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COMPROMISE PROGRAMMING BASED SCENARIO ANALYSIS OF URBAN WATER SYSTEMS MANAGEMENT OPTIONS: CASE STUDY OF KERMAN CITY

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ABSTRACT

Supplying adequate water for urban water systems (UWSs) suffering from lack of water resources has always been a major concern in urban water management. Integrated simulation models are useful tools for sustainable planning and management of UWSs. This paper presents an integrated, conceptual modeling approach for simulation and analysis of an UWS by which different envisaged scenarios of water demand and resources are assessed. Other than water flow, the simulation model quantifies flows of energy, GHG emissions and cost in UWS. The performance of the developed model is demonstrated through its application to the UWS of Kerman City located in an arid region of south-eastern Iran. Given a number of potential scenarios, a range of water allocation policies from surface and groundwater resources were examined over a long term planning period and compared then based on five sustainability performance criteria. The scenarios analyzed included a combination of three different rates for both population growth and groundwater withdrawal. The water allocation policies were then ranked for each scenario using the compromise programming technique of multi-criteria decision analysis (MCDA). The highest ranked policy was unchanged in all scenarios as the one resulted from a policy compromising among different criteria. The lowest ranked policies are those withdrawing water from merely one type of water resource.

Keywords: Urban water systems; simulation; operational policy, MCDA

INTRODUCTION

One of the main concerns of urban water management is to supply sufficient water for different uses over some planning period. Urban water models can be used as decision-support tools for water supply in urban water system (UWS), which allow quantitative comparison of different conventional and non-conventional water management strategies (Mackay *et al.*[1]), More specifically, conceptually based simulation models such as UVQ (Mitchell *et al*. [4]), CWB (Mackay *et al.*[1]), WaterMet^2 (Behzadian *et al*. [2]) with the ability of calculating key performance indicators (KPIs) are useful tools for analysing and evaluating management options of an UWS.

This paper presents a conceptual simulation model with a daily time step that can be used to simulate the operation of UWSs and calculate some pre-specified KPIs over a long term planning period. The model is tested through its application to the Kerman City UWS under different scenarios. Water allocation policies are also evaluated for each of scenarios .The rest of the paper is organized as follows: the conceptual simulation model is demonstrated briefly in the next section. Then, the Kerman UWS and its components in the simulation model are explained. Subsequently, the scenarios, water allocation policies and the analyzing KPIs are defined. Then, the simulation results are discussed in which ranking of the water allocations with respect to resulting KPIs. Finally, the paper finishes with a summary followed by making some concluding remarks.

URBAN WATER SYSTEM SIMULATION MODEL

This paper develops a conceptual, mass balance-based model based on the WaterMet[2] model developed by Behzadian *et al.* [2]. This model simulates the UWS operation with a daily time step over a long term planning period. This model comprises main components of an UWS which is shown in Figure 1. These components are briefly outlined below:

1-Water resources comprising groundwater and surface water resources; 2-Conduits transferring water from water resources to water treatment works; 3-Water treatment works (WTW) that treat raw water by physical and chemical processes; 4-Trunk mains which transfer treated water to service reservoirs within the city either gravitationally or by pumping; 5-Service reservoirs which store treated (potable) water for a short period and are used as water sources in a water distribution system; 6-Distribution subsystem which spread stored water in service reservoirs to water demand points; 7-Water demand areas containing domestic, public, industrial, leakage and other water consumers in the network which may vary over time according to the rate of population increase. 8-Wastewater collection subsystem which collects and transfers wastewater to wastewater treatment works; 9-Waste water treatment works (WWTW) which treat the collected wastewater that can be either reused for some purposes (e.g. plant irrigation and non-drinking usages) or discharged into receiving waters (e.g. sea and aquifer). Modelling water flow through the components is based on the mass balance equations. For storage nodes including water supply resources, WTWs, WWTWs and service reservoirs, the volumetric balance equation is simply expressed as follows:

$$O_i(t)=S_i(t)+I_i(t)-S_i(t+1) \qquad (1)$$

where t=daily time step; $S_i(t)$=volume of water stored at storage node i in time step t; $I_i(t)$ and $O_i(t)$= inflow and outflow at storage node i in time step t, respectively. Note that outflow in time step t should equal the water demand providing that enough storage is remained for time step $t+1$, which also depends on the inflow and the storage in time step t.

In addition to the water flow, other principal fluxes can be quantified including: 1- Energy flux which is consumed either in a direct form (i.e. electricity energy and fossil fuel) or an indirect form (i.e. embodied energy) in various UWS components; 2-Green house gas emissions (GHG) flux generated directly (from electricity or fossil fuel consumptions) or indirectly as embodied GHG (from materials used in pipeline rehabilitations and chemicals used/produced in water and wastewater treatment operations) and 3-Chemical flux consumed for water treatment in WTWs, service reservoirs and WWTWs.

The rate of GHG emissions resulting from consumption of electricity and chemicals is calculated according to the following Eq.:

$$GHG\ emissions = EC \times \lambda_1 + CU \times \lambda_2 \quad (2)$$

where EC= amount of electricity used per unit volume of water (KWh/m^3); λ_1 = conversion coefficients for GHG emissions per KWh of electricity consumption (1.69 $KgCO_2/KWh$); CU=Chemical used per unit volume of water treatment (Kg/m^3); λ_2= conversion coefficients for GHG emissions per unit mass of a chemical used (here it is assumed 1.05 $KgCO_2/Kg$ for chlorine consumption).

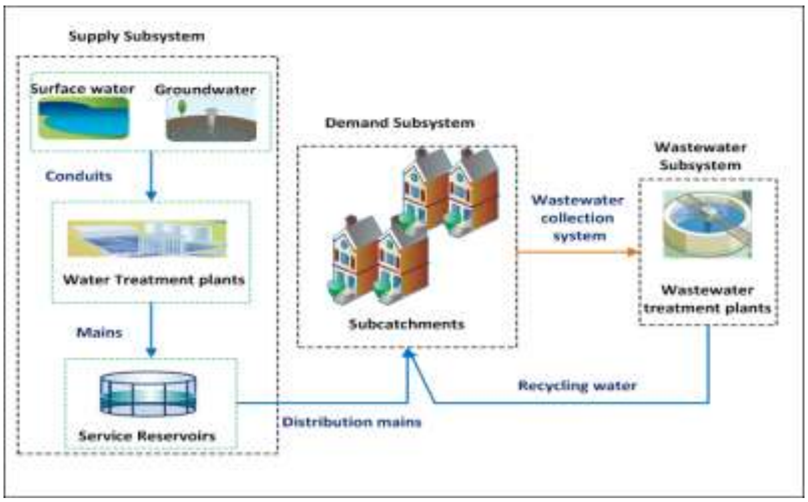

Figure 1. Main components modeled in an UWS

CASE STUDY

The case study selected is the Kerman City UWS which is suffering from a decreasing trend of available water resources due to overexploitation of groundwater resources. The city of Kerman with population of ~640,000 inhabitants in 2011 and a total area of 140 Km^2 is located in the south-eastern part of Iran in an arid region as shown in Figure 2. Currently, groundwater is the only resource for water supply to domestic and non-domestic demands of the city. An increasing rate of population growth and numerous droughts have been the most important challenges of the Kerman UWS in recent years. As a result, the aquifer water level has been decreasing because of excessive water withdrawals. To alleviate this problem, a reservoir dam as a new water resource is under construction and will be put into operation in the next five years (i.e. 2018). This dam is 150 Km far from the city, and a new WTW will also be built for water treatment. Water transfer from the surface reservoir to the Kerman UWS can help solve the problems of water shortages and overexploitation of groundwater resources, but it demands a significant rate of energy consumption (around 3.9 KWh/m^3) due to the significant difference of water be pumped (e.g. about 1000 meters). This is approximately 10 times larger than the energy required for water abstraction from groundwater (average 0.4 KWh/m^3).

As shown in Figure 3, Kerman water demands are met by four groundwater sources including: (R1) comprising of 3 aqueducts, (R2) comprising of 63 wells, (R3) comprising of 16 wells, and finally (R4) comprising of 17 wells. All the sources located outside the city. Raw water is transferred from these sources to five service reservoirs which are located within the city area. The service reservoirs transfer water to different areas of the city by pumping except service reservoir 2 from which water is distributed gravitationally. The total capacity of the service reservoirs is 113,000 M^3. Water treatment of the city only benefits from a chemical process as disinfection by chlorine.

Figure 2. Location map of Kerman City as the Case study

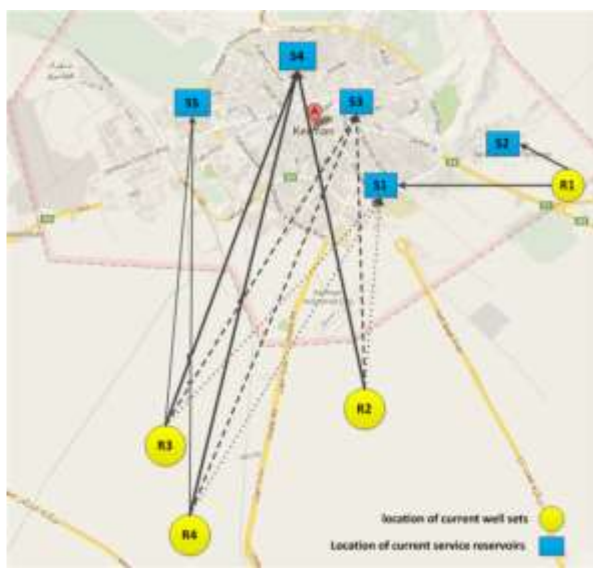

Figure 3. Kerman City UWS and its current components

SCENARIOS, OPERATIONAL POLICIES AND PERFORMANCE CRITERIA

We analyze the Karman City UWS operation and performance over a 30-year planning period under six different scenarios depending on two important social and physical input parameters, i.e. rate of population growth and groundwater withdrawals, respectively. The scenarios are characterized by combination of three rates of growth population (i.e. low, medium and high) and three states of groundwater withdrawal (i.e. lower-than-historical, historical and higher-than-historical rate of groundwater (GW) exploitation), respectively. The resulting nine scenarios and their names are shown in Figure 4.

When the surface water resource (reservoir dam) becomes operational in near future, we need to specify in the simulation model the relative share of groundwater or surface water resources in supplying water for the UWS. It is assumed that the surface reservoir with a capacity of 71 MCM will come into operation at year 5 of the planning analysis. Moreover, the maximum possible groundwater withdrawal is assumed to equal 42.5 MCM annually. Based upon the percentage water use from each water resource, six optional polices are defined and analyzed here as shown in Table 1.

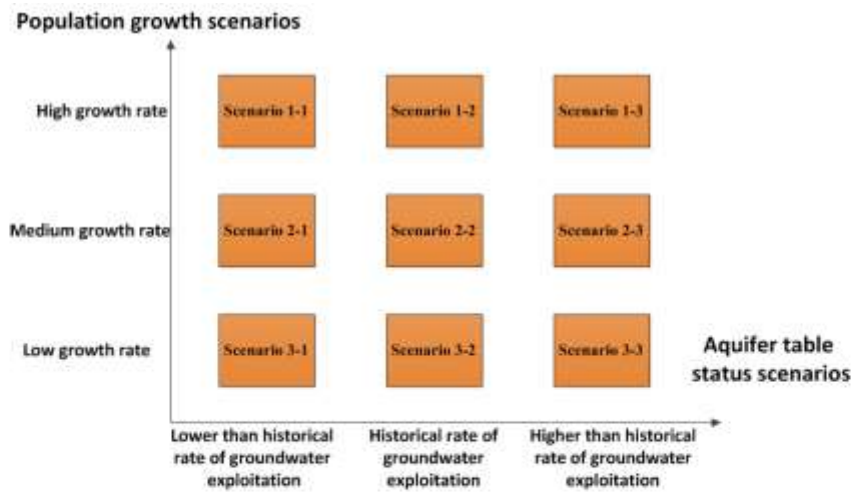

Figure 4. Nine analyzed scenarios

Table 1. Water allocation policies

water allocation policy no	Percentage of groundwater use	Percentage of surface water use
1	100	0
2	80	20
3	60	40
4	40	60
5	20	80
6	0	100

Having run the simulation model, a number of performance criteria need to be evaluated which quantify how well the UWS performs under each scenario and each operational policy. These criteria are also a basis for ranking different scenarios and allocation policies. The sustainability-based criteria include four quantitative criteria and one qualitative criterion. These criteria are: 1- The electricity energy consumed by different components of the UWS over the planning period and calculated as per capita, 2-Total costs including operational and maintenance costs of the UWS over the planning period. These costs are calculated in the form of present value assuming an annual interest rate of 14% (Behdad. [5]), 3-GHG emissions including both types of direct GHG resulted from electricity and fossil fuel and indirect GHG resulted from embodied energy over the planning period which is calculated as per capita, 4-Reliability of water supply expressed as the ratio of the total water delivered to customers to the total water demand over the planning period, and finally 5-Social acceptance quantified based on public satisfaction from the use of drinking water. Note that as a maximum water abstraction from groundwater is assumed as a key issue, any groundwater overexploitation will be limited by this constraint and thus would cause declining the water supply reliability.

The last criterion (#5) is assessed using five linguistic terms (extremely low, low, medium, high and extremely high) to represent different categories of subjective judgments. Instead of qualitative categories (linguistic terms), they are represented as scoring on a scale of acceptance ranging from 0 to 100% as: extremely low (0-20%), low (30-40%), medium (50-60%), high (70-80%) and extremely high (90-100%).

In order to compare the operational policies, they are ranked by using the multi-criteria decision analysis (MCDA) method of compromise programming (CP) (Andre´ *et al.* [6]) with respect to the mentioned evaluation criteria. The CP approach calculates a distance function for each operational policy based on a subset of efficient solutions (called compromise set) that is the nearest one with respect to an ideal point for which all the criteria are optimized (Andre´ *et al.* [6]) We assign equal weights to all the criteria in this study.

RESULT AND DISCUSSION

Once the Kerman UWS model was built, the result of the developed simulation model (i.e. the KPIs) was first verified by comparison with the relevant results obtained from the WaterMet^2 model (Behzadian *et al.* [7]).

The developed model ran for the simulation of the Kerman UWS operation in six allocation policies for each of the nine scenarios. This resulted in 54 sets of model runs for each of which the performance criteria were evaluated. According to the results obtained and with respect to the performance criteria, the system's performance for scenarios 1-2, 2-2 and 3-2 were almost the same as that for scenarios 1-3, 2-3 and 3-3, respectively. This can be due to the fact that the energy consumed for transferring water from the surface reservoir to the city is much more than that for transferring water from groundwater resources. As a result, scenarios 1-2, 2-2 and 3-2 were removed from further consideration and the analysis was focused on the other scenarios. Figure 5 shows the trend of variations for the percentage of the water supplied for different water allocation policies under scenario 1-3. Note that the variations of this KPI for other scenarios follow the same trend but have with different rates (not shown here).

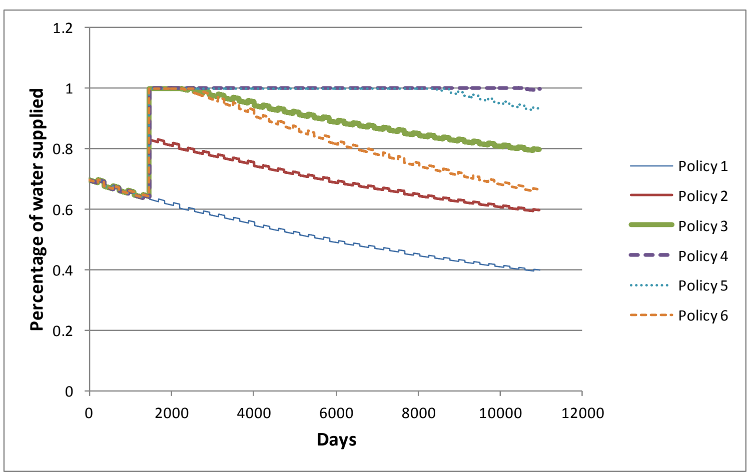

Figure 5. Trend of the variation of the supplied water over time for scenario 1-3

Based on the evaluation and analysis of the results obtained for all the considered scenarios and allocation policies, the following remarks can be made:

1-The maximum reliability obtained in policy 1 (100% of groundwater supply) for all scenarios is 61% which indicates that the policy, under no circumstances, is unable to completely supply the UWS demand and confirms the need for additional new water resources.

2-Shifting from scenarios 1-1, 2-1 and 3-1 to scenarios 1-3, 2-3 and 3-3 (aquifer level declines more severe than current trend) causes the energy consumption in all policies to decline due to the less energy required for water abstraction from the aquifer.
3-For scenarios 1-1 and 1-3 (high rate of population growth), only policy 4 is able to supply 100% of water demand over the planning period. However, policy 6 (100% of surface reservoir supply) holds the sixth rank. This can be due to both the limitation in storage capacity of the surface reservoir and the increased water demand.

After comparing different policies relative to each evaluation criterion separately, they were compared and ranked with respect to all evaluation criteria by the CP method. For example, ranking of all six policies with respect to five evaluation criteria under scenario 1-3 is shown here in Table 2. As can be seen in this Table, higher social acceptance is directly proportional to the percentage of water allocation from the surface reservoir due to its high water quality. The overall rankings of the six water allocation policies relative to all scenarios are also given in Table 3. When comparing these evaluations and rankings in these Tables, the following can be inferred:
1-The highest rank is held by policy 3 in all scenarios. As can be seen in Table 2, the highest rank for this policy resulted from a compromise among the ranks which were obtained with respect to each single criterion separately. More specifically, this policy is ranked third or fourth with respect to each of the five criteria but first with respect to all criteria.
2-There is not a constant second and third ranked policy among different scenarios. In other words, policies 4 and 2 hold the second and third ranks, respectively, for scenario 1-3 and 1-1 (high rate of population growth) while these ranks are held by policies 2 and 4, respectively, for other scenarios.

Table 2**.** Evaluation and overall ranking of water allocation policies under scenario 1-3

Criteria	**Social acceptance**	**Electricity energy**	**GHG emissions**	**Reliability**	**Total costs**	**Ranking**
Units **Policy no**	**%**	**per capita KWh**	**per capita Kg**	**%**	**per capita Euros**	
Policy 1	10	176	7	52	25.5	**4**
Policy 2	20	251	10	69	36.25	**3**
Policy 3	**40**	**325**	**14**	**86**	**46.75**	**1**
Policy 4	60	400	18	96	57.25	**2**
Policy 5	80	474	22	95	68	**5**
Policy 6	100	549	25	81	78.5	**6**

3-The position of the three lowest ranked policies (policies 1, 5, 6) is constant under all scenarios. This means the least favorite water allocation policies are consistent and need to be disregarded under any circumstances.
4-Water abstraction from merely surface reservoir (policy 6) is the worst way of UWS operation and management. Even, considering a small share of water abstraction (20%) from groundwater (Policy 5) is ranked low although it is better than policy 6. Under any scenarios, water abstraction fully from groundwater (policy 1) is always a better policy than 100% or 80% abstraction from the surface water.
5-Furthermore, to make a final decision for selecting the best policies, other criteria such as risk may be added as influent factors. It is worth mentioning that different weighting schemes resulted from various expert’s perspective should not be overlooked (Behzadian *et al.* [7]).

Table 3. Overall rankings of water allocation policies relative to all scenarios

Scenario name	S 1-1	S 2-1	S 3-1	S 1-3	S 2-3	S 3-3
Policy no						
Policy 1	4	4	4	4	4	4
Policy 2	3	2	2	3	2	2
Policy 3	1	1	1	1	1	1
Policy 4	2	3	3	2	3	3
Policy 5	5	5	5	5	5	5
Policy 6	6	6	6	6	6	6

SUMMARY AND CONCLUSIONS

The Kerman UWS was simulated here by an integrated model in which six policies of relative share of water utilization from groundwater and surface water resources were evaluated and compared against nine scenarios related to different rates of population growth and groundwater exploitation. Due to high energy consumption for water supply from the surface reservoir, the policies allocating larger portion of water from the surface reservoir consume more energy and subsequently total costs and GHG emissions than others. The results of a MCDA using the compromise programming (CP) approach suggested policy 3 (40% of water supply from the surface water and the rest from groundwater) as the best rank among all scenarios while policies 5 and 6 (maximum abstractions from surface water) are the lowest ranked policies. However, the selection of the best policy may be further analyzed with respect to the inclusion of other criteria and the sensitivity analysis for various weighting schemes from experts' perspectives.

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