational results are shown. Finally, some conclusions are made.

PROBLEM STATEMENT

In this work, we consider insular water deficient areas. The considered area is divided into several sub-regions based on population distribution and land terrain. The population centres are the potential locations for the installation of wastewater treatment and water reclamation plants, while the potential locations for desalination plants are on selected areas near the seaside. The locations of groundwater abstraction wells are fixed and known. Only urban water uses have been considered, as agricultural irrigational water come from different individual sources. The urban potable water demands may be satisfied by desalinated water from seawater, and by available groundwater, while the urban non-potable demands, including water demands for landscape irrigation and for urban non-irrigational applications, may be satisfied by the above water sources and/or by reclaimed water from wastewater. Only the main water/wastewater conveyance pipeline networks are considered (local networks have not been taken into account). A schematic diagram for the urban water management is shown in Figure 1.

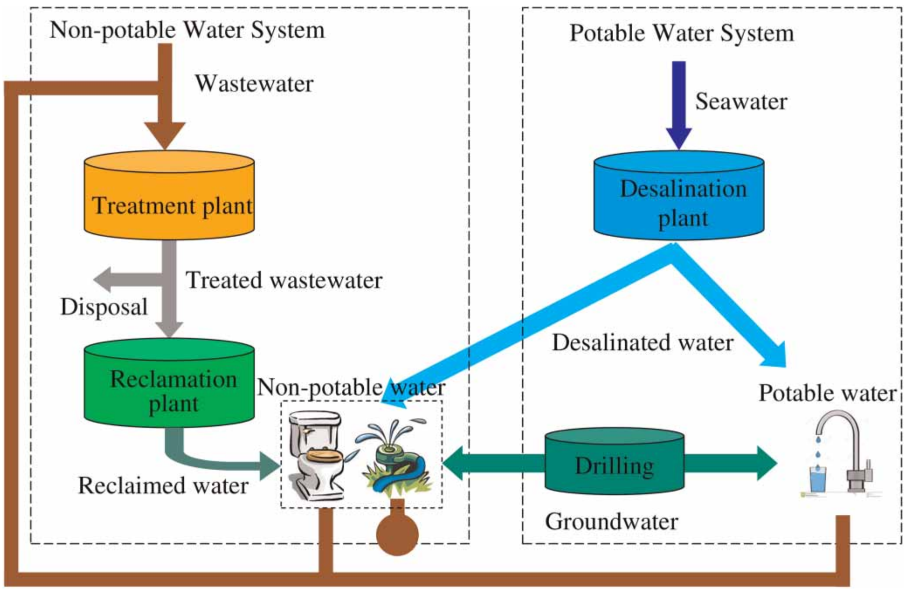

Figure 1 | Schematic of the potable and non-potable water systems.

In this work, the integrated water/wastewater management optimisation problem is calculated on the ground basis (the existing infrastructure is not taken into account). The following data are given:

- regions (built around the population centres);
- pairwise distances between the relative population centres and elevations;
- daily seasonal urban potable and non-potable water demands and wastewater productions in each region;
- capital costs of water/wastewater infrastructure (as a function of plant capacity);
- operational costs of desalinated water and reclaimed water production (additional treatment following wastewater treatment), and wastewater treatment;
- costs of pipelines (installed), as a function of pipeline length and pipe diameter;
- cost of steel storage tanks, as a function of storage capacity;
- types and costs of pumping stations;
- unit cost of electric power.

These will determine:

- locations and capacities of desalination, wastewater treatment and reclamation plants;
- pipeline main network for desalinated water, wastewater and reclaimed water, including piping diameters (local piping networks are not considered);
- daily volumes of desalinated water, wastewater and reclaimed water production;
- main flows of desalinated water, wastewater and reclaimed water between the regions;
- number, types and operation time of pumps for each established link.

These will minimise the total annualised cost, including both capital and operating costs. As mentioned above, the cost of the local water distribution systems and wastewater collection systems is not included here.

MATHEMATICAL MODEL

In this work, we propose an optimisation model based on the MILP model proposed by Liu *et al.* (2011). To reduce the computational complexity, it has been assumed that the directions of water/wastewater flows remain the same in all time periods. Based on our previous studies (Liu *et al.* 2011, 2012), we have noted that the direction of the flow within pipelines very rarely changes with season. Thus, a new binary variable, $\bar{Y}^w_{ijp}$, is introduced here to represent whether there is flow of water/wastewater w from location i to j in a pipe of size p. This new variable is to replace the binary variable Y^w_{ijp} in the model of Liu *et al.* (2011), which indicates whether pipe of size p is selected for water/wastewater w between locations i and j. The proposed model is formulated as an MILP model to minimise the total annualised cost. Here, we only present the constraints related to the new variable $\bar{Y}^w_{ijp}$ in the proposed model, which are different from the literature model. Please refer to Liu *et al.* (2011) for the details of the missing part of the proposed model.

Thus, for each link between two locations, only one pipe size can be installed and only in one flow direction.

$$\sum_p (\bar{Y}^w_{ijp} + \bar{Y}^w_{jip}\big|_{\{j,i\}\in L^w}) \leq 1, \quad \forall w, \{i,j\} \in L^w \tag{1}$$

where L^w refers to the allowed links in the network of water/wastewater w.

The pipeline capital cost (PLCC) is calculated based on unit pipe cost (PLC_p) and each link's distance (L_{ij}):

$$\mathrm{PLCC} = \sum_w \sum_p \sum_{\{i,j\}\in L^w} PLC_p \cdot L_{ij} \cdot \bar{Y}^w_{ijp} \tag{2}$$

By substituting the corresponding constraints and variable Y^w_{ijp} in the model proposed by Liu *et al.* (2011), with the above two constraints and newly introduced variable $\bar{Y}^w_{ijp}$, an MILP optimisation model is developed to minimise the annualised total cost (under the assumptions stated above in this section).

CASE STUDY

The model is tested on Santorini Island and the neighbouring Therasia Island in the Cyclades complex of the Aegean Sea. We take into account groundwater, which can be used for both potable and non-potable water needs. The estimated theoretical daily water consumption was increased by 25% due to water losses in the supply network. Based on realistic data, the potable water demand is assumed to be 60% of the total urban water demand, and the urban non-potable water demand is assumed to account for the remaining 40%. It is assumed that all the wastewater generated from the potable water system is collected for wastewater treatment. 75% of the non-potable water usage is for landscape urban irrigation (and thus it does not flow to the wastewater treatment plant after utilisation), while the remaining 25% is collected for treatment. Thus, the total wastewater collected for treatment accounts for 70% of total water usage. It is also assumed that the exploited groundwater in each population centre cannot exceed 80% of the groundwater that is currently used in an attempt to avoid aquifer overexploitation.

The whole area is divided into eight regions (R1–R14), in which R14 refers to the whole Therasia Island. There are six potential desalination plant locations at the sea side (D1–D6), and the wastewater treatment plants, reclamation plants and storage tanks are assumed to be at the population centre of each region (P1–P14). At each population centre, the water demands and maximum available groundwater supplies are shown in Table 1. Water and wastewater conveyance between Santorini and Thirasia, using submarine pipelines, is an option. The offshore length of such pipeline is about 2 km, and the cost (installed) has been assumed to be $600 per meter (regardless of pipe diameter-for the range of diameters that would suit the present case).

In this example, we consider a project of 20 years, and an annual interest rate of 5%. Two time periods in each year are considered (high-demand season for 4 months, and low-demand season for 8 months). We consider four potential pipe diameters, two pump types (for water or wastewater pumping), each with five potential sizes, and four potential storage tank capacities. A total of five breakpoints are taken into account for the piecewise linear functions of infrastructure capital costs and operating costs. It has been assumed that wastewater treatment is by activated sludge process, while water reclamation is by ultrafiltration (UF) membranes. Reverse osmosis (RO) membranes have been assumed for seawater desalination. The unit energy cost ($\$/m^3$) at each breakpoint and the capital cost (k$) of water/wastewater infrastructures have been derived from Gikas & Tchobanoglous (2009b), and have been adjusted with current market costs, and are given succinctly in Table 2. More details about the costs of plants,

Table 1 | Estimated water demands and available groundwater supplies for Santorini Island (m^3/day)

	Volume per day (summer/winter)						
	P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**
Total water demand	2,040/647	320/112	559/183	214/117	1,687/643	333/102	2,373/462
Available groundwater	34/31	86/91	95/65	74/45	131/104	70/68	1,329/575
	P8	P9	P10	P11	P12	P13	P14
Total water demand	443/137	712/291	325/120	992/385	403/187	880/268	162/70
Available groundwater	266/205	34/24	219/153	236/294	758/378	616/410	0/0

Table 2 | Unit energy cost ($\$/m^3$) and capital cost (k$) of water production and treatment infrastructures

	Unit energy cost ($\$/m^3$)			Capital cost of infrastructure (k$)		
Plant capacity (m^3/day)	**Desalination**	**Wastewater treatment**	**Reclamation[a]**	**Desalination**	**Wastewater treatment**	**Reclamation[a]**
50	1.500	0.045	0.023	100	190	80
1,000	0.750	0.038	0.018	650	1,300	320
2,500	0.600	0.030	0.012	1,500	2,400	800
5,000	0.525	0.023	0.008	2,300	5,100	1,200
10,000	0.450	0.015	0.005	3,200	10,000	1,600

[a]Additional cost following standard wastewater treatment.

pipes, pumps and storage tanks can be found in Gikas & Tchobanoglous (2009b) and in Liu *et al.* (2011).

RESULTS

The proposed MILP model was implemented in GAMS 24.0 (Brooke *et al.* 2012) using solver CPLEX 12.5 with four threads on a Windows 7 based machine with 3.20 GHz six-core Intel Xeon processor and 12.0 GB RAM. The optimality gap in this case study is set to 2%.

For this example, we examine the following three scenarios to calculate the financial benefits from the water reclamation and reuse.

1. 'Optimal': the optimal planning of the water and wastewater management, with option for water reclamation and reuse in each region, is investigated. In this scenario, both a literature model (Liu *et al.* 2011) and the proposed MILP model in this work are solved for comparison. For the next two scenarios, only the proposed new model is applied.
2. 'No reclamation': no water reclamation plant is installed. Then, the reduced proposed MILP model is solved with allowance for water reclamation plants.
3. 'Retrospective reclamation': in this case, initially the optimal infrastructure without water reclamation is calculated (exactly as calculated for the Scenario 2); then, the additional optimal infrastructure for water reclamation is calculated. This case differs from Scenario 1, as the optimal reclamation infrastructure is considered retrospectively, to the system that has been initially optimally designed without water reclamation.

Based on parallel run of the new model and the model proposed previously (Liu *et al.* 2011) it was concluded that, for Scenario 1, both approaches lead to the same optimal solution; however, the new model requires less than 4% of the computational effort that is required by the previous approach (Liu *et al.* 2011), saving about two orders of magnitude in CPU time (Table 3). Thus, the computational advantage of the proposed model is very significant. As to the cost comparison among all scenarios, Scenario 2 has the highest total annualised cost, while Scenario 1 has the lowest. Assuming Scenario 1 as the basis for cost

Table 3 | Computational results of three scenarios for Santorini–Thirasia Islands

	Scenario 1			
	Literature model (Liu *et al.* 2011)	This model	Scenario 2 (this model)	Scenario 3 (this model)
Total annualised cost ($)	2,153,694	2,153,694	2,571,940	2,342,906
Cost difference	–	–	19.4%	8.8%
CPU (s)	10,744	414	28	29

calculations, the total annualised cost of Scenario 2 is 19.4% higher, and that of Scenario 3 is 8.8% higher.

The breakdowns of the total annualised cost for all three scenarios are given in Figure 2(a). Obviously, Scenario 1 has the lower annualised cost; however, in Scenario 1 the annualised capital and operational costs of wastewater treatment and water reclamation plants, as well as the annualised capital cost of pumps, is higher, compared with Scenario 2. The overall lower annualised cost of Scenario 1 (compared with Scenario 2) is primarily attributed to its much lower annualized capital and operational costs of the desalination plants. If water reclamation is considered retrospectively, after the implementation of Scenario 2 (Scenario 3), then about 10% total annualised savings primarily occur due to the reduced operational costs of desalination plants and pumps. Figure 2(b) presents the plant locations and pipeline networks for all scenarios. All scenarios suggest the construction of four desalination plants, but Scenario 1 indicates the desalination plant in D1, while D4 is selected when no reclamation is considered in Scenario 2. Scenario 1 suggests eight wastewater treatment plants, one more than Scenario 2. Wastewater treatment plants at P1 and P10 are suggested by Scenario 1, however, those plants are not suggested by Scenario 2, in which a wastewater treatment plant at P4 is proposed instead. Scenario 1 suggests eight water reclamation plants, two more (P1 and P10) than for Scenario 3. When considering the installation of retrospective reclamation in Scenario 3, no water reclamation occurs at P4, where a wastewater treatment plant already has been suggested by Scenario 2. It can be observed that Scenario 1 has neither a centralised network that incurs

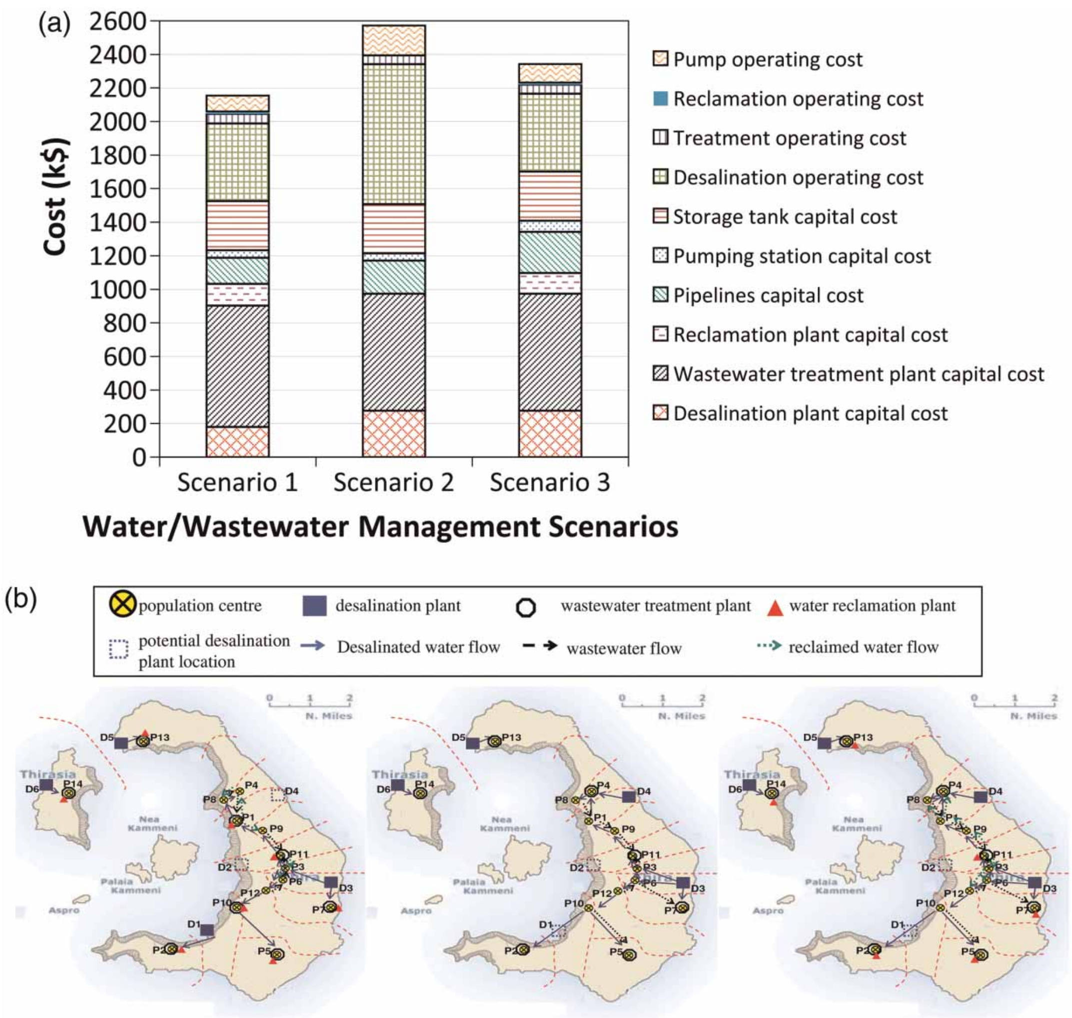

Figure 2 | (a) The breakdowns of the optimal annualised total cost and (b) the optimal plant locations and networks of the three scenarios for Santorini and Thirasia Islands.

high pipeline and pump costs, nor many local plants without interactions, which adds heavy costs onto the production. Thus, the optimal solution with minimum total annualised cost is the result of trade-offs among all relevant cost terms.

Figure 3 shows the optimal water production at all established plants. In the four desalination plants built at sites D1, D3, D5 and D6, most of the production (>90%) occurs at D3. Also, it can be noted that the desalination plants at D1 and D5 operate only in summer. Wastewater treatment plants and water reclamation plants are suggested to be established in eight population centres. It can be observed that the wastewater treatment plants at P1, P5, P7 and P11 have higher treatment rate. As to reclamation, the water reclamation plant at P1 has the highest production in both summer and winter. Meanwhile, the water reclamation plant at P7 has very low production during winter, although it operates at high flows in the summer. Both reclamation plants at P10 and P13 do not operate during winter.

CONCLUSIONS

In this work, we developed an efficient MILP optimisation model for integrated management of the water and wastewater in insular areas. In the model, the total annualised cost, including both capital and operating costs, are

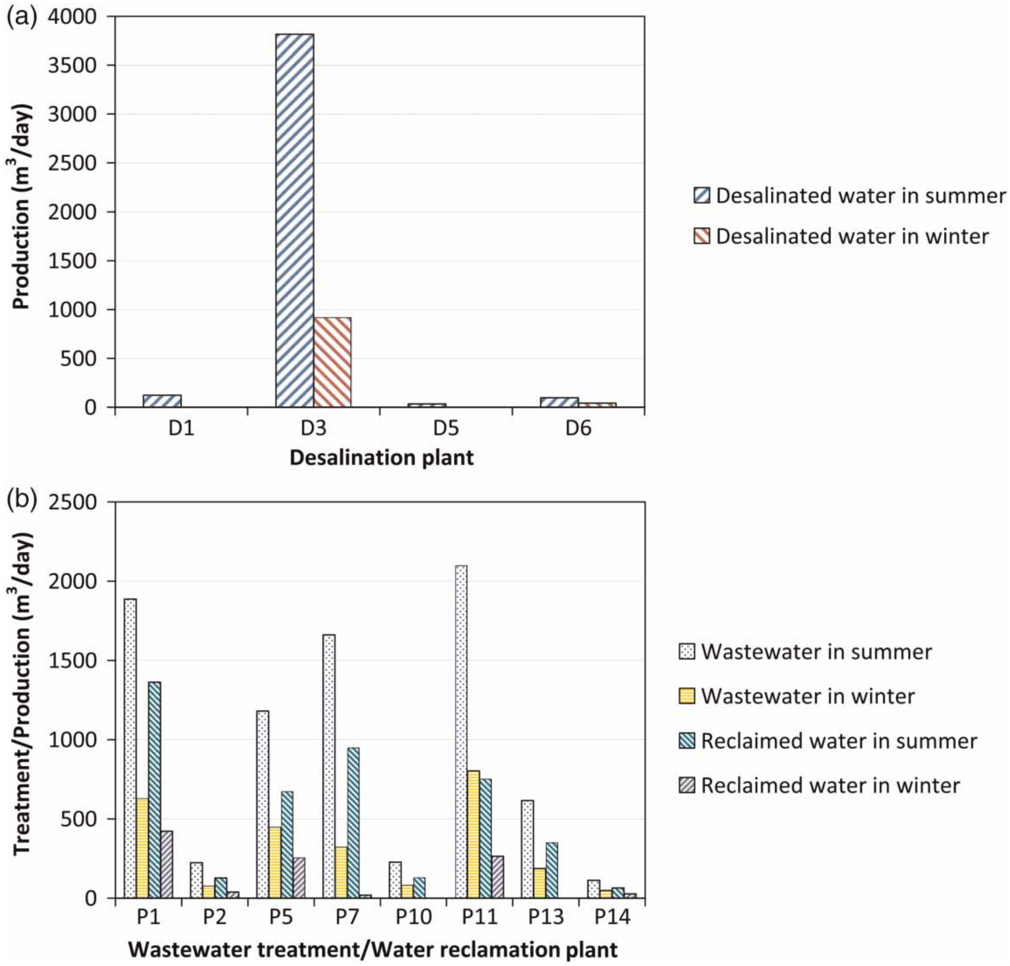

Figure 3 | Optimal productions of (a) desalination plants and (b) wastewater treatment and water reclamation plants for Santorini and Thirasia Islands.

minimised to determine the locations and capacities of the desalination, wastewater treatment and water reclamation plants, and the water conveyance pipeline networks. The computational results from the case study in the complex Santorini–Thirasia Islands, in Greece indicate that the proposed MILP model has obvious computational advantages compared to the previously presented model (Liu *et al.* 2011). Also, the comparisons between the investigated scenarios show that water reuse can significantly reduce the total water and wastewater management cost. The benefit is maximised if water reclamation facilities are planned along with the remainder of the water and wastewater infrastructure, as retrospective decision for water reclamation results to increased costs (though lower compared with the complete absence of water reclamation).

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