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Resilience-Based Performance Assessment of Water-Recycling Schemes in Urban Water Systems

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Abstract

Water reuse schemes in urban water system are assessed in this paper against a number of hydraulic performance indicators. A city metabolism model, WaterMet^2, is used to evaluate the performance of water reuse schemes. A multi-objective evolutionary algorithm is employed to identify Pareto optimal solutions for the following three objectives: resilience, reliability and total cost. The demonstration of the suggested approach on a real-world case study show the importance of using the resilience index for determining the appropriate schemes. The results suggest, in the case analysed here, the rainwater-harvesting scheme plays a significant role for improvement of resilience index.

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Keywords: Resilience index, reliability, urban water system, water reuse schemes, rainwater harvesting, grey water recycling;

1. Introduction

Given increasing water scarcity, owing principally to climate change and population growth, water reuse is receiving more attention as a viable option in the planning and management of urban water systems [1]. This can be especially critical when the expansion of water resources for handling water deficits is impossible owing to either limited capital budget or the absence of additional water resources. The application of water recycling schemes in urban water management has gained considerable attention, worldwide, in the recent decades as an alternative and supplementary water resource in the context of integrated water resources management [2]. Due to the high costs of

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collection and treatment, public concerns about public health and environmental issues, the application of water reuse has been limited, primarily, to non-potable use such as agricultural and landscape irrigation [2]. However, the scale of water recycling application depends on some important factors, such as increased water scarcity of water sources, technological advancements, the high cost of providing fresh water, increased public acceptance and improved understanding of public health risk. In an integrated urban water system (UWS) including water supply, stormwater and wastewater subsystems, the advantages of employing water reuse schemes are shared between all three subsystems [3]. For example, while rainwater harvesting and grey water recycling schemes can reduce, respectively, stormwater runoff and sanitary sewage discharging into the sewer system, they simultaneously result in a reduction in potable water demand. Therefore, an appropriate selection of these schemes, with respect to economic and environmental criteria, appears to be a viable alternative for non-potable water demand. Despite the existence of advanced technologies in water recycling, and aside from public concerns, there remain issues relating to the extent of the performance improvement in an integrated UWS when water reuse is included. Generally, previous research has principally addressed the potential potable water reduction, environmental and economic criteria [4, 5]. In addition, experience suggests that the successful design and implementation of these novel practices are not always straightforward [6]. In one of the recent work, Rozos *et al.* (2010) identified and assessed the optimal size of water recycling schemes under three basic climatic categories (oceanic, Mediterranean, and desert) [4]. The performance indicators used for comparison between the schemes were cost, potable water reduction and energy consumption of the schemes. The consideration of reliability and resilience measures has become a common practice in recent years for the evaluation of water system performance [7]. However, the impact assessment of recycling schemes in UWS with respect to these measures has yet to be included. In this paper, these performance measures are integrated into the assessment of water reuse schemes in UWS. The methodology is described in the next section, followed by an introduction to the case study and the presentation of results and discussion. Finally, conclusions are drawn and some recommendations are made.

2. Methodology

This study seeks to evaluate the performance of water reuse schemes in an existing UWS using a number of hydraulic performance indicators (PIs). The schemes analysed here are rainwater harvesting (RWH) and grey water recycling (GWR) as two common water-reuse mechanisms [4]. The performance assessment of these schemes in an UWS is undertaken by using the WaterMet^2 model. WaterMet^2 is a conceptually-based model which evaluates the performance of an integrated UWS over a long-term planning horizon [8]. WaterMet^2 quantifies the principal water-related flows and other metabolism-based fluxes in the UWS such as materials, chemicals, energy and greenhouse gas emissions [3]. A number of indicators derived from agreed-upon sustainability criteria can be introduced to describe the possible performance of UWS. A resilience index, reliability of water supply and total costs are three indicators which are used here as performance measures in the UWS. Note that these indicators are of quantitative measures in the sustainability framework in water systems [9] but a comprehensive comparison should also include qualitative criteria. These indicators are described in the next section in more detail. Two different approaches for designing the aforementioned schemes are examined here: (1) predefined strategies based on conventional designs for water reuse schemes recommended in the literature; (2) using an optimization model for determining an optimal design of the schemes. The detailed description of these two approaches is presented below.

2.1. Performance indicators

The three PIs analysed here are: (1) reliability of water supply; (2) a resilience index and (3) total cost. The first two PIs are based on the system performance measures initially proposed by Hashimoto *et al.* (1982) [10]. They describe system performance from three different perspectives: (1) how often the system fails, reflecting system reliability; (2) how quickly the system returns to a satisfactory state once a failure has occurred, reflecting system resilience; and (3) how significant the likely consequences of a failure may be, reflecting the vulnerability of a system and its customers. While the failure is essentially related to the actual structural failure in a system component, the operational status of the system can be described as either satisfactory or unsatisfactory relative to a failure threshold [10]. This concept is used here for defining the occurrence of supply/demand balance failures in the UWS. More specifically, any undelivered water demand (occurring in a time step) is defined here as a failure occurrence. The reliability of water supply system combines the system reliability and vulnerability metrics defined previously by Hashimoto *et al.* (1982) [10]. Hence, the reliability of water supply is expressed as the ratio of the total water delivered to customers (S_i) to the total water demand (D_i):

$$\text{Reliability} = \sum_{i=1}^{ntimestep} S_i \Big/ \sum_{i=1}^{ntimestep} D_i \times 100 \tag{1}$$

Several approaches have described a resilience index based on how quickly the UWS can recover from a failure [7]. Let T_F be the length of time (i.e. a number of consecutive time steps) during which water demand is not fully delivered. The following two definitions of resilience index are used here:

(1) Resilience defined as the inverse of the maximum duration of failure time that the UWS can experience over a specified planning horizon:

$$\text{Resilience1} = \frac{1}{MaxT_F} \tag{2}$$

(2) Resilience defined as the inverse of the expected value of T_F over a specified planning horizon, as expressed in Eq. (3). Hashimoto *et al.* (1982) [10] showed that this is equivalent to the ratio of the probability of a satisfactory state following an unsatisfactory state (i.e. $X_t \in F$ and $X_{t+1} \in S$) to the probability that a system is in an unsatisfactory state ($X_t \in F$) as below:

$$\text{Resilience2} = \frac{1}{E(T_F)} = \frac{\text{Prob}\{X_t \in F \text{ and } X_{t+1} \in S\}}{\text{Prob}\{X_t \in F\}} \times 100 \tag{3}$$

where X_t and X_{t+1}=system output at time t and $t+1$ respectively; F and S=set of all unsatisfactory and satisfactory outputs, respectively. Given that the planning horizon is definite, the second resilience definition can be expressed as the ratio of the number of times a satisfactory state follows an unsatisfactory state to the number of times an unsatisfactory state occurs [11]. Note that failure durations lower than the smallest time step in the simulation model (i.e. daily in the case of WaterMet^2) cannot be captured by this metric. The total cost in this paper comprises all capital and operational expenditure of the UWS including water-recycling schemes over the planning horizon, discounted to the present value with a specified discount rate. The capital cost relates in particular to the water recycling schemes, which are installed in the UWS at specific times over the planning horizon. The operational costs include any fixed (e.g. labour and maintenance) and variable (e.g. energy) costs incurred in the different UWS components.

2.2. Design of water reuse schemes

Some of the general scheme design parameters, which are similar between the two proposed design approaches (i.e. conventional and optimised), are outlined in this section. The costs of the two recycling schemes (i.e. RWH and GWR) are as follows. The household RWH scheme has an upfront capital investment and an annual operational expense of €530/m^3 and €24/m^3/year, respectively [12]. Similarly, a household GWR scheme capital and operational costs are estimated to be €1,512/m^3 and €38/m^3/year, respectively [13]. The electricity required for the operation of the RWH and GWR schemes is estimated to be 0.54 and 1.84 kWh/m^3, respectively [13, 14]. The many small RWH and GWR units located across the UWS are represented in WaterMet^2 by using a single RWH and GWR scheme located in each WaterMet^2 subcatchment modelled. The water recycled from both schemes is assumed to be used for toilet flushing, irrigation and industrial uses. Other RHW and GWR scheme design parameters such as tank size, year of installation, inflows and overflows for each type of tank is determined by using either of the two approaches outlined below. For any additional inflow/overflow added to either of the two schemes, it is assumed that an increase of 10% in the basic capital and operational costs is incurred.

2.2.1. Predefined design of water recycling schemes

In this approach, the tank capacities of the household RWH and GWR schemes considered are predefined at 3m^3 and 0.244m^3, respectively, based on the recommendations of conventional designs [12]. The RWH scheme is assumed to collect runoff from roofs, roads and pavements and to supply water for toilet flushing, garden watering and industrial usages. The RWH scheme can overflow into the GWR tank if available. The GWR scheme also collects grey water from the hand basin, dishwasher, shower, washing machine and frost tapping. Both recycling schemes are assumed to be installed in year 5 of the planning horizon as it could be the start time of water deficit. Two rates of adoption (25% and 50% of all households) are considered for both schemes. Based on these two rates, six individual/combined intervention options for conventional design of these schemes are defined as shown in Table 1 (i.e. options #2-7). This Table also includes a business as usual (BAU) option in which no water recycling schemes are added to the analysed UWS over the planning horizon.

2.2.2. Optimised design of water recycling schemes

Unlike in the above approach, the design parameters of the two water recycling schemes are determined by using a multi-objective optimization model. More specifically, the objective functions are to (1) maximize the reliability; (2) maximize the resilience (second definition) and (3) minimize the total cost. The multi-objective evolutionary algorithm NSGA-II [15] is used to solve this optimisation problem. The decision variables (genes) of each solution (chromosome) are shown in Fig. 1 and include 13 design parameters for both schemes related to each WaterMet^2 subcatchment. Of these genes, the capacity of tanks is a real value ranging between 0 and 3.125 m^3 for a household RWH scheme and between 0 and 0.3125 m^3 for each household GWR scheme. The start year of installation for both schemes is an integer value ranging between 5 and 10. Other genes with Boolean values are parameters related to the possibility of using different inflows for each scheme plus a single overflow for RWH scheme.

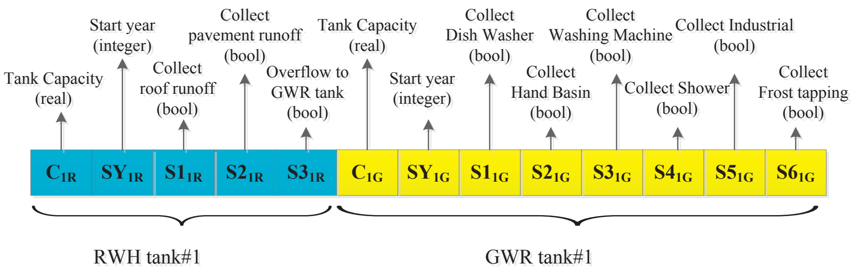

Fig. 1. Chromosome representation

3. Case study

The above methodology is demonstrated here on a real-world UWS of the city of Oslo in Norway as a reference city combined with assumptions when necessary. The city is likely to face challenges in the future due to population growth and increasing urbanization. To analyse this, a planning horizon of 30 years was established. The real-world UWS was modelled an integrated UWS including water supply, wastewater and stormwater collection. Two existing water resources, each connected to a WTW, and water distribution pipelines comprise the current water supply subsystem. The wastewater subsystem is characterised by a largely combined/separate sewer system along with two WWTWs. The UWS was modelled here by using the WaterMet^2 tool as an aggregated model with a daily time step. Single WaterMet^2 subcatchment with associated Local area is used to define water consumption. The water demand in the UWS is split into domestic, industrial (commercial), garden watering, frost tapping and unregistered public use.

The domestic (indoor) water demand per capita is further split into six types of appliances and fittings including dishwasher, washing machine, hand basin, toilet, shower and kitchen sink. The UWS consists of 320,000 household properties. Additional detail of the WaterMet^2 model in the UWS can be found in [3, 8, 16].

4. Results and discussion

The performance of the six recycling scheme-based intervention options and the Business As Usual strategy (BAU) is compared first. The PIs of all intervention options including BAU calculated by the WaterMet^2 model are displayed in Table 1. As it can be seen from this table, the implementation of all water reuse schemes has improved the UWS performance in all cases when compared to the BAU option. However, the improvements in two resiliencies obtained by using the options based on GWR only (#4 and #7) is rather modest and has even declined for resilience 2 in strategy #7. Opposite of that, the intervention options based on RWH only (#3 and #6) are demonstrating more substantial improvements in UWS resiliencies. This is possibly because of high potential of rainwater to compensate water deficits over failure periods. This introduces RWH scheme as a good supplementary water source in this region for long-time water failures. The maximum increase of resilience and reliability has been obtained from the intervention option with the highest rate of adoption for GWR and RWH schemes (#2), however this increased the total costs the most. Following above, optimisation based approach was used to determine the design parameters of RWH and GWR schemes. After a limited number of trial runs, the NSGA-II parameters were set as follows: population size of 50, tournament selection operator, one-point crossover with the probability of 0.9 and mutation probability of 0.4 & 0.1 for real and integer/Boolean genes, respectively. These values were rigorously checked so that a fast convergence could be obtained, and the solutions reached were robust enough in different optimisation runs.

Table 1. Performance indicators for different conventional water recycling intervention options

	Maximum failure duration (days)	Resilience1 (1/day)	Resilience2 (%)	Reliability (%)	Total costs (Million Euros)
#1 BAU (business as usual)	2945	0.0003	2.5	94.4	1600
#2 (50% GWR + 50% RWH schemes)	27	0.0370	23.8	98.6	2118
#3 (50% RWH scheme)	76	0.0132	17.7	96.6	2033
#4 (50% GWR scheme)	420	0.0024	3.0	97.5	1688
#5 (25% GWR + 25% RWH schemes)	43	0.0233	18.5	97.5	1853
#6 (25% RWH scheme)	76	0.0132	16.3	96.3	1810
#7 (25% GWR scheme)	1820	0.0005	2.3	96.2	1645

The Pareto optimal front was obtained from running the optimization model with 600 generations, which no further progress was observed afterwards. Fig. 3 illustrates the three Pareto optimal trade-offs between respective objective functions (reliability, resilience 2 and total cost). As it can be seen from Fig. 3, each optimal solution in this front represents a set of optimal values for water reuse schemes in the UWS. The PIs of the seven intervention options using conventional designs (see Table 1) are also shown in the plots of this figure.

The following can be inferred from Fig. 2: (1) The Pareto optimal front obtained from the optimization model represents the range of achievable improvements of the UWS performance indicators in terms of different sizing of these schemes. For instance, the reliability and resilience indices with respect to the BAU strategy (i.e. 94.4% and 2.5% respectively) can be improved considerably, up to 99.8% and 34.0%, respectively with a total cost of around €1,960m; (2) Fig. 2c shows a relatively direct correlation between resilience and reliability indices for optimal solutions. This correlation would suggest that increasing either of these indices can improve the other one and vice versa. (3) The suitability of the predefined strategies can be assessed better in these trade-offs relative to the Pareto optimal solutions. For example, the best predefined strategy obtained prior to optimisation (strategy #2 in Table 1) represents a far worse solution than the corresponding Pareto optimal solutions. In other words, for some predefined strategies, there are equivalent optimal solutions in which both reliability and resilience indices improved while the total cost has been significantly reduced. (4) The closest strategies to the Pareto optimal solutions with respect to reliability-cost trade-off (Fig. 2a) are those containing only GWR schemes (i.e. #4 and #7) although their resilience values are much lower than the similar solutions in the Pareto optimal front (see Fig. 2c). The lower value of resilience for these strategies can be attributed to the lack of the RWH scheme; (5) On the other hand, adding a RWH scheme with 25% adoption would cause resilience to increase considerably up to around 20% but any further increase in RWH tank size represents no significant improvement in resilience. This can be attributed to the maximum potential of the RWH tank for resilience improvement in the UWS.

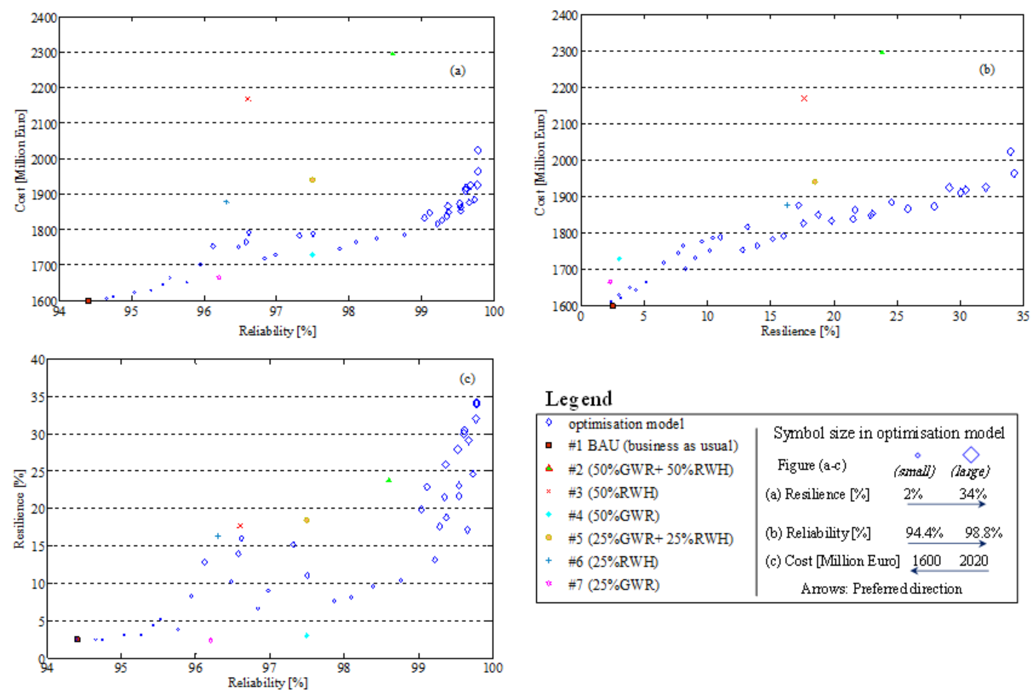

Fig. 2. Pareto trade-offs in the optimised design approach for: (a) cost and reliability; (b) cost and resilience and (c) reliability and resilience.

To further explore whether there is a link between the two defined resilience indices, i.e. Eq. 2 and 3, they are illustrated in a scatter plot in Fig. 3a for all strategies and a trend line fitted between them. The power relation with a high R^2 value depicted in this figure shows a high correlation between these two resilience measures. The same can be observed between 52 Pareto optimal solutions in Fig. 3b which depicts the link between these two resilience indices by fitting a similar power trend line. The line with a high R^2 value confirms (again) a high correlation between the two definitions of resilience. All this indicates that either of the two definitions of resilience can be used to represent the UWS supply/demand balance resilience, i.e. no need to use both.

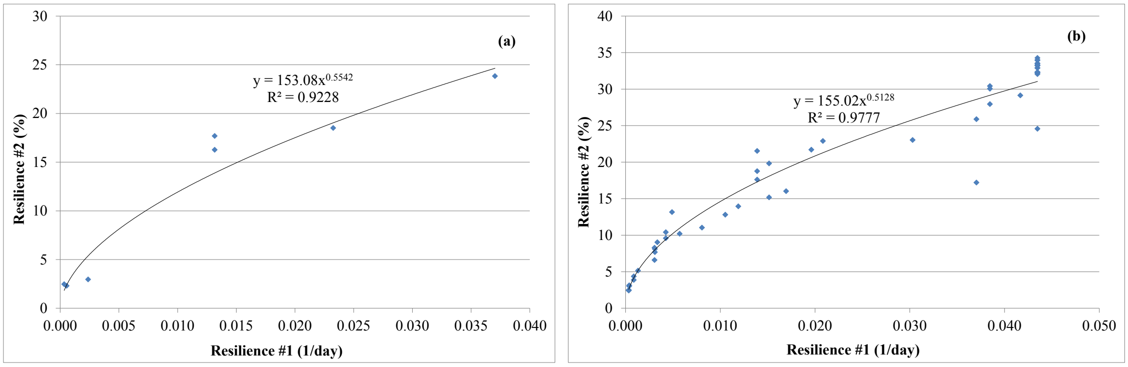

Fig. 3. Correlation between resilience 1 and resilience 2 obtained from (a) conventional design; (b) optimised design.

Fig. 4 demonstrates the variations of the tank size for both RWH and GWR schemes versus the total UWS cost obtained from the optimization model and seven pre-defined strategies. As shown in Fig. 4a, the optimal RWH tank size varies in a range between 0 and 158,000m^3 with an average size of 55,000m^3 - although this decision variable was in the range from 0 to 1,000,000 m^3. However, no correlation between the total cost and the RHW tank size is observed. The predefined strategies also seem to overestimate the RWH tank size compared to the optimal range. This suggests that rang of the optimum RHW tank size is lower than those recommended in the literature for the case analysed here. On the other hand, there is a stronger correlation between the optimal size of GWR tank and the total cost, as shown in Fig. 4b. The optimal GWR tank size of Pareto optimal solutions varies between the whole range of the decision variable (i.e. between 0 and 100,000m^3) with an average of 48,000 m^3. This also suggests it would be worth to relax the range of this decision variable to include more potential optimal solutions. In addition, the GWR tank sizes in the predefined strategies are within the optimized size and thus can be deemed as acceptable values for the UWS. As seen in Fig. 2a and 4b, the strategies which contain only GWR schemes (i.e. #4 and #7) appear to be the closest ones to the Pareto optimal solutions due to no overestimated RWH components in the system. However, further analysis militates against selecting them as appropriate solutions. For instance, comparing strategy #4 (50% GWR scheme) with the closest optimal solution to it (red rectangle in Fig. 4b) demonstrates that the reliability and resilience indices of the optimal solution (i.e. 97.9% and 7.7%, respectively) outperform those of this strategy (i.e. 97.5% and 3% respectively). Although the negligible improvement in reliability index can be compensated with respect to slightly increased total cost, the difference in the resilience index between these solutions is significant. This difference can be due to the existence of a RWH tank with a tank size of 47,500 m^3 in the optimal solution when there is little difference between the GWR tank sizes (i.e. 34,500 and 39,000 m^3).

5. Conclusion

The long-term performance of RWH and GWR schemes as two common water recycling schemes was analysed in the real-world UWS with respect to resilience and reliability of water supply/demand balance. The principal features of the two water recycle systems were obtained and compared by two approaches including predefined strategies, based on conventional designs and the strategies obtained using the MOEA optimisation. The three objectives used in the MOEA model were resilience, reliability and the total cost of the UWS. The results show that the two approaches examined here for resilience index are highly correlated and that either of them can be used as a resilience measure. The Pareto optimal solutions obtained show that both resilience and reliability of the conventional design can be significantly improved by means of optimisation. Specifically, the RWH scheme plays a substantial role in the resilience index improvement but an upper limit for its tank size was suggested in the optimisation model. They also demonstrate that, in the case analysed here, the selection of the appropriate RWH tank size is more critical for the overall cost reduction than the selection of the GWR tank size. The optimal range of tank sizes for both RWH and GWR schemes was also specified in the optimisation model. The results finally indicate the importance of using a resilience index for determining the optimal sizes of these schemes, especially for the RWH tank. The obtained results should be further evaluated on other case studies with different climates in order to derive some robust conclusions for applying water reuse schemes with respect to different PIs.

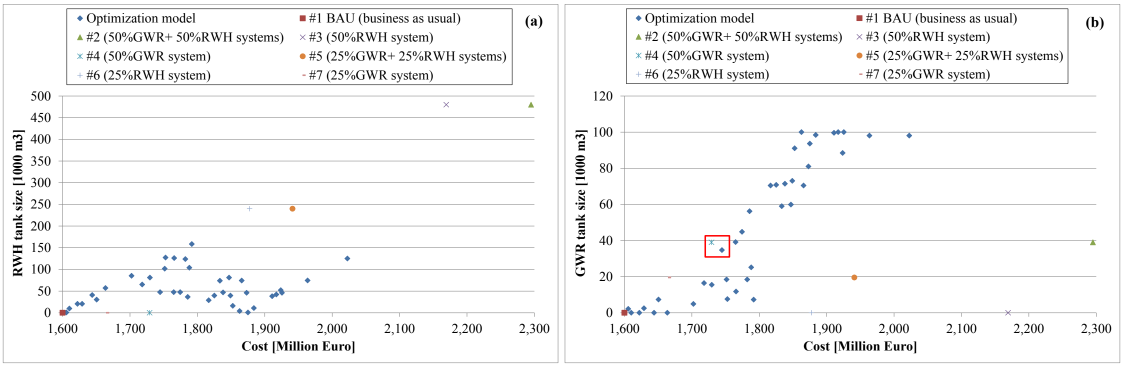

Fig. 4. Tank size versus total UWS cost obtained from optimization model and seven intervention options for (a) RWH tank; (b) GWR tank.

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