**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 against two types of 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 externally 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 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 with population growth rates on groundwater conservation is quite minor with an average recovery rate of 11% compared to scenarios of 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 (Li et al. 2019). 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 (Dong et al. 2019). 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 (Sharawat et al. 2018). In addition, sustainability of groundwater resources is highly dependent on complex feedback loops between human and natural systems in line with policy developments (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). The SD is suitable for long-term performance assessment of the WRSS in which feedbacks and complex human interactions can be observed among variables and stock changes. The SD can also be used for strategic planning of complex systems of water supply and resources (Sangchini et al. 2021). For instance, 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 domestic water sectors. 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. 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) evaluate 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). In addition, appearance of externally derived scenarios such as population growth and climate change can impose more complexity on decision making to find the most sustainable intervention strategies for water demand and supply management.

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 to simultaneously analysis both plausible scenarios and intervention strategies for water resources and supply management. This paper makes use of integrating the SD with the CP tool to develop a systematic assessment framework and find the most sustainable intervention strategies under potential future scenarios for management of a complex 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 period (e.g. 30-50 years) with monthly timesteps. 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 an SD modelling approach.
* **Step 2**: Performance assessment of the SD model for sustainability of water resources and supply indicators for plausible scenarios and 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 subsystems (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 subsystems (e.g. resources and reservoirs) as stocks connected to each other through flow and causal loop diagrams. 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. ‎ Note that more details of each subsystem including the model abbreviations and the schematic charts of the model development are available in S.1 and S.2 of the supplementary materials.

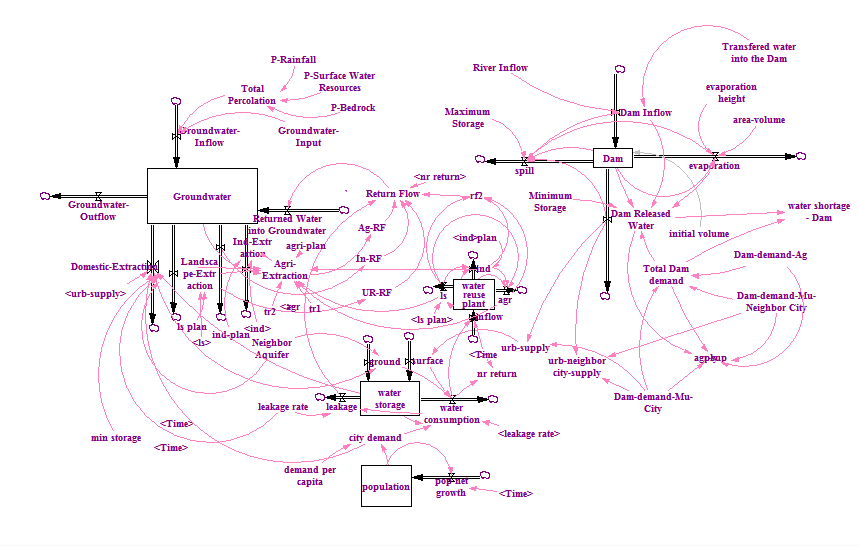


Figure 1: The SD model of the WRSS (see more details of subsystems in Figure S.1 and abbreviations in Table S.1)

## 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). The following section outlines scenarios and strategies set out in the SD modelling.

### ‎Plausible scenarios

Two scenario types are defined here as Population Growth "PG" and Groundwater Extraction Limits (Table 1). These scenario types are further divided into two population growth rates and three threshold limits for groundwater extraction. The two population growth rates are normal (NPG) and rapid (RPG) representing current and highest predicted rates 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 the volume between the two thresholds and no supply for the 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 compositions of population growth rates and groundwater extraction limits.

### Intervention strategies

Intervention strategies are defined as a combination of intervention options and policies set out by water authorities for performance improvement of water systems over a long-term planning horizon. Based on the investigation of potential intervention options in water systems, we analyse three types of intervention strategies including agricultural water demand control, urban wastewater reuse and water loss reduction in pipeline (Table 1). These strategies can also be highly beneficial to preservation of water resources and lead to making more informed decisions for domestic water supply. More specifically, agricultural irrigation typically accounts for the largest water demand and hence any strategy derived from it would have a key role to minimise depleting aquifers (Maliva & Missimer 2012). "Agricultural water control" inspired by UN Water (2015) represents the role of decision makers in regional authorities to make ‎policies for ‎water preservation. The agricultural water control strategy is divided here into three further trends of agricultural water demands (i.e. increasing, constant and decreasing) over the planning horizon. "Water Demand Increase" indicates business as usual (i.e. do nothing) as water demand increases proportional to population growth and demand increase for agricultural products. "Constant Water Demand" and "Water Demand Decrease" can be considered as measures introduced by stakeholders to harness agricultural water demands such as new water technologies, policies and 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 1 based on the 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 1) that can be analysed for each of the six scenarios introduced above for the assessment criteria outlined in the next section.

Table 1: Scenario and strategy types and numbering in the SD model

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Scenario type** |  | **Groundwater extraction limits** | | | |
|  | **State of scenario** | | 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 |
| **Strategy type** |  | **Agricultural water control** | | | |
|  | **State of strategy** | | 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 2 are selected to represent sustainability indices of water resources and supply systems. They include Sustainability Index (SI), Reliability Index for domestic purpose (RId), Reliability Index for agricultural purpose (RIag), 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. RId=1) while the impact of any water shortage is expected to be seen through water allocation of agricultural demands that influence agricultural reliability index (RIag). RSI is a measure to demonstrate the growth rate of one region based on available water resources. SSI indicates contribution of neighbouring water resources in water supply. The index shows the ratio of water volume supplied by local water resources to water volume supplied by neighbouring water resources.

Table 2: List of KPIs used in this study

|  |  |  |  |
| --- | --- | --- | --- |
| Key Performance Indicators | Equations | Description | Reference |
| Sustainability Index (SI) |  | 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 (RId) |  | TWSd= total domestic water supply and ‎TWDd= total domestic water demand. If there is no domestic water shortage, total water supply is equal to ‎total water demand (RId = 1). For any domestic water shortage, RId < 1. | Behzadian et al. (2014) |
| Reliability Index for Agricultural purpose (RIag) |  | TWSag= total agricultural water supply; ‎TWDag= total agricultural water demand. If there is no agricultural water shortage, total agricultural supply equals ‎total agricultural demand (RIag = 1). For agricultural water shortage, RIag < 1. | Behzadian et al. (2014) |
| Resource Stress Index (RSI) |  | 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) |  | 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) |

## Compromise Programming (CP) method

The CP method belongs to a class of MCDA technique called "distance-based" methods. As KPIs may have different units, normalised functions are used to ensure the same range for all KPIs (Behzadian and Kapelan 2015). Multiple KPIs for each strategy are converted to one distance function and strategies are then ranked according to these distances. Without loss of generality, assuming all criteria are maximising, the overall distance function for an intervention strategy with an evaluation function (), maximum absolute (ideal) value (), minimum absolute (anti-ideal) value (), weight or relative importance () for criterion *i*, a topological metric of *p* and number of KPIs equal to *n* is calculated for the combination of the normalised evaluation functions as below assuming that the scaling function is linear:

|  |  |  |
| --- | --- | --- |
|  |  | (1) |

Parameter changes from 1 to and it has higher sensitivity if it takes higher value. For the CP used in the paper, was equal to 2. belongs to a corresponding KPI calculated by the SD over the planning horizon. and is the maximum and minimum value of the corresponding KPI among all strategies analysed. The relative weights () 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 Water Catchment of Kerman located in the southeast of Iran (Figure 2a). 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 2b illustrates the monthly precipitation of the case study. Available water resources and annual water withdrawals in the case study are presented in Figure 2c, which is from groundwater resources in Aquifer #1 (293 Million Cubic Meters (MCM)) and Aquifer #2 (11 MCM) (water supply since Oct 2004) and (2) surface water resources in dam #1 (32.27 MCM) and dam #2 (20.1 MCM) (water supply since Oct 2018). 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 2d). The future population of Kerman projected by Statistical Centre of Iran (2016) for the two scenarios is shown in Figure 2e for 25 years of the simulation period between Oct 2012 and Sep 2037 (see more information of water supply and demands in S.3 of the supplementary materials).

|  |  |  |  |
| --- | --- | --- | --- |
| (a) | C:\Users\NOOR26.COM\Documents\momeniFigurekurosh.jpg | (b) |  |
| (d) |  |
| (c) |  |
| (e) |  |

Figure 2: a) Layout of the case study b) monthly precipitation, c) water supply from available resources for different sectors, d) annual variation of historic groundwater level and e) projected normal and rapid population growths

The calibration result for the first 300 timesteps is shown in Figure 3a. The close agreement of groundwater volume between the observed data and model output indicates a good model calibration (see statistical tests in S.4 of the supplementary materials). 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 3b) and significant spills occurred due to large inflows (Figure 3d) while reservoir volume gradually reduced as inflow decreased significantly within the remaining timesteps of the planning horizon (Figure 3c).

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 (*ASt*) for scenarios with two thresholds is calculated based on Eq. (2):

|  |  |
| --- | --- |
|  | (2) |

where *Vat*=the aquifer volume at timestep *t* (MCM), *ADt*=the agricultural demand at timestep *t* (MCM), *DDt*, *IDt*, *LDt*= domestic demand, industrial demand and landscape demand at timestep *t*, respectively (MCM). Agricultural water demands consider the relevant strategies (i.e. increase, constant or decrease) between timesteps 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 3e 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 more details in S.5 of the supplementary materials).

|  |  |  |  |
| --- | --- | --- | --- |
| (a) |  | (b) |  |
| (c) |  | (d) |  |
| (e) |  | | |

Figure 3: Water volume in aquifer #1 for observed data and model output; variables of dam #1 for b) reservoir volume, c) inflow, d) overflow and e) 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 4 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 4a 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. 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 (Figure 4b). The performance of all strategies discussed here are given only for aquifer #1 as the main water resource of the study. As can be seen in Figure 4c and Figure 4d, 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 minor for conservation of groundwater resources in these two scenarios. Furthermore, there is no sensible impact of different population growth rates on the groundwater volume in these scenarios (see more results in S.6 and S7).

|  |  |  |  |
| --- | --- | --- | --- |
| (a) |  | (b) |  |
| (c) |  | (d) |  |
| (e) |  | (f) |  |
| (g) |  | (h) |  |
| (i) |  | (j) |  |

Figure 4: a) Self Sufficiency Index, b) Groundwater extraction from aquifer #1 for domestic consumption.‎ Variation of volume in aquifer #1 for all strategies and scenario c) C#1, d) C#4, e) C#2, f) C#5, g) C#3and h) C#6. The volume difference of aquifer #1 between minimum volume and time step No. 600 i) S#5, and S#6 and j) S#3, S#4, S#1, and S#2‎

For the scenario with one threshold (C#2 and C#5) in Figure 4e and Figure 4f, 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 Figure 4g and Figure 4h, 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 4i and Figure 4j show 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 4g, 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 (Figure 4h). 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%.

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. Each row in Table 3 gives the normalised values of KPIs for the overall distance function calculated by Eq. (1) for each strategy over the planning horizon and hence corresponding rankings of strategies is calculated 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 () 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. Note that the SD model outputs for water demands and supplies for each scenario and strategy are available in S.7 of the Supplementary materials.

Table 3: 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 |

Despite the same rank of strategies in different scenarios, there are significant differences in groundwater volume between similar strategies of different scenarios. According to Table 4, the 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 can provide decision makers with the most appropriate strategies leading to long-term sustainability of water resources for each plausible 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.

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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.

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

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