A Scenario-Based Management of Water Resources and Supply Systems Using a Combined System Dynamics and Compromise Programming Approach

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Research Article

Keywords: compromise programming, groundwater resources, water conservation, sustainable groundwater extraction, system dynamics, water supply systems

Posted Date: June 4th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-574796/v1>

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A Scenario-based Management of Water Resources and Supply Systems using a Combined System Dynamics and Compromise Programming Approach

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Abstract

Long-term sustainability in water supply systems is a major challenge due to water resources depletion, climate change and population growth. This paper presents a scenario-based approach for performance assessment of intervention strategies in water resources and supply systems (WRSS). A system dynamics (SD) approach is used for modelling the key WRSS components and their complex interactions with natural and human systems and is combined with a multi-criteria decision analysis for sustainability performance assessment of strategies in each scenario. The scenarios combine population growth rates with groundwater extraction limits and three intervention strategies. The methodology was demonstrated on a real-world case study in Iran. Results show scenario-based analysis can provide suitable strategies leading to long-term sustainability of water resources for each scenario imposed on the water systems. For scenarios with either no threshold or one threshold of groundwater extraction limit, the only effective strategies for sustainable groundwater preservation are those involving agricultural water demand decrease with an average recovery rate of 130% for groundwater resources while other strategies

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of agricultural groundwater abstraction (constant/increase rates) fail to sustainably recover groundwater resources. However, all analysed strategies can provide sustainability of water resources with an average recovery rate of 33% for groundwater resources only when scenarios with two threshold limits are in place. The impact of scenarios on groundwater conservation is quite minor for population growth rates with an average recovery rate of 11% compared to groundwater extraction limits with an average recovery rate of 79% between no threshold and two threshold limits.

Keywords: compromise programming; groundwater resources; water conservation; sustainable groundwater extraction; system dynamics; water supply systems.

Introduction

While some regions in the world benefit from abundant freshwater supply, recent droughts showed an urgent need for changing public perception of water and its efficiency globally (Ziolkowska & Ziolkowski 2016). The severe scarcity of water resources is currently a global concern that will exacerbate in the future. While rapid population growth and economic development have also led to higher water demand, climate change has increased the uncertainties of water resources (Xi & Poh 2013). Consequently, freshwater resources are depleted faster than the renewed ones due to the high rates of consumption and changing water cycles. Water resources and supply systems (WRSS) have always been faced with many drivers such as population growth, demand increase, change in consumption patterns, urbanisation, climate change and infrastructure ageing that put a high pressure on urban water services (Arfanuzzaman & Atiq-Rahman 2017).

Countries in arid and semi-arid areas are more dependent on groundwater resources than other water resources (Zahedi, 2017; Yousefi et al. 2019). However, this water resource has mainly been

affected by climate change with altered precipitation regimes (Yousefi et al. 2018). Management of agricultural water demands as the main consumer of water resources can specifically be used for developing new water policies to reduce the tensions of water resources that also have a major impact on domestic water supply (Michelsen & Young 1993). In addition, sustainability of groundwater resources is highly dependent on complex feedback loops between human and natural systems in line with policy developments (Jia et al. 2019; Lizjen et al. 2014). This requires continuous assessment of sustainable groundwater management by deep knowledge of present and projected status of groundwater quantity and quality (Hosseini et al. 2019). Furthermore, employing new management strategies can have a key role for reducing the impact of global challenges on the performance of water supply systems. However, the complexity of interactions between economic, social, and environmental issues features an intertwined challenge within the context of groundwater resources management that needs rigorous analysis of potential solutions with respect to various scenarios and assessment criteria to identify the best priorities for each scenario. A major step for this is a proper modelling approach for performance simulation of real-world systems. System Dynamics (SD) has shown to be an effective approach for integrated modelling of long-term planning of socio-economic performance in complex systems (Sušnik et al. 2012). The SD is also suitable for long-term performance assessment of the WRSS in which feedbacks and complex interactions can be observed among variables and stock changes. The SD can also be used for strategic planning of complex systems of water supply from water resources (Hassanzadeh et al. 2012). For instance, Fang et al. (2019) developed a SD-based model to analyse water allocation based on rapid urbanisation, excessive exploitation of resources and environmental pollution. Phan et al. (2018) presented a feedback-driven SD model for simulation of the supply and demand sides of a coastal freshwater system to assess and quantify potential

climatic and socio-economic influences on the system vulnerability. Tianhong et al. (2019) developed a SD-based model to investigate the complexity of social-economic-ecological interactions throughout the urban water cycle.

Some research works have combined the SD modelling with other simulation models for decision making in the water system context. For example, Baki et al. (2018) coupled the SD modelling with the Urban Water Optioneering Tool (UWOT) to simulate urban water cycle and investigate the diffusion of water conservation technologies into the domestic water sector. Few research works have focused on the combination of the SD modelling with multi-criteria decision analysis (MCDA) methods in the context of water resources management (Yang et al. 2019). For example, Vo et al. (2002) coupled the SD modelling with Simple Additive Weighting method coupled to analyse different lags in economic, social, and technical effects of large-scale urban water management. Yang et al. (2019) assess the carrying capacity of water resources systems by coupling the SD modelling with Analytic Hierarchy Process (AHP) to evaluate socio-economic performance of the systems. The Compromise Programming (CP) method has also been used to evaluate the performance of integrated urban water management and prioritise potential strategies in urban water systems (Behzadian et al. 2014).

Despite the widespread use of the SD modelling in various applications of water systems, to the best of the authors' knowledge, there is no previous work integrating the SD modelling with an MCDA technique for a combined analysis of both plausible scenarios and strategies for water resources and supply management. This paper makes use of integrating the SD with the CP tool to develop an assessment framework for analysis of intervention strategies under future scenarios for management of a complex system dynamics (SD) comprising groundwater and surface water resources, water reuse and municipal water distribution networks. The water resources in this

system can have interactions with neighbouring groundwater and trans-basin surface water resources to support water supply of specific areas based on the sustainability indicators in water systems. The SD model of the WRSS aims to evaluate the sustainability performance of depleting groundwater for plausible scenarios and identify the most robust strategies over a long-term planning horizon. Next section presents the methodology and then model development for business as usual of the real-world WRSS. The results are then presented with critical analysis and discussion along with summarising key findings and recommendations for future works.

Methodology

This paper presents a hybrid framework based on the combination of the SD and CP tools to evaluate long-term sustainability performance of potential intervention strategies in WRSS under plausible future scenarios. The modelling tools required for developing the methodology were the VENSIM software for SD modelling (Niazi et al. 2014) and Excel platform for modelling the CP method (Behzadian and Kapelan 2015). The planning horizon of the SD model was set for a long-term (e.g. 3-50 years) as monthly timestep. Water demands were supplied from either groundwater or surface water resources in the following order of priority: domestic, industrial and irrigation. The methodology framework was developed based on the following steps:

- **Step 1:** Model development and calibration of water resources and supply systems by using the SD modelling approach;
- **Step 2:** Performance assessment of the SD model for sustainability of water resources and supply indicators for plausible scenarios, potential intervention strategies;

- **Step 3:** prioritisation of the intervention strategies for each scenario with respect to key performance indicators (KPIs) derived from the sustainability performance based on the multi-criteria decision analysis by using the CP method.

Further details of the methodology and model development for the above steps are described below.

SD model development

The SD model is used here mainly due to the dynamic and nonlinear behaviour of water management systems that is subject to evolution and feedbacks in the decision-making environment. This feature can be translated into various forms such as structural changes, time delays, improvement (evolution), and interventions through policy-making. Causal loop diagrams can be converted into stock and flow diagrams in the SD model to represent storage and conveyance elements in the WRSS, respectively. More specifically, a stock is defined as a storage element in the WRSS (e.g. water resources and service reservoirs) that accumulates or depletes over time. A flow is defined as a conveyance element in the WRSS (e.g. trunk mains and distribution mains) that shows the rate of change in a stock. The SD modelling adopts mass balance equations of monthly inflows and outflows to stocks.

The SD was used here to develop the WRSS model in four main sub-systems (Figure 1) including (1) surface water resources, (2) groundwater resources, (3) service reservoirs and water demands (4) wastewater reuse. The SD defines the core of these sub-systems (e.g. resources and reservoirs) as stocks connected to each other through flow and causal loop diagrams. More details of each subsystem are outlined below.

Figure 1: The SD model of the WRSS

The surface water subsystem (Figure 2a) supplies water for domestic and agricultural demands and the main flows include (1) inflows from either directly its catchment or other upstream catchments and (2) outflows for supplying demands. The groundwater subsystem (Figure 2b) is developed based on the parameters of water budget in relevant aquifers. The parameters defined here as flows are effective precipitation, percolation from surface water resources, recharging from aquifer bedrock and inflow from or outflow to adjacent aquifers. Besides, groundwater extraction has some flows that indicate the interactions of domestic, industrial, agricultural and landscape demands. Part of the groundwater supplied for water demands can be assumed to return to relevant aquifers. A regression-based model can be used for estimation of the groundwater water volume. The service reservoir subsystem (Figure 2c) is fed by two inflows from groundwater and surface water resources. It also has two outflows for distribution main leakage and domestic water consumption. The service reservoir is connected to water demand stock and estimates future

domestic water demand based on continues-time equations of population growth over a simulation period. Water and wastewater reuse subsystem (Figure 2d) can be defined as a stock connecting to water reuse plant and provides the process of returning the treated effluent for reuse in industrial, landscape irrigation, and agricultural demands, respectively.

Due to the high priority of preserving groundwater resources from depletion due to excessive extraction. it is assumed water demands are first supplied from surface water resources and any remaining unmet demands are supplied from groundwater resources. (see also the schematic charts of model development in S.1 of the supplementary materials).

Scenarios and strategies

Strategic planning and management of water systems require an analysis of potential intervention strategies to mitigate the challenges related to environment (e.g. climate change origins such as low precipitation, high temperature, limited volume of available water resources), society (e.g. high population rate), economy (e.g. high pressure for increase in agricultural productions), and policy (e.g. legislation enforced by national or federal responsible organisations). These probable future events are defined here as plausible scenarios that are likely to happen but either affected by external factors or made by those out of direct control of local organisations such as water companies. Intervention strategies are defined here as technological and management measures planned and implemented by local organisations (e.g. regional water utilities). The following section outlines scenarios and strategies set out in the SD modelling.

Figure 2: Main subsystems of the SD model: a) surface water, b) groundwater, c) service reservoir and water demand, d) water reuse

Plausible scenarios

Two types of scenario are defined here as Population Growth "PG" and GroundWater Extraction Limits (Table 1). These scenario types are further divided into two rates of population growth and three threshold limits for groundwater extraction. The two population growth rates are normal (NPG) and rapid (RPG) representing current and highest predicted rate of population growth projected to occur over a planning horizon, respectively. The three threshold limits of groundwater extraction include (1) no threshold (NT) for abstraction although a minimum for the aquifer volume needs to be defined to prevent complete depletion of the aquifer; (2) one minimum threshold (T) is set for the aquifer volume such that no agricultural demands are supplied when the aquifer volume is less than the threshold; and (3) two thresholds (TT) are set for the aquifer volume such that water demands are fully supplied for the volume more than upper threshold and partly supplied to agriculture for volume between the two thresholds and no supply for volumes less than the lower threshold. In the cases of the groundwater abstraction reaching the threshold limits, agricultural demands are supplied either partially or fully depending on the aquifer volume relative to the threshold limits. Ground water extraction limits inspired by UN Water (2015) defines any limit that is considered as national laws of water conservation imposed by national or federal government to control groundwater resources in a country. While no Threshold limit "NT" scenario considers no control for groundwater abstraction by relevant organisations, one threshold "T" and two thresholds "TT" scenarios resemble some restrictions on groundwater abstraction imposed by responsible organisations. In total, six scenarios as shown in Table 1 can be made for covering various composition of population growth rates and groundwater extraction limits.

Table 1: Scenario type and numbering in the SD model

Scenario type	State of Scenario	Groundwater extraction Limits		
		No threshold "NT"	One threshold "T"	Two thresholds "TT"
Population growth "PG"	Rapid population growth "RPG"	C#1	C#2	C#3
	Normal population growth "NPG"	C#4	C#5	C#6

190 *Intervention strategies*

191 Intervention strategies are defined as a combination of intervention options and policies set out by
192 water authorities for performance improvement of water systems over a long-term planning
193 horizon. Based on the investigation of potential intervention options in water systems, we analyse
194 three types of intervention strategies including agricultural water demand control, urban
195 wastewater reuse and water loss reduction in pipeline (Table 2). These strategies can also be highly
196 beneficial to preservation of water resources and lead to making more informed decisions for
197 domestic water supply. More specifically, agricultural irrigation typically accounts for the largest
198 water demand and hence any strategy derived from it would have a key role to minimise depleting
199 aquifers (Maliva & Missimer 2012). "Agricultural Water Control" inspired by UN Water (2015)
200 represents the role of decision makers in regional authorities to make policies for water
201 preservation. The agricultural water control strategy is divided here into three further trends of
202 agricultural water demands (i.e. increasing, constant and decreasing) over the planning horizon.
203 "Water Demand Increase" indicates business as usual (i.e. do nothing) as water demand increases
204 proportional to population growth and demand increase for agricultural products. "Constant Water
205 Demand" and "Water Demand Decrease" can be considered as measures introduced by
206 stakeholders to harness agricultural water demands such as new water technologies, policies and
207 regulations set out for water allocation or restriction of water abstraction and public engagement

and social awareness for efficient use of water supply. Treated wastewater reuse for non-potable demands and water loss reduction in pipeline in urban water distribution systems are grouped here as wastewater reuse & leakage reduction strategy type for alleviation of the pressure on severely depleting water resources. This strategy type is divided here into two further strategies defined in Table 2 based on policies for wastewater reuse and improving the system efficiency. While "NWR-LR" strategy assumes no wastewater reuse application is developed and pipeline water loss is constant from service reservoirs over the planning horizon, "AWR-LR" strategy considers treated wastewater reuse is allocated for non-potable use. In total, six combinations of intervention strategies can be envisaged here (Table 2) that can be analysed for each of the six scenarios introduced above for the assessment criteria outlined in the next section.

Table 2: Strategy types and numbering in the SD model

Strategy type	State of strategy	Agricultural water control		
		Water demand increase	Constant water demand	Water demand decrease
Wastewater reuse & leakage reduction "WR-LR"	No wastewater reuse and water loss reduction "NWR-LR"	S#1	S#3	S#5
	Wastewater reuse and leakage rate improvement "AWR-LR"	S#2	S#4	S#6

Key Performance Indicators (KPIs)

Five KPIs shown in Table 3 are selected to represent sustainability indices of water resources and supply systems. They include Sustainability Index (SI), Reliability Index for domestic purpose (RI_d), Reliability Index for agricultural purpose (RI_{ag}), Resource Stress Index (RSI) and Self-Sufficiency Index (SSI). As the priority of water supply is first for domestic demands and then for agricultural demands, domestic demands are expected to be fully supplied for all conditions (i.e. RI_d=1) while the impact of any water shortage is expected to be seen through water allocation of agricultural demands that influence agricultural reliability index (RI_{ag}). RSI is a measure to

228 demonstrate the growth rate of one region based on available water resources. SSI indicates
 229 contribution of neighbouring water resources in water supply. The index shows the ratio of water
 230 volume supplied by local water resources to water volume supplied by neighbouring water
 231 resources.

232 Table 3: List of KPIs used in this study

Key Performance Indicators	Equations	Description	Reference
Sustainability Index (SI)	$SI = \begin{cases} \frac{TAW - TWD}{TAW} & \text{If } TAW > TWD \\ 0 & \text{If } TAW \leq TWD \end{cases}$	TAW= total available water; TWD= total water demand; the ratio is always between 0 and 1 in which 0 indicates no sustainability where there is no adequate available water or available water is equal or less than water demand, while for redundant supply, it is greater than zero. Thus, when TAW>TWD, TWD equals to total water supply. The ratio is 1 for ideal case (i.e. max sustainability when no water demand exists)	Madani and Mariño (2009)
Reliability Index for domestic purpose (RI _d)	$RI_d = \frac{TWS_d}{TWD_d}$	TWS _d = total domestic water supply and TWD _d = total domestic water demand. If there is no domestic water shortage, total water supply is equal to total water demand (RI _d = 1). For any domestic water shortage, RI _d < 1.	Behzadian et al. (2014)
Reliability Index for Agricultural purpose (RI _{ag})	$RI_{ag} = \frac{TWS_{ag}}{TWD_{ag}}$	TWS _{ag} = total agricultural water supply; TWD _{ag} = total agricultural water demand. If there is no agricultural water shortage, total agricultural supply equals total agricultural demand (RI _{ag} = 1). For agricultural water shortage, RI _{ag} < 1.	Behzadian et al. (2014)
Resource Stress Index (RSI)	$RSI = \frac{TWD}{TAW}$	TWD= total water demand; TAW= total available water. This index represents potential growth based on the available water resources and evaluates the sustainability of water supply based on water demand.	Abadi et al. (2014)
Self-Sufficiency Index (SSI)	$SSI = \frac{TWS - TIW}{TWD}$	TWS= total water supply including recycled wastewater, harvested rainwater, or desalinated water; TIW= total imported water from neighbouring catchments; TWD= total water demand. A concept of urban water self-sufficiency has been proposed as a measure of urban dependency on water imports.	Rygaard et al. (2011)

233

234 **Compromise Programming (CP) method**

235 The CP method belongs to a class of MCDA technique called "distance-based" methods. As KPIs
 236 may have different units, normalised functions to ensure they have the same range (Behzadian and
 237 Kapelan 2015). Multiple KPIs for each strategy are converted to one distance function and
 238 strategies are then ranked according to these distances. Without loss of generality, assuming all
 239 criteria are maximising, the overall distance function for an intervention strategy with an

evaluation function (f_i), maximum absolute (ideal) value (f_i^*), minimum absolute (anti-ideal) value (f_i^-), weight or relative importance (w_i) for criterion i , a topological metric of p and number of KPIs equal to n is calculated as below assuming that the scaling function is linear:

$$\text{minimise } L_p = \left[\sum_{i=1}^n (w_i (f_i^* - f_i) / (f_i^* - f_i^-))^p \right]^{1/p}, w_i > 0, 1 \leq p \leq \infty \quad (1)$$

Parameter p changes from 1 to ∞ and it has higher sensitivity if it takes higher value. For the CP used in the paper p was equal to 2. f_i belongs to a corresponding KPI calculated by the SD over the planning horizon. f_i^* and f_i^- is the maximum and minimum value of the corresponding KPI among all strategies analysed. The relative weights (w_i) represent the importance of the KPI usually determined based on expert opinions. The weights considered in the paper were all equal to 1 due to the equal importance of the KPIs for decision makers.

Case study and SD model calibration

The methodology was demonstrated here on a real-world case study for water systems of the Kerman Catchment located in the southeast of Iran (Figure 3). The SD model was developed for 600 monthly timesteps (50 years) from Oct 1987 to Sep 2037. The first 300 timesteps (from Oct 1987 to Sep 2012), i.e. 25-year historical data, were used for building the SD model, its calibration and validation. The next 300 timesteps (from Oct 2012 to Sep 2037) were used as the planning horizon to evaluate intervention strategies under plausible scenarios. The case study is located within the arid climate with average annual precipitation of 138 mm based on the annual average rainfall of the catchment. Figure 4a illustrates the monthly precipitation of the case study. Available water resources in the case study (Table 4) are (1) groundwater in Aquifer #1 and Aquifer #2 and (2) surface water in dam #1 and dam #2. Aquifer #1 comprising 1,197 tube-wells,

27 qanats and 4 springs is traditionally the main water resource of the Kerman WRSS but has been depleted significantly due to the extremely excessive water extraction in the recent decades with an average of 1.2-metre drop per year (Figure 4b). Table 4 summarises annual water withdrawals of available water resources and after completing the construction. The future population of Kerman projected by Statistical Centre of Iran (2016) for the two scenarios is shown in Figure 4c for 25 years of the simulation period between Oct 2012 and Sep 2037.

Figure 3: Layout of the case study

Table 4: Annual water withdrawals of available and future water resources in Million Cubic Meters (MCM)

	Groundwater resources		Surface water resources**	
	Aquifer #1	Aquifer #2	Dam #1	Dam #2
Agricultural	240	0	6.11	0
Domestic	44.4	11*	24.16	20.1
Industrial	7.7	0	0	0
Landscape	0.9	0	0	0
Rabor Region	0	0	2	0
Total	293	11	32.27	20.1

* water supply after Oct 2004

** water supply after Oct 2018

Figure 1: a) Monthly precipitation, b) annual variation of groundwater level and c) population growth in the case study

The calibration result for the first 300 timesteps is shown in Figure 5a. The close agreement of groundwater volume between the observed data and model output indicates a good model calibration (see statistical tests in Supplementary S.2). Water demands are supplied by groundwater resources only within timestep 301-373 (Oct 2012 to Oct 2018) while the surface water resources are used from timestep 373 (Oct 2018). At the early years of surface water operation, dam #1 filled up rapidly (Figure 5b) and significant spills occurred due to large inflows (Figure 5d) while reservoir volume gradually reduced as inflow decreased significantly within the remaining timesteps of the planning horizon (Figure 5c).

The threshold of "groundwater extraction limits" was defined as: 1) 10 MCM set for scenarios with no threshold, i.e. C#1 and C#4, as the minimum volume avoiding complete depletion of the aquifers; 2) 700 MCM threshold set for scenarios with one threshold, i.e. C#2 and C#5, as agricultural water demands were supplied when the aquifer volume is greater than this amount; and 3) for scenarios with two thresholds, i.e. C#3 and C#6, 1000 MCM for the upper threshold and 700 MCM for the lower threshold of the aquifer volume. Agricultural water supply at timestep t (AS_t) for scenarios with two thresholds is calculated based on Eq. (2):

$$AS_t = \begin{cases} AD_t & \text{if } Va_t - AD_t \geq 1000 \\ \alpha \times AD_t & \text{if } 1000 > Va_t - AD_t > 700 \\ 0 & \text{if } 700 > Va_t - AD_t \end{cases} \quad \alpha = \frac{Va_t - DD_t - ID_t - LD_t - 700}{1000 - 700} < 1 \quad (2)$$

where Va_t =the aquifer volume at time t (MCM), AD_t =the agricultural demand at timestep t (MCM), DD_t , ID_t , LD_t = domestic demand, industrial demand and landscape demand at time t , respectively (MCM). Agricultural water demands consider the relevant strategies (i.e. increase, constant or decrease) between timestep 301-600 (Oct 2012 and Sep 2037). Agricultural water demand strategy

for constant rate considers the same water demands as water year 2011-12 for the entire remaining
timesteps. However, "wastewater reuse & leakage reduction" strategies "WR-LR" considers to be
in place from timestep 400 (Jan 2021). "No wastewater reuse & leakage reduction" strategy
considers a constant rate of water loss (35% of total domestic water supply) for all timesteps while
"wastewater reuse and leakage rate improvement" strategy assumed that water loss reduced
uniformly from 35% to 20% from timestep 400.

Figure 2: a) Water volume in aquifer #1 for observed data and model output; variables of dam #1 for b) reservoir volume, c) inflow, d) overflow.

Figure 6 summarises the timeframe for all scenarios, strategies, and water resources over the entire 600 timesteps. As can be seen, all scenarios and strategies except "wastewater reuse & leakage reduction" strategy "WR-LR" starts from timestep 301 (Oct 2012) when planning horizon starts while the "WR-LR" strategy starts from timestep 401 (Feb 2021) and new surface water transfer/resource (dam #1) was added from timestep 373 (Oct 2018). The model developed here was also analysed under extreme condition tests to control the model output values under limited conditions (see supplementary S.3).

Figure 3: Timeframe of scenarios, strategies and water resources over the planning horizon

Results and discussion

After the SD model calibration with the historic data, the long-term performance of the intervention strategies was evaluated for each plausible scenario. Figure 7 shows the variation of two KPIs (SSI and RId) for some strategies and scenarios over the simulation period. The variation of the SSI in Figure 7a illustrates how water supply is dependent on local and external (neighbouring) water resources. The SSI is 1 for the first 205 timesteps when aquifer #1 is the only water resource but the index drops twice significantly due to adding the two new water resources: (1) aquifer #2 in timestep 205 (Oct 2004) following a slightly increasing trend with fluctuations which are the same for all strategies and (2) dam #1 in timestep 373 (Oct 2018) following a slightly steeper increasing trend with fluctuations. Both new water resources (aquifer #2 and dam #1) are allocated for domestic water demands (see Table 3). As can be seen in the figure, domestic water demands are more supplied from aquifer #1 in rapid population growth "RPG" scenarios regardless of the strategy type.

The performance of all strategies discussed here are given only for aquifer #1 as the main water resource of the study. Figure 8 shows the variation of volume in aquifer #1 for all strategies in each scenario. As can be seen in figures 8a and 8b, for both scenarios with no threshold for groundwater extraction (C#1 and C#4), the groundwater volume is severely depleted in all strategies except strategies S#5 and S#6 by the end of the planning horizon. This is due to the large groundwater extraction from the aquifer in all strategies except S#5 and S#6 which have positive effect on groundwater volume. This is due to the sustainable yield of groundwater in both strategies with "Water Demand Decrease" (S#5 and S#6) that lead to reclamation of groundwater by reducing the extraction volume. The impact of "wastewater reuse and leakage reduction" strategies is also

335 minor for conservation of groundwater resources in these two scenarios. Furthermore, there is no
336 sensible impact of different population growth rates on the groundwater volume in these scenarios.

Figure 4: a) Self Sufficiency Index, b) Groundwater extraction from aquifer #1 for domestic consumption.

Figure 5: Variation of volume in aquifer #1 for all strategies and scenario a) C#1, b) C#4, c) C#2, d) C#5, e) C#3 and f) C#6

For the scenario with one threshold (C#2 and C#5) in figures 8c and 8d, the performance of all strategies and their impact on the preservation of groundwater resources are quite similar to those in the previous two scenarios (C#1 and C#4). In other words, minor impact of "wastewater reuse and leakage reduction" strategies on groundwater resources recovery and similar response of all strategies in both population growth scenarios indicate that these scenarios and strategies can be

discarded for the management of groundwater resources conservation when either no threshold or one threshold of groundwater abstraction is the prevailing scenario. On the other hand, strategies S#5 and S#6 (agricultural demand decrease), can again recover groundwater resources coming off the threshold limit of 700 MCM at the end of the planning horizon. The only concern is that there is no alarm for water extraction from the aquifer in these two scenarios until the aquifer volume dropped to 700 MCM. As a result, water withdrawal is sharply depleting groundwater resources until reaching the threshold level between timesteps 347 (Sep 2016) and 516 (Sep 2030). The agricultural water extraction is gradually decreased until it can lead to the recovery of the groundwater by the end of the planning horizon. Hence, excessive agricultural water extraction is considered as the main unavoidable consequences of this depletion.

For the scenarios with two threshold limits (C#3 and C#6) in figures 8e and 8f, groundwater resources are sustainably recovered in almost all strategies although the recovery rate varies significantly between strategies with different agricultural water withdrawal. Despite the groundwater resources recovery in all strategies, groundwater extraction may not be able to fully supply agricultural demands in some periods due to the restrictions imposed by the two threshold limits. However, it is evident that the aquifer is likely to be more sustainable for all strategies when scenarios with two threshold limits (i.e. C#3 and C#6) occur.

Figure 9 shows the recovery rate of groundwater in all scenarios and strategies analysed (i.e. difference of the aquifer volume between the minimum value and the last timestep). As can be seen in figure 9a, in the case of scenarios with either no threshold (C#1, C#4) or one threshold (C#2, C#5), the strategies involving agricultural water demand decrease (S#5, S#6) can significantly recover the groundwater volume with an average recovery rate of 130%. However, other strategies of agricultural groundwater abstraction (i.e. constant rate S#3, S#4 and increase

rate S1, S#2) fails to sustainably recover groundwater resources under these scenarios. The figure also shows for the scenarios with two threshold limits of groundwater extraction, all strategies can sustainably recover the aquifer with an average recovery rate of 33%.

Figure 9: The volume difference of aquifer #1 between the timestep with minimum volume and timestep 600 for strategies with a) water demand decrease S#5 S#6 and b) water demand constant S#3 S#4 and water demand increase S#1 S#2

Comparing the two types of scenarios shows the impact of population growth on the aquifer volume is much less than groundwater threshold. More specifically, the difference of the impact of groundwater recovery between the scenarios with normal and rapid population growths is an average of 11% compared to 79% for the difference of groundwater recovery rates between the groundwater extraction limits with no threshold and two threshold limits. However, when comparing the two population growth scenarios, the results show the rapid population growth has more influence on depleting groundwater aquifer than the normal population growth in all strategies. Similarly, the influence of strategies with wastewater reuse and leakage reduction category on groundwater volume is almost negligible compared to those strategies without wastewater reuse and leakage reduction.

Ranking strategies

The CP method is used here to rank the six strategies based on the four KPIs for each scenario. Table 5 gives the overall distance function of KPIs calculated by Eq. (1) for each strategy over the planning horizon and corresponding rankings of strategies for each scenario. The calculation of the distance function in Eq. (1) assumes parameter P is equal to 2 and all weights are equal to 1 and extreme (ideal) values (f_i^*) are maximum of SI, RId and RIag and minimum of RSI. The consistency of overall rank for all strategies across the six scenarios indicates the robustness of the performance for the strategies regardless of occurring any scenario. The order of priority of strategies can also be defined as (1) agricultural water demand control; and (2) wastewater reuse and leakage loss reduction.

Table 5: Overall distance function of the CP method for KPIs in each strategy and ranking of strategies in each scenario

Scenarios	KPIs	Strategies					
		S#1	S#2	S#3	S#4	S#5	S#6
C#1	SI	0.38	0.422	0.466	0.563	0.917	0.951
	RId	0.805	0.778	0.879	0.914	1	1
	RSI	0.621	0.377	0.535	0.361	0.083	0.048
	RIag	0.767	0.747	0.85	0.9	1	1
	Rank	6	5	4	3	2	1
C#2	SI	0.951	0.956	0.958	0.964	0.967	0.972
	RId	0.689	0.695	0.802	0.837	0.915	0.959
	RSI	0.049	0.029	0.042	0.029	0.033	0.025
	RIag	0.626	0.644	0.755	0.807	0.894	0.954
	Rank	6	5	4	3	2	1
C#3	SI	0.959	0.963	0.966	0.971	0.974	0.978
	RId	0.646	0.644	0.747	0.765	0.86	0.876
	RSI	0.041	0.024	0.034	0.022	0.026	0.018
	RIag	0.579	0.589	0.69	0.72	0.826	0.848
	Rank	6	5	4	3	2	1
C#4	SI	0.409	0.448	0.527	0.614	0.937	0.957
	RId	0.798	0.775	0.922	0.961	1	1
	RSI	0.592	0.359	0.473	0.352	0.063	0.043
	RIag	0.77	0.753	0.91	0.957	1	1
	Rank	6	5	4	3	2	1
C#5	SI	0.952	0.957	0.96	0.964	0.969	0.973
	RId	0.7	0.706	0.818	0.85	0.924	0.961
	RSI	0.048	0.029	0.04	0.029	0.031	0.024
	RIag	0.651	0.668	0.784	0.828	0.908	0.954
	Rank	6	5	4	3	2	1
C#6	SI	0.96	0.964	0.968	0.972	0.975	0.979
	RId	0.652	0.652	0.761	0.777	0.869	0.881
	RSI	0.04	0.023	0.032	0.022	0.025	0.018
	RIag	0.601	0.612	0.718	0.744	0.842	0.858
	Rank	6	5	4	3	2	1

399 Despite the same rank of strategies in different scenarios, there are significant differences in
400 groundwater volume between similar strategies of different scenarios. According to Table 5, the
401 roles of the national water organisation and regional water authorities can be highlighted in policy

making for water allocation and resources conservation in a region. Obviously, appropriate national regulations (e.g. groundwater extraction limits) can facilitate the process of decision making by the regional authorities. For example, scenarios with two groundwater thresholds (C#3, C#6) are likely to preserve the groundwater resources when it is combined with the "water demand decrease" strategies (S#5, S#6) or "constant water demand" strategies (S#3, S#4) made by the regional authorities. However, under the scenario with no threshold limits (C#1, C#4), only the strictest strategies of agricultural water withdrawal (S#5, S#6) made by regional water authorities can lead to the preservation of groundwater resources. As groundwater resources are the main water resources of arid and semi-arid areas, the amount of water allocation for each sector (domestic, industry, agriculture, landscape, and services) signifies the regional decision making due to the natural limitations of arid lands in supplying water. In this situation, the regional decision-makers must determine domestic water demand as the priority of water supply to avoid transferring the tensions of water scarcity towards the local inhabitants.

Conclusions

This paper conducted a scenario-based assessment of potential intervention strategies for long-term planning of complex water resources and supply systems with respect to multiple sustainability criteria by using the SD and MCDA modelling approaches. The model was demonstrated on a real-world case study that was calibrated for historic 25-year data and simulated for long-term strategic planning for the next 25-year period. Results show scenario-based analysis can provide the most appropriate strategies leading to long-term sustainability of water resources for each scenario imposed on the water systems. The following can also be concluded from the results discussed here:

1. When dealing with either no threshold or one threshold of groundwater extraction limit, the only effective strategies for sustainable groundwater management are those involving agricultural water demand decrease over the planning horizon while other strategies of agricultural groundwater abstraction (i.e. constant or increase) fails to recover groundwater resources.
2. The groundwater resources can be sustainable in almost all analysed strategies only when scenarios with two threshold limits occur although with variable recovery rates.
3. "Wastewater reuse and leakage reduction" strategies have minor impacts for groundwater resources conservation compared to agricultural water abstraction strategies.
4. Scenarios with any population growth rates have negligible impact on groundwater conservation and no impact on ranking of strategies but scenarios with strict groundwater extraction limits (one or two thresholds) have major impact on groundwater conservation although again no impact on ranking strategies.
5. National organisations can have pivotal role for setting out regulations for water resources conservation and sustainability, but regional authorities can select suitable strategies based on the available scenario to either achieve sustainable performance of water resources or avoid the adverse consequences of unsustainable resources.

Institutional support should also be implemented to prevent the undesired consequences of ineffective and unsustainable exploitation of shared public resources. Aligning the long-term interests of people and governmental principals through efficient institutions is a crucial issue, requiring continuous monitoring as well as positive interactions between the governments and the public to address the dynamics and complexities of sustainable water supply. These social science factors need to be included in future studies of intervention strategies and plausible scenarios.

Declarations

Funding

No funds, grants, or other support was received.

Conflicts of interest/Competing interests

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Availability of data, code and material

The data and code used in the article is available upon the request.

Consent for publication

The authors give explicit consent to submit this article for review and publication.

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 533

Figures

Figure 1

a) Monthly precipitation, b) annual variation of groundwater level and c) population growth in the case study

Figure 2

a) Water volume in aquifer #1 for observed data and model output; variables of dam #1 for b) reservoir volume, c) inflow, d) overflow.

Figure 3

Timeframe of scenarios, strategies and water resources over the planning horizon

(a)

(b)

Figure 4

a) Self Sufficiency Index, b) Groundwater extraction from aquifer #1 for domestic consumption.

Figure 5

Variation of volume in aquifer #1 for all strategies and scenario a) C#1, b) C#4, c) C#2, d) C#5, e) C#3 and f) C#6

(a)

(b)

Figure 6

The volume difference of aquifer #1 between the timestep with minimum volume and timestep 600 for strategies with a) water demand decrease S#5 S#6 and b) water demand constant S#3 S#4 and water demand increase S#1 S#2

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