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A spatial decision support system for optimally locating treatment plants for safe wastewater reuse: an application to Saudi Arabia

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ABSTRACT

In this study, we developed a non-linear optimizing spatial decision support system that combines multi-criteria analysis with a geographical information system. We consider dedicated tertiary treatment for agricultural, industrial, and landscape uses by evaluating economic, social, and environmental objectives based on distances from opportunity costs and water quality standards. Saudi Arabia is used to illustrate decisions. Numerical simulations revealed that the budgeted number of plants is completely used, although tertiary treatment for all uses is seldom supported. Agricultural reuse is almost always suggested, whereas reuse in the industrial sector is not always suggested in provinces with current or planned industrial districts. Landscape reuse is always coupled with agricultural uses. The optimal wastewater treatment plants' location significantly improves welfare, although to a different extent for different sectors. The system achieves a satisfactory sectoral equity, in terms of the ability to meet the needs of, and reduce the impacts for industrial, agricultural, and landscape sectors except for social features in small cities. Sensitivity analyses revealed that the best location is robust with respect to the relative weights of economic, social and environmental features and the predicted future treatment efficiencies, but not robust with respect to water quality standards.

Keywords: Decision support system; Multi-criteria analysis; Geographical information system; Optimal location; Wastewater treatment plant; Safe reuse; Saudi Arabia; .NET framework; ODBC

1. Introduction

In arid and semi-arid regions, in general, and the Middle East, in particular, it's crucial to provide a feasible and sustainable source of water; desalination is not always feasible and economical, and groundwater may run out in the long-run. The severity of these problems varies widely around the world [1,2].

Wastewater treatment accomplishes two fundamental functions: the treated effluent can be used as a water resource for beneficial purposes such as irrigation, thus increasing the available water resource [3], and the treated effluent keeps pollutants out of streams, deserts, and beaches, thus reducing pollution of surface and groundwater [4].

In terms of water uses, five main categories of wastewater reuse have been identified [5]: agricultural irrigation [6], landscape irrigation, industrial recycling and reuse, and groundwater recharge [7]. The relative magnitudes of the demands in these categories vary widely among areas.

In the context of water pollution, several parameters (chemical and biological) should be controlled to permit water reuse [8], although the most common is biochemical oxygen demand (BOD: it is the amount of dissolved oxygen needed by aerobic biological organisms to break down organic material present in a given water sample at certain temperature over a specific time period, and it is used as a surrogate of the degree of organic pollution of water), turbidity

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or suspended solids (TSS: it refers to organic and inorganic suspended particles, that are not dissolved, in a sample of water, and it is used to measure the conventional pollution of water), the count of coliform bacteria (total or faecal), nitrogen, and residual chlorine [9]. The total dissolved solids salts (TDS: it is the number of minerals, metals, organic material and salts that are dissolved in a certain water volume, and it is directly associated with the turbidity and purity of water) is often used as an additional water quality indicator.

The purpose of this study was to develop a decision support system (DSS) based on geographical information system (GIS) software to determine the optimal locations of new wastewater treatment plants (WWTPs) for dedicated uses (e.g., irrigation), according to weighted economic, social, and environmental achievements, within a multi-criteria analysis (MCA) framework.

Note that the analysis, which is at a national level, disregarded impacts on specific species or habitats, population displacement, or the alteration of existing residential areas or land uses. By so doing, we disregard the "not in my backyard" problem. Moreover, we did not consider how the type of environment that receives the treated water, as well as its characteristics, affect the extent to which wastewater components are assimilated. Finally, we did not attempt to identify the environmental functions to be protected; that is, we did not perform an environmental impact assessment.

In other words, our primary goals were to develop an archetypal software tool for spatially explicit consideration of many criteria that could be used to interactively explore the impacts of preferences (here, the weights for economic, social, and environmental features; the concern for the groundwater future depletion; the maximum content of TDS, TSS, and BOD) and optimize the investment in WWTPs to support planning of sustainable water use.

By using GIS, we were able to depict the spatial specificities described in the model. For example, a cheaper local alternative to treated wastewater reduces the likelihood of establishing a WWTP and increases the risk of worse water quality; in contrast, a larger national budget for wastewater treatment means more numerous WWTPs and better water quality. In addition, we were able to depict the spatial specificities disregarded in the model. For example, political coalitions and adversarial relationships between regions or provinces are likely to affect the locations of the WWTPs and the costs of treated wastewater, including transport of treated wastewater between nearby regions or provinces.

The DSS allows changes over time in decisions that affect the optimal location of the WWTPs: these include water quality standards; the relative importance attached to economic, social, and environmental features; the total planned number of WWTPs or total budget for their establishment; technical improvements or cost reductions; the degree of concern about future groundwater availability; the value of relevant discount rates; and planning of industrial districts. Note that groundwater recharge is included in possible uses as an implicit decision variable by letting DSS users specify different levels of concern for its future depletion as a groundwater shadow price (i.e., the groundwater marginal value which includes the economic, social, and environmental benefits arising for future generations from its preservation based on the maximization of the social welfare of current and future generations). Indeed, a larger concern for future reserves theoretically amounts to a larger shadow price which implies a larger groundwater recharge. In practice, this use is suggested everywhere if the concern for its future depletion is large, and it is never suggested otherwise.

By using MCA, we were able to specify the relative importance of economic, social, and environmental achievements, and to combine the different incommensurable features associated with these achievements: economic features are expressed as monetary costs and linked to TDS, social features are expressed as sickness and mortality rates for specified diseases and linked to TSS, and environmental features are expressed in terms of biological and chemical risks and linked to BOD.

Optimization lets us minimize distances from the economic, social, and environmental opportunity costs or water quality standards that represent optimal solutions for agricultural, industrial, and landscape uses in terms of social welfare. In particular, we will use an overall welfare score based on the available volume (m^3) of water per capita as a social welfare measure.

Note that the optimization of social welfare implies efficiency. The DSS lets users simulate population dynamics in cities as well as changes in industrial development and planning. MCA can result in strong sustainability (i.e., focused on impacts) if the environmental standards are properly chosen, and approaches a cost–benefit analysis welfare value (i.e., weak sustainability) if the environmental and social monetary measures are properly identified. The DSS also lets users perform sensitivity analyses for the most representative parameters to account for the most significant demographic, economic, technological, and environmental uncertainties. The GIS lets users measure distributional equity in water quality and WWTP investment. The DSS also lets users depict alternative relative degrees of public acceptance by modifying the distribution of overall treatment costs among farms, industrial firms, and municipalities. In other words, the spatial DSS developed in this study can be used to support sustainable spatial planning whenever public acceptance (i.e., the approval of the final users and consumers of the reclaimed water) and public participation (i.e., the involvement of stakeholders in decision-making) are required.

2. Methodology

2.1. Literature

This section will refer to the main features involved in decision making for locating WWTP for safe reuse discussed in the previous section (i.e., DSS, GIS, MCA, and optimizations) and their combination to discuss the relevant literature.

Much of the literature on decision making for wastewater treatment is quite recent, due to the recent development of software tools to cope with the several features involved in such decisions. Table 1 summarizes the main characteristics of some recent contributions, whereas Supplementary information discusses papers in detail.

Note that we do not consider the design of wastewater infrastructures, the management of WWTPs, and the selection of wastewater infrastructures.

Table 1
Main recent (2007–2017) references on regional planning for wastewater treatment plants (WWTPs) that accounts for at least two of the four main features

	DSS	GIS	MCA (sustainability)	Optimization (efficiency)	WWTP location	Alternative reuse	National scale	Cost-benefit analysis (welfare)	Sensitivity analyses (uncertainty)	Spatial distribution (equity)
Hidalgo et al. [24]			++	++		++				
Zeng et al. [28]		++	++		++	++	++			
Makropoulos et al. [27]		++	++		++					
Zarghami et al. [25]			++	++						
Vasiloglou et al. [22]	++		++ (1)				+			
Ahmadi and Merkley [29]	++	++			+	++	+			
Molinos-Senante et al. [23,47,49]			++	+ (2)	++			++		
Zeferino et al. [26,34]			++ (3)	++	+ (4)		++		++ (5)	
Anagnostopoulos and Vavatsikos [33]	++	++	++							
Massei et al. [37]		++	++							
Udias et al. [35]			++	++					++	
Dubber et al. [30]	++	++			++	++				
Neji and Turki [31]		++	++	++						
Pedrero et al. [32]		++	++	++						
This paper	++	++	++	++	++	++	++	+ (6)	++	++

Legend: ++ = relevant; + = potentially relevant.
Notes: (1) Normalization based on the absolute distance from a standard as opposed to the percentage of a standard. (2) Choice of projects based on normalized scores. (3) Water quality in terms of dissolved oxygen content, so environmental impacts only. (4) Population as a source of wastewater, but no alternative uses. (5) Uncertainty from river flows only. (6) Standards-based on social optima or opportunity costs in the short run and long run.
DSS: decision support system; GIS: geographical information system; MCA: use of multi-criteria analysis; optimization.

2.2. Optimisation algorithm

The purpose of this paper is to present an archetypal software tool that can be applied in many contexts. This section will present its optimization algorithm, by committing section 4 to introduce additional assumptions needed to apply the suggested tool to the case study depicted in section 3. In summary, the applicability of the tool drove us to use an opportunity cost approach based on per capita available water, whereas the exemplary of the tool drove us to refer to three quantitatively major uses (i.e., agricultural irrigation, industrial reuse, and landscape irrigation) and three water quality indicators (i.e., TDS for economic impacts, TSS for social impacts, and BOD for environmental impacts), by disregarding quantitatively minor uses such as recreational and environmental uses, non-potable urban uses, and potable urban uses.

Indeed, two main approaches could be followed to depict the economic features of safe reuse of treated wastewater within an MCA framework: cost-effectiveness and opportunity costs.

The cost-effectiveness approach identifies the options that maximize the total net benefits for each unit cost of the dedicated treatment process [10]. However, the implementation of such an approach typically requires information on sources of funds, water demands, and requirements for current and future uses economic net returns from agricultural and industrial reuse and environmental impacts from all kinds of reuse. Unfortunately, such information is unlikely to be available. Alternatively, the opportunity cost approach identifies the dedicated treatment processes that minimize total costs by comparing the two current alternative water sources (e.g., seawater desalinization and groundwater) with the three potential wastewater reuse categories (i.e., agriculture, industry, landscape). For the sake of simplicity, infrastructures such as sewer networks, treatment plants, and possible pumping stations are summarized as water unit costs (i.e., costs per m^3 of water). Without loss of generality, we have assumed that agriculture is currently using only groundwater, the industry is currently using only desalinized water, and landscape is currently using only groundwater.

Note that this approach does not require a field survey to assess the water demand (i.e., the willingness to pay for treated wastewater) by taking into account social and environmental aspects, nor does it require estimation of the water need for agriculture (which depends on cropping patterns) or for industry (which depends on production structures). Instead, the volume of available water per capita will be used. Moreover, the same logic of comparing the current and potential conditions can be applied to depict economic, social and environmental features of safe wastewater reuse within an MCA framework by introducing standards for the three water quality indicators (i.e., BOD, TDS, TSS). Finally, within an MCA framework, the relative weights attached to the three impact categories (economic, social, and environmental) must be specified by the user of the spatial DSS. Note that Mahjouri and Pourmand [11] applied a social choice methodology (i.e., plurality voting) to define the weights for treated wastewater reuse in urban and suburban areas.

In other words, to prioritize dedicated tertiary WWTPs for the three potential reuse, in both small and medium cities, we based the optimization algorithm on both convenience (with respect to the costs of the locally existing water sources) and adequacy (in relation to the locally required water quality standards). Note that we disregarded large cities to increase equity for smaller cities, and we neglected primary and secondary treatments to focus on the most challenging decisions in implementing a sustainable water reuse plan. In contrast, Jing et al. [12] prioritized industrial over municipal or agricultural uses by applying an analytic hierarchy process with stochastic intervals, in which they considered technical, economic, and environmental criteria. However, both convenience and adequacy depend on the people who are affected. The optimization of economic, social, and environmental aspects for a representative individual will be weighted according to the population distribution in small and medium cities for each province. Moreover, the wastewater demand for industrial wastewater reuse cannot be assumed to be the same in all provinces and cities because the current and planned industrial structures vary spatially. In terms of industrial reuse in different provinces, we introduced a factor to correct for this variation by summing the number of existing or planned industrial districts. Finally, we assumed that the concern for the groundwater future depletion is depicted by its shadow price.

Note that the user of the spatial DSS can change the distribution of industrial districts to depict the effects of alternative industrial plans, and the population distribution in small and medium cities to represent alternative expected urban dynamics, and can change the groundwater shadow price to depict different levels of concern for its future depletion.

In this context, we defined the following objective function that must be minimized, subject to constraints:

Choose x_{ij}, y_{ij}, and z_{ij} in order to minimize:

$$\text{Obj}=\sum ij\left(\text{POP}_{ij} / \text{POP}\right)$$
$$w_{\text{eco}}\left\{\begin{array}{l} w_{\text{agr}}\left[\left(\text{cc}_{\text{agr},ij}+\text{sp}_{\text{gro}}\right)/\text{tc}_{\text{agr}}\right]\left(1-\left[\left(\text{cc}_{\text{agr},ij}+\text{sp}_{\text{gro}}-\text{tc}_{\text{agr}}\right)/\left(cc_{agr,ij}+\text{sp}_{gro}\right)\right]\times x_{ij}\right)+ \\ w_{\text{ind}}\,\text{inddis}_{ij}\left(\text{cc}_{\text{ind},ij}/\text{tc}_{\text{ind}}\right)\left(1-\left[\left(\text{cc}_{\text{ind},ij}-\text{tc}_{\text{ind}}\right)/\text{cc}_{\text{ind},ij}\right]\times y_{ij}\right)+ \\ w_{\text{lan}}\left[\left(\text{cc}_{\text{lan},ij}+\text{sp}_{\text{gro}}\right)/\text{tc}_{\text{lan}}\right]\left(1-\left[\left(\text{cc}_{\text{lan},ij}+\text{sp}_{\text{gro}}-\text{tc}_{\text{lan}}\right)/\left(\text{cc}_{\text{lan},ij}+\text{sp}_{\text{gro}}\right)\right]\times z_{ij}\right) \end{array}\right\}+ \tag{1}$$
$$w_{\text{soc}}\sum_{ij}\left(\text{POP}_{ij}/\text{POP}\right)\left[\left(\text{TSS}_{ij}/\text{TSS}_{\text{sta}}\right)\left(1-\text{te}_{\text{TSS}}z_{ij}\right)\right]+w_{\text{env}}\sum_{ij}\left(\text{POP}_{ij}/\text{POP}\right)\left[\left(\text{BOD}_{ij}/\text{BOD}_{\text{sta}}\right)\left(1-\text{te}_{\text{BOD}}x_{ij}\right)\right]$$

where

$$w_{\text{eco}}+w_{\text{soc}}+w_{\text{env}}=1 \tag{2}$$

$$w_{\text{agr}}+w_{\text{ind}}+w_{\text{lan}}=1 \tag{3}$$

Subject to

$$\sum_{ij}x_{ij}+y_{ij}+z_{ij}\le \text{mnp} \tag{4}$$

where the applied notation is summarized in Table 2.

The model is based on the following logic. Note that DSS users can specify any value of relative weights attached to economic, social and environmental features, whereas here for simplicity we will refer to extreme values. The goal is to minimize either economic opportunity costs (w_{eco} = 1) or impacts on social welfare (w_{soc} = 1) or impacts on environmental welfare (w_{env} = 1) or a combination of these costs and impacts, according to the value attached to the economic, social, and environmental criteria represented by the relative weights w_{eco}, w_{soc}, and w_{env}.

When w_{eco} = w_{soc} = 0, the algorithm will choose the dedicated marginal treatments that reduce the environmental impacts to the largest extent possible. For example, if the focus is on dedicated treatment for agricultural reuse:

$$w_{\text{env}}\left(\text{BOD}_{ij}/\text{BOD}_{\text{sta}}\right)\left(1-\text{te}_{\text{BOD}}\times x_{ij}\right) \tag{5}$$

If x_{ij} = 1, then water quality indicators with respect to the standard in province *i* and city *j* (i.e., $\text{BOD}_{ij}/\text{BOD}_{\text{sta}}$) will refer to the dedicated tertiary treatment of effluent since the current level is reduced according to the treatment efficiency te:

$$w_{\text{env}}\left(\text{BOD}_{ij}/\text{BOD}_{\text{sta}}\right)\left(1-\text{te}_{\text{BOD}}\right) \tag{6}$$

Alternatively, if x_{ij} = 0, then water quality indicators in province *i* and city *j* ($\text{BOD}_{ij}/\text{BOD}_{\text{sta}}$) will refer to the secondary treatment of effluent since the treatment efficiency te is irrelevant:

$$w_{\text{env}}\left(\text{BOD}_{ij}/\text{BOD}_{\text{sta}}\right) \tag{7}$$

A similar logic I used for the impact of dedicated treatment for landscape reuse (z_{ij} = 1 or z_{ij} = 0) on social achievements. When w_{soc} = w_{env} = 0, the algorithm will choose the dedicated marginal treatments that reduce the cost per m^3 of water to the largest extent possible. For example, if the focus is on dedicated treatment for agricultural reuse (w_{agr} = 1 and w_{ind} = w_{lan} = 0), by assuming a zero shadow price for groundwater:

$$\left(\text{cc}_{\text{agr},ij}/\text{tc}_{\text{agr}}\right)\left\{1-\left[\left(\text{cc}_{\text{agr},ij}-\text{tc}_{\text{agr}}\right)/\text{cc}_{\text{agr},ij}\right]\times x_{ij}\right\} \tag{8}$$

Table 2
Applied notation

BOD_{ij}	Average BOD after secondary treatment processes in province *i* and city *j*
BOD_{sta}	BOD standard
cc	Current cost
$inddis_{ij}$	Number of industrial districts in province *i* and city *j*
index *i*	Provinces
index *j*	Small and medium cities
mnp	Maximum number of dedicated tertiary treatment plants (i.e., the budgeted number of plants which must be allocated by the analysis)
pop	Total population
pop_{ij}	Population in province *i* and city *j*
sp_{gro}	Shadow price for groundwater
tc	Dedicated treatment cost including tertiary treatment (agr: agricultural irrigation; ind: industrial recycling and reuse; lan: landscape irrigation)
TDS_{ij}	Average TDS after secondary treatment processes in province *i* and city *j*
TDS_{sta}	TDS standard
te	Dedicated tertiary treatment efficiency (BOD or TSS)
TSS_{ij}	Average TSS after secondary treatment processes in province *i* and city *j*
TSS_{sta}	TSS standard
w	Relative weights for economic (eco), social (soc), and environmental (env) aspects, as well as for agricultural, industrial, and landscape reuse (agr: agricultural irrigation; ind: industrial recycling and reuse; lan: landscape irrigation, respectively)
x	Treatment for agricultural reuse (0 = no treatment and 1 = treatment)
y	Treatment dedicated to industrial reuse (0 = no treatment and 1 = treatment)
z	Treatment dedicated to landscape reuse (0 = no treatment and 1 = treatment)

Two possible causes can be observed. If the dedicated treatment for agricultural reuse is more expensive than the current water cost, then reuse in agriculture is not feasible, and it will not be implemented ($x_{ij} = 0$):

$$\left(\mathrm{cc}_{\mathrm{agr},ij}/\mathrm{tc}_{\mathrm{agr}}\right) < 1 \tag{9}$$

In contrast, if the dedicated treatment for agricultural reuse is less expensive than the current water cost, then the economic cheapness will not be compared across provinces and cities, and reuse in agriculture could be implemented ($x_{ij} = 1$):

$$\left(\mathrm{cc}_{\mathrm{agr},ij}/\mathrm{tc}_{\mathrm{agr}}\right)\left\{1-\left[\left(\mathrm{cc}_{\mathrm{agr},ij}-\mathrm{tc}_{\mathrm{agr}}\right)/\mathrm{cc}_{\mathrm{agr},ij}\right]\right\} = 1 \tag{10}$$

A similar logic is used for dedicated treatment for landscape and industrial reuse.

Note that the objective of the model is to minimize the per capita economic costs and the per capita social and environmental impacts. In this context, the estimated population dynamics can affect the dedicated treatment processes to be implemented. In particular, if the current water cost divided by the treatment cost is larger than 1, or the pollutant level divided by the standard is larger than 1, but a decrease of the population or an increase of the population smaller than the average increase is observed (so that pop_{ij}/pop decreases), then it might be the case that the per capita cost or impact becomes smaller than 1, so that a dedicated treatment plant is no longer suggested.

If the maximum number of potential treatment processes (mnp) is large enough, all dedicated treatments for reuse will be suggested whenever current costs are larger than treatment costs since this replaces 1 with a quantity that is larger than 1: the choice, in this case, does not require a model. In contrast, if the total number of potential WWTPs is small enough, priorities must be identified, and the model becomes useful.

Therefore, the model will suggest one or more reuse types, based on features characterizing each province: both suggested uses and characterizing features could be represented by different colors for each province in case of few items or by differently colored bars attached to each province in case of many items.

Moreover, overall welfare scores and specific sectoral scores will be calculated. In particular, for each (small and medium) city in each province the economic score is 100 if water treatment costs are equal or smaller than the current water costs, and it is smaller than 100 otherwise; the social score is 100 if the TSS standard is met and smaller than 100 otherwise; the environmental score is 100 is the BOD standard is met and it is smaller than 100 otherwise. In other words, the overall score (i.e., the sum of weighted sectoral scores) is theoretically 100 if all standards are met and all water costs are minimized, whereas the maximum operational overall score to be referred to is smaller than 100 and represents the maximum overall welfare which can be achieved if all dedicated treatments are implemented everywhere. These scores will be represented as differently colored bars attached to each province.

Finally, the sectoral scores (i.e., economic, social and environmental scores) for each province will be averaged over provinces in terms of population to get a national measure of sectoral impacts, and they can be used to calculate Gini indexes (i.e., a synthetic measure of inequality with value 0 in case of perfect equality and value $(n-1)/n$ in case of maximum inequality among n items) to get an equity measure of impacts across provinces.

Note that the model will not suggest one or more reuse types if:

- The water quality of effluent from tertiary treatment is not sufficient for possible reuse.
- The tertiary treatment level implementation is uneconomical because the implementation costs are greater than the cost of the actual available water source.
- The tertiary treatment level implementation in one province is inappropriate with respect to the other provinces because implementation costs are greater than the cost of the actual available water source.
- The potential demands being considered are not present (e.g., industrial districts are not present or foreseen in a given region).

Needless to say that the opportunity cost approach behind the suggested optimization algorithm could be extended to additional and/or alternative wastewater uses, city sizes, treatment levels, and water quality indicators.

3. Study context

The development of a national-scale spatial DSS to support the optimal location of WWTPs for safe wastewater reuse requires some contextual assumptions. In this study, Saudi Arabia is used as a case study. The country's 13 provinces have different treatment technologies and targets, as well as different current and potential water treatment needs (Table 3). This has many implications for the spatial scale to be applied, the national objectives to be achieved, and the WWTPs to be considered while using consistent MCA and DSS approaches.

In terms of spatial scale, the analysis will be performed at a provincial level by disregarding the impacts of wastewater production and disposal at specific sites. The government identified three main categories of cities that would be used to plan its objectives in terms of per capita water consumption in 2020 and 2035: very intensively populated (VIP) cities (larger than 1 million), medium cities (between 85,000 and 1 million), and small cities (smaller than 85,000). In 2005, the three VIP cities (Jeddah, Makkah, and Riyadh) had an average population of 2,727,600, whereas the medium and small cities had average populations of 264,546 and 17,858, respectively. In the present study, we disregarded the three VIP cities to avoid the introduction of biases in the optimal national locations, because their large populations would give them greater weight in our calculations, so we, therefore, focused only on the small and medium cities.

Note that a preliminary analysis of water costs suggested disregarding groundwater recharge [13]. Indeed, if the concern for groundwater stock preservation is large, groundwater recharge would be suggested everywhere. In contrast, if the concern for groundwater stock preservation is small, groundwater recharge is never suggested, although the water treatment does not require reverse osmosis (RO) filtration to remove salinity, due the following reasons: in case of natural recharge from the surface, the probability of water reaching deep aquifers is very low; in case of recharge through reinjection, the wastewater treatment cost is increased by the cost of reinjection; if after reinjection it is foreseen to use groundwater for agriculture or landscape irrigation, the wastewater treatment cost is increased by extraction costs. The user of the spatial DSS can change the groundwater shadow price to depict different levels of concern for its future depletion. In other words, groundwater recharge turns out to be theoretically suggested in the unlikely scenarios of excess water supply for all uses or no tertiary treatment for any use. In practice, agriculture reuse or wadi disposal can be considered similar to groundwater recharge by natural infiltration.

In terms of treatment technologies, we distinguished three levels of treatment: Primary treatment involves separation of heavier from lighter solid materials and implements grit removal and septage handling. Secondary treatment is accomplished using biological processes and sedimentation and allows the removal of organic material that is both colloidal in size and dissolved. Tertiary treatment permits the removal of specific contaminants that are not normally removed during conventional secondary treatment, such as nutrients and pathogens. Secondary treatment assumes that primary treatment has already been performed, and tertiary treatment assumes that secondary treatment has already been performed.

The current water quality standards suggest that a secondary treatment will be implemented everywhere. However, the king's royal decree in 2000 stated that all wastewater should be treated at the tertiary level, regardless of reuse types and discharge locations. Note that this decree has been recently challenged [14]: the optimal locations identified in this paper will allow us to provide some insights on this issue.

In terms of treatment costs, we will focus on the treatment efficiencies of dedicated tertiary processes, which we will express as the cost increase compared with the secondary treatment processes only (i.e., we will not explicitly consider primary treatment processes). Thus, we will assume that the advantages and disadvantages of the ultra-filtration technology proposed by the 2000 royal decree are lumped into the total average cost per m^3 by including investment, operation, and maintenance costs [15]. Since an essential parameter for agricultural and landscape reuse is the water's salinity, the king's royal decree suggested coupling of the ultra-filtration treatment with the RO process whenever salinity problems are relevant. Note that the marginal cost to reduce the TDS is taken into account, although it is not mentioned in Saudi Arabia regulations.

The current water costs with the marginal dedicated tertiary treatment costs, for agriculture and landscape are 3.5 riyals per m^3 without salinity criteria and 5.7 riyals per m^3 with; for industry, they are 1.75 riyals per m^3 without salinity criteria and 2.85 riyals per m^3 with [3]. These costs refer to

Table 3
Current wastewater production (×10^6 m^3 per year) and target wastewater reuse (I, II, and III level) in Saudi Arabia

Province	Agricultural reuse	Industrial reuse	Landscape reuse	Desert disposal	Sea disposal	Wadi disposal
Al-Bahah						
Al-Qassim	9 (II)					13 (II), 8 (I)
Al-Jouf						
Aseer	13 (III)		5 (III)			
Eastern area			1 (I)	13 (I)	143 (II), 24 (I)	
Hail						1 (II)
Jizan					4 (II)	
Medina	63 (III)				8 (III)	
Makkah	17 (III)	9 (RO)	19 (II)		77 (II), 9 (III)	46 (I), 18 (II)
Najran						
North border						3 (II)
Riyadh	50 (III)	5 (II)	2 (III)	3 (II)		165 (III), 8 (II), 9 (I)
Tabuk			1 (II)			21 (II)
Target	330	30	20			

Treatment levels: (I) means primary, (II) secondary, and (III) tertiary treatment. (RO) means reverse osmosis
See the text for descriptions of each treatment level. Makkah and Riyadh provinces exclude the cities of Makkah and Riyadh, respectively.

ultra-filtration whenever salinity problems are not relevant, but refer to ultra-filtration coupled with RO when salinity is relevant, as in the case of agricultural reuse. They refer to the average costs for industrial uses in the case of symmetric distributions (i.e., the frequency of costs above the average is the same as the frequency of costs below the average): any quality level required by the industrial sector can be obtained, provided that a suitable process is implemented and a sufficient cost is paid. Note that the use of ultra-filtration is considered when the TDS is ≤1,000 mg/L, and ultra-filtration coupled with RO when TDS is >1,000 mg/L. However, these parameters can be modified within the spatial DSS described later in this paper to represent potential changes in standards or costs (Table 4).

In terms of treatment efficiency, the average current levels of the water quality indicators (BOD, TDS, and TSS) recorded by managers of the five existing tertiary WWTPs (i.e., Aseer, 6; 215; and 8 mg/L, respectively; Eastern area, 4; 2,444; and 6; Medina, 10; 900; and 6; Makkah, 2; 676; and 1; Riyadh, 12; 1,371; and 13) show that the efficiency of ultra-filtration tertiary treatment with respect to the secondary process (i.e., the reduction compared with the concentration produced by secondary treatment or the proportion of the concentration produced by secondary treatment that remained after tertiary treatment) was 35% and 30% for BOD and TSS, respectively. In contrast, the estimated treatment efficiency for TDS is assumed to be 100% if RO is implemented but 0% otherwise. However, these parameters can be modified within the spatial DSS to depict potential changes in technology (Table 4).

In terms of treatment objectives, a lack of reliable data on future water demands, water needs and water availability forced us to refer to the volume of available water per capita. In particular, targets will be defined in terms of the volume of

Table 4
Costs and efficiencies in the baseline scenario

	Cost (RSA/m^3)	Cost (RSA/m^3)	BOD	TDS	TSS
Costs	Ultra-filtration only	Ultra-filtration and reverse osmosis	Efficiency %	Efficiency %	Efficiency %
Dedicated III treatment for agricultural reuse	3.5	5.7	35	100	
Dedicated III treatment for industrial reuse	1.75	2.85			
Dedicated III treatment for landscape reuse	3.5	5.7		100	30

Abbreviations: III: tertiary treatment; RSA: Saudi Arabian riyals; BOD: biochemical oxygen demand; TDS: total dissolved solids; TSS: turbidity or suspended solids.
Source for costs: Aleisa and Al-Zubari [3].
See the text for definitions of efficiency for each water quality indicator.

water treated per year or in terms of the volume of available water per capita.

Note that to achieve public acceptance, wastewater reuse projects should recover their overall costs, including the costs of the distribution systems. In addition, sectoral demand will depend on the perceived value of the water sources as well as on the prices charged. Although these prices should be based on costs, specific subsidies could be introduced to establish effective incentives for particular groups of users within an economic or regulatory framework.

In summary, we will consider economic, social, and environmental criteria in terms of the volume of available water per capita, to let our spatial DSS optimally locate tertiary WWTPs at a province-level for small and medium cities. Our criteria depend on the potential for agricultural, industrial, and landscape wastewater reuse.

Note that cultural factors limit the potable and non-potable urban uses of treated wastewater in Muslim countries in general, and in Saudi Arabia, in particular. Thus, we assumed that recreational or environmental uses are included in the landscape category.

Similarly, because quantitative data was unavailable for many pre-treatment water quality indicators for our case study in Saudi Arabia, due to a lack of laboratory analysis, non-working plants, or a lack of treatment plants, we were limited in which water quality indicators we could include. Thus, our analysis of wastewater pollution focused on BOD and TSS by assuming that health impacts are linked to TSS (think of communicable diseases of the intestinal tract such as cholera, typhoid, and dysentery, and water-borne diseases such as infectious hepatitis). We also assumed that environmental impacts are linked to BOD (think of short- and long-term effects on soils and crops), but we disregarded aesthetics for simplicity. In particular, the reference to changes in percentages of social and environmental achievements allowed us to avoid the need of detailed data on mortality and morbidity rates as well as on biological and chemical risks, under the assumption of a linear relationship between the observed TSS and BOD and the social and environmental impacts, respectively.

Therefore, the context described in this section supports the exemplary model developed in section 2.2 as the most realistic in terms of alternative uses, city sizes, and treatment levels as well as the most feasible in terms of available data for water quality indicators.

4. Developing the spatial DSS

In Section 2, we suggested a non-linear optimization approach that combines MCA with a spatial DSS, were three criteria that are considered (economic, social, and environmental criteria) in terms of the volume of available water per capita. In Section 3, we described the case study. Section 4.1 describes how we applied MCA to the case study, by specifying costs, standards, population, and industrial districts. Section 4.2 describes the interface.

4.1. Data and assumptions

Without loss of generality, we have assumed that agriculture is currently using only groundwater (with an average cost of Saudi Arabian riyals (RSA) 1.52/m^3), industry is currently using only desalinized water (with an average cost of RSA 3.49/m^3, although some companies have water wells), and landscape is currently using only groundwater (with an average cost of RSA 1.52/m^3) (Table 5). Note that, for simplicity, the suggested tertiary treatment processes, as well as the costs per m^3 of water, are assumed to be identical in small

Table 5
Average costs per unit volume of available water per capita for the main water sources. Average current values are provided for water quality indicators after secondary treatment. The number of current and planned industrial districts are provided for each province

	Cost (per capita riyals/m^3)		Water quality indicator (mg/L)			Total population in 2020		No. of industrial districts	
Province	Desalinized water	Groundwater	BOD	TDS	TSS	Medium cities	Small cities	Current	Planned
Al-Bahah	2.62	0.74	16	1,569	20	187,401	202,272	0	0
Al-Qassim	2.94	2.27	5	1,990	5	940,895	411,722	1	0
Al-Jouf	1.92	0.81	16	1,569	20	343,065	122,652	1	0
Aseer	5.44	1.57	16	1,569	20	1,313,583	713,272	1	0
Eastern area	3.70	1.67	9	2,246	12	2,899,092	1,007,520	3	0
Hail	0.74	0.89	25	*700*	34	656,358	59,641	1	0
Jizan	0.98	0.68	16	1,569	20	406,782	1,224,304	0	1
Medina	2.67	0.88	16	1,569	20	1,940,096	214,218	1	0
Makkah	2.62	0.98	14	1,877	17	903,760	454,787	2	1
Najran	0.98	1.92	16	1,569	20	446,755	153,972	1	0
North border	1.67	5.37	16	1,569	20	196,522	131,160	0	1
Riyadh	2.94	0.98	25	*700*	34	306,667	988,287	2	1
Tabuk	16.10	0.98	17	1,900	17	737,832	244,495	1	0

Abbreviations: BOD, biochemical oxygen demand; TDS, total dissolved solids; TSS, turbidity or suspended solids.
Bold = above efficiency and quality standards specified in the text. Italics = below quality standards specified in the text.

and medium cities. Comparing these efficiency standards with Figs in Table 5 (i.e., efficiency is here defined as using a water source which is cheaper than an available alternative water source) suggests that industrial reuse is almost always efficient (i.e., costs are larger than RSA 1.75/m^3) (exceptions are Al-Jouf, Hail, Jizan, Najran, and the northern border area), whereas agricultural and landscape reuse is almost always inefficient (i.e., costs are larger than RSA 3.5/m^3) (except in the northern border area). We assumed that the groundwater stock will be completely depleted by around 2030. Indeed, since the estimated stock in 1999 was 500 × 10^9 m^3 and agricultural uses require an additional 20 MCM per year, it is precautionary to say that the groundwater stock will be completely depleted by 2030 or 2035 [16]. We chose a positive shadow price of 1.52 RSA/m^3 (i.e., its national average) of available water for the groundwater stock to depict the concern for its future depletion. Comparing these efficiency standards with figures in Table 4 suggests that $tc_{agr} = 5.7$ if $TDS_{ij} > TDS_{sta}$, 3.5 otherwise and that $tc_{lan} = 5.7$ if $TDS_{ij} > TDS_{sta}$, 3.5 otherwise.

Next, BOD and TSS standards can be fixed at 20 mg/L [17], although Saudi Arabia regulations suggest 10 mg/L for unrestricted uses, this contrasts with the concept of dedicated treatment, in which a specific treatment process is implemented for a given reuse. Similarly, TDS can be fixed at 1,000 mg/L [18], although no Saudi Arabia regulations have been specified for TDS, by implicitly excluding salt-sensitive crops (e.g., sesame, carrot, okra, onion, mango, orange, and tangerine). Note that the same quality of secondary treated water is assumed to be used in small and medium cities (because the same treatment technology is applied) and that the same standards apply to small and medium cities (because Saudi regulations are typically applied at the national level). Comparing these quality standards with figures in Table 5 suggests that TDS is almost always above the value required (except for Hail and Riyadh), whereas BOD and TSS are almost always below the required values (except for Hail and Riyadh). Note that users of the spatial DSS can change the water quality standards to explore the effects of technological change (i.e., changes in treatment efficiency).

Afterward, the optimization of economic, social, and environmental aspects for a representative individual will be weighted according to the population distribution in small and medium cities of each of the 13 provinces (Table 5).

Lastly, in terms of industrial reuse in different provinces, we introduced a factor to correct for this variation by summing the number of existing or planned industrial districts (Table 5). Note that we assumed that there were no industrial districts in cities smaller than 85,000 inhabitants; Saudi statistics on industrial production show that less than 5% of the country's industrial output (riyals) is produced by these small cities, and current industrial development plans show no new industrial development for these cities.

4.2. Interface

The spatial DSS architecture consists of four internal elements: a graphical user interface (GUI), a wrapper for calculations, a data access layer, and a GIS (i.e., Bing Maps). The DSS also has three external components: an operating system (e.g., Windows, Linux), Microsoft SQL Server, and the Wolfram Mathematica kernel (www.wolfram.com).

On the DSS external side, the GUI lets users insert input data (e.g., weights, values) and check the output (e.g., scores, graphics). On the DSS internal side, it consists of two components. First, the GUI lets the user load input data from the database and store output data in the database by recording the date, hour, and minute of calculations. It sends calculation requests in any language (e.g., Wolfram Mathematica, MATLAB) to the wrapper, and it receives the calculation results from the wrapper. Note that the user only has access to the GUI. Moreover, all elements in the DSS are coded using the Microsoft .NET framework. In general, this framework permits the development of platform-independent applications (i.e., it allows researchers to code programs for any operating system that supports the .NET framework), so our DSS should run on most operating systems. This provides a high degree of platform compatibility. Finally, the wrapper and the data access layer are insulated so that they can be updated independently.

Second, the GUI sends output results to the Microsoft SQL Server (www.microsoft.com) (where it is stored as part of the user's scenario) and it loads scenarios from Microsoft SQL Server by relying on a data access layer. Any software that complies with the open database connectivity (ODBC) standard (e.g., Microsoft Excel, OpenOffice) can read and process the output results (e.g., to perform statistical analysis) as well as to insert and process input data (e.g., to carry out simulations within the DSS with a set of scenarios defined in advance by the user). In other words, the maximum degree of exportability and importability of results is obtained.

Note that the wrapper translates the calculation requests received from the GUI for the Wolfram Mathematica kernel, and it receives numbers, graphics, and error messages from the kernel. Any calculation software can be used since the wrapper abstracts the language and logic that characterize the Wolfram Mathematica kernel. In other words, the highest degree of software applicability is achieved. Both Microsoft SQL server and the Wolfram Mathematica kernel are coded in the native language of these software environments: the wrapper will be updated only if a new version of the Wolfram Mathematica kernel or an alternative software package is used for calculations; similarly, the use of a different database will only require updating of the database.

The following components are currently required to install the DSS: Wolfram Mathematica or the Wolfram CDF Player, Microsoft SQL Server, and .NET Framework version 4.0. Wolfram Mathematica can be bought from Wolfram, but the Wolfram CDF Player can be freely downloaded from www.wolfram.com. Microsoft SQL Server can be bought from Microsoft, but a free version (SQL Server Express) can be downloaded from www.microsoft.com. The .NET framework for a given operating system can be freely downloaded from www.microsoft.com. Thus, a high degree of software availability is obtained.

The spatial DSS is an executable file. However, since it is supported by four external elements, it is not possible to implement installation software that will work on any computer: although the .NET framework is not an obstacle, installation of Microsoft SQL server and the Wolfram Mathematica kernel require specific procedures for each operating system. Nonetheless, the installation instructions are simple, so a high degree of software applicability is achieved.

5. Results

The purpose of this section is two-fold. First, we illustrate how a decision is reached by applying plausible parameters for the case study under consideration. Second, we perform sensitivity analyses for the decision with respect to the values of some preferences (i.e., the relative weights attached to economic, social and environmental criteria), guidelines (i.e., water quality standards), and expectations (i.e., future treatment efficiencies). An exe file of the suggested spatial DSS is available online at www.eurosoftlab.com/lab/DWTsoftware.zip.

5.1. Spatial DSS data, choices, and outcomes

Figs. 1–4 show insertion of the input data (i.e., average costs for the main water resources, the number, and location of provinces, the size of cities, average values of water quality indicators after secondary treatment, predicted population in medium and small cities, current and planned locations of industrial districts). Fig. 5 shows the setting of guidelines in the spatial DSS, including preferences and expectations (i.e., treatment costs and efficiencies, water quality standards, preferences for features and sectors as relative weights, focus on salinity issue and groundwater future depletion, budget constraint as the maximum number of WWTPs). Figs. 6 and 7 show how the spatial DSS user can analyze the results obtained by applying an opportunity cost approach within a MCA framework (i.e., optimal sectoral uses and impacts for small and medium cities).

Note that the flexibility of the software in terms of the number and location of provinces, the size of cities, the presence or absence of salinity issues, relative weights attached to sectors (together with water quality indicators, relative weights attached to features, treatment costs and efficiencies, number of plants, water quality standards), enables the spatial DSS user to generate many alternatives in taking decisions about locations of new WWTPs for dedicated usage [19].

Therefore, within the baseline scenario, in which we estimated the population distribution is 2020, the treatment costs for industrial reuse are symmetric, and the groundwater shadow price is fixed at the current average water extraction cost, the main recommendations can be summarized as follows:

- The maximum number of plants is reached, although a tertiary treatment for all purposes (agriculture, industry, landscape) is supported in only two provinces (i.e., Aseer and Riyadh) (Fig. 6).

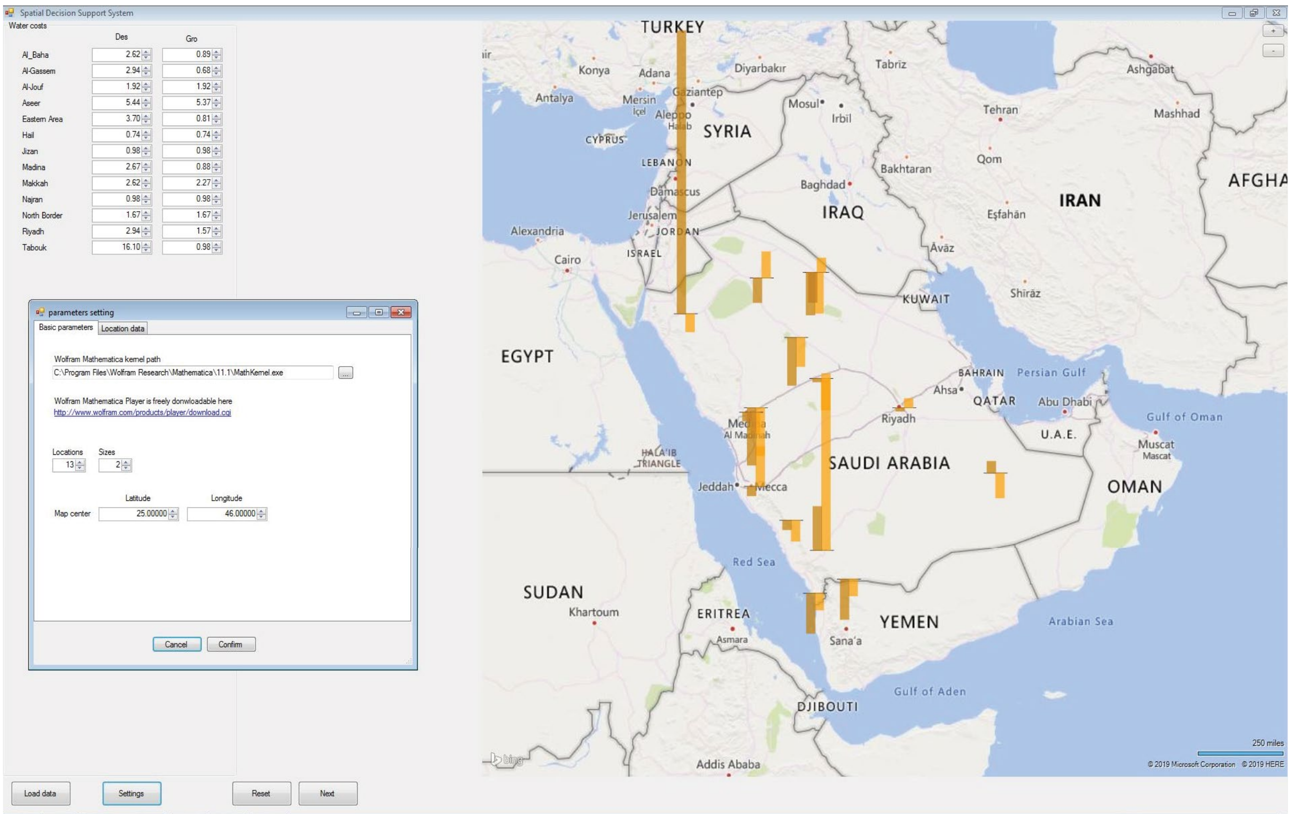

Fig. 1. Input of average costs (Saudi riyals) per volume of available water (m^3) per capita for the main water sources, number and location of provinces, and size of cities. The two bars displayed for each of the 13 provinces represent the differences (%) compared with the national average costs for desalinization (dark orange) and groundwater (light orange) costs.

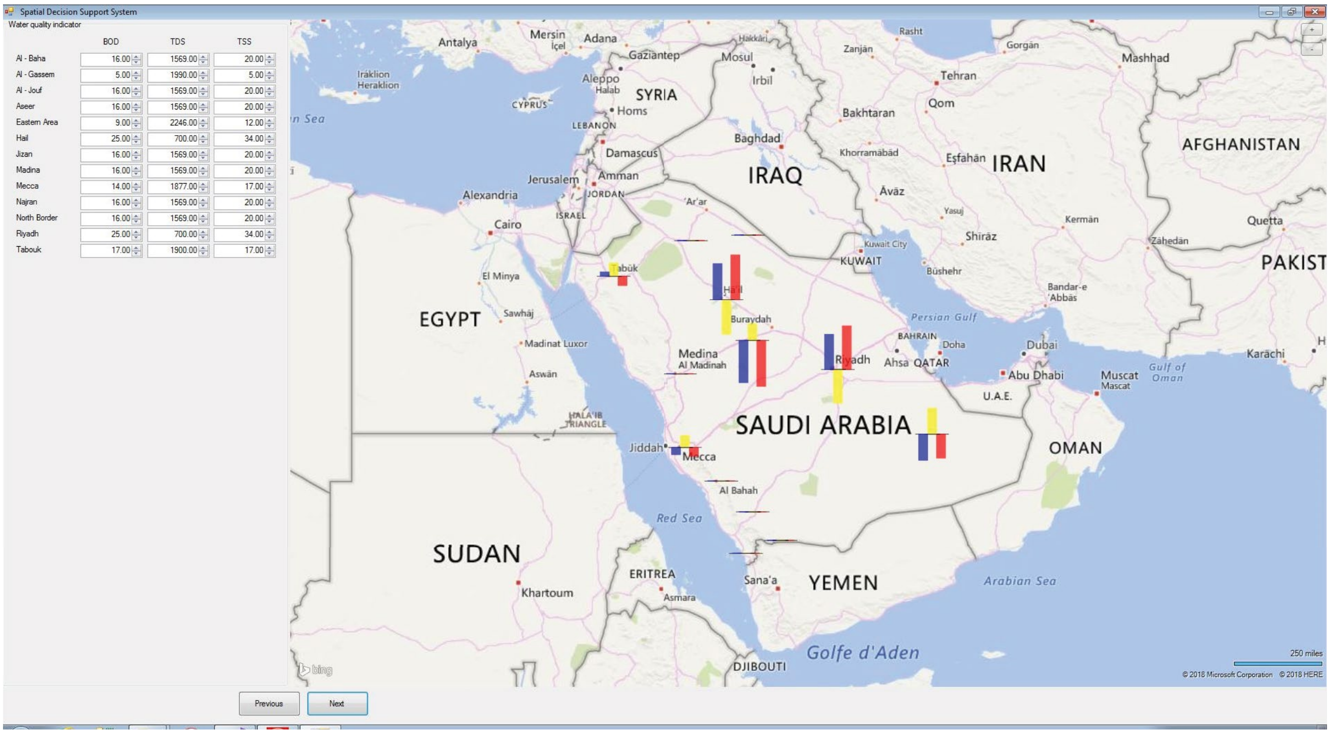

Fig. 2. Input of average current values (mg/L) of the water quality indicators after secondary treatment. The three bars for each of the 13 provinces represent the % differences with respect to the national average for the three water quality indicators: biochemical oxygen demand (BOD, blue), total dissolved solids (TDS, yellow), and turbidity or suspended solids (TSS, red).

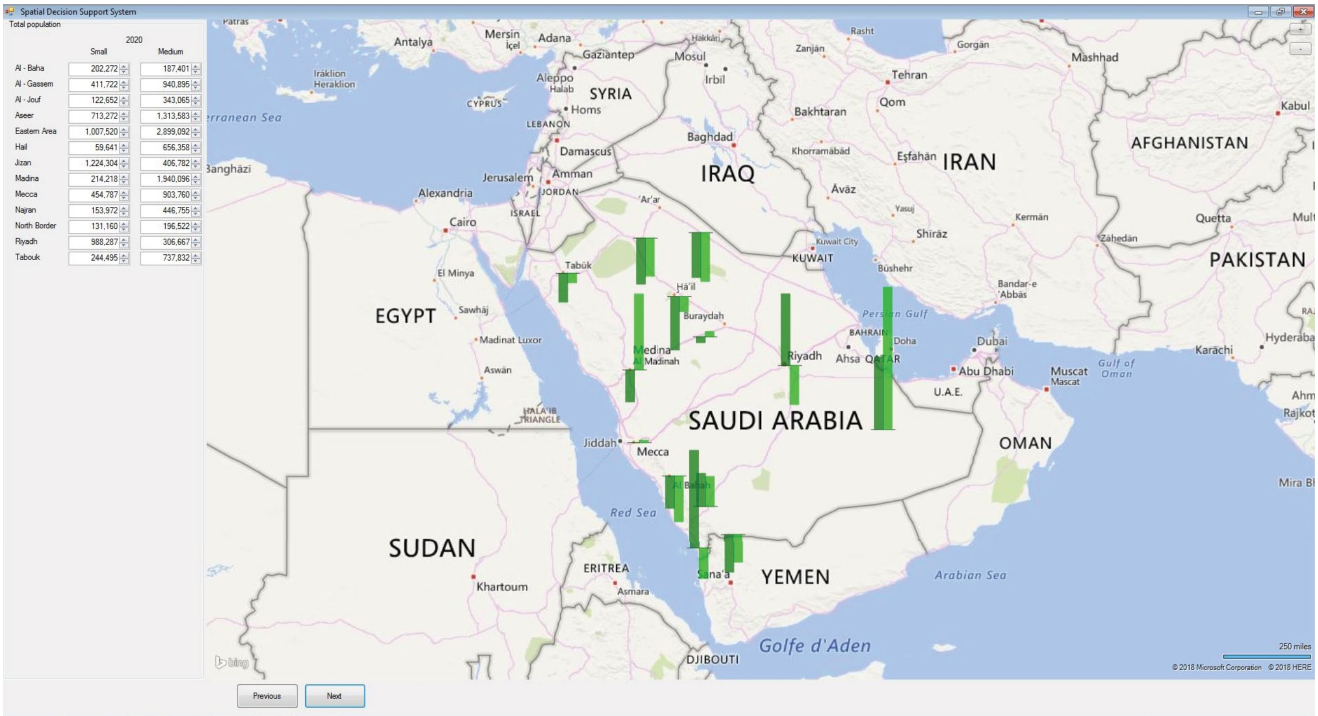

Fig. 3. Input of total predicted populations in the medium and small cities in 2020. The two bars for each of the 13 provinces represent the differences (%) with respect to the national average for the small (dark green) and medium (light green) cities.

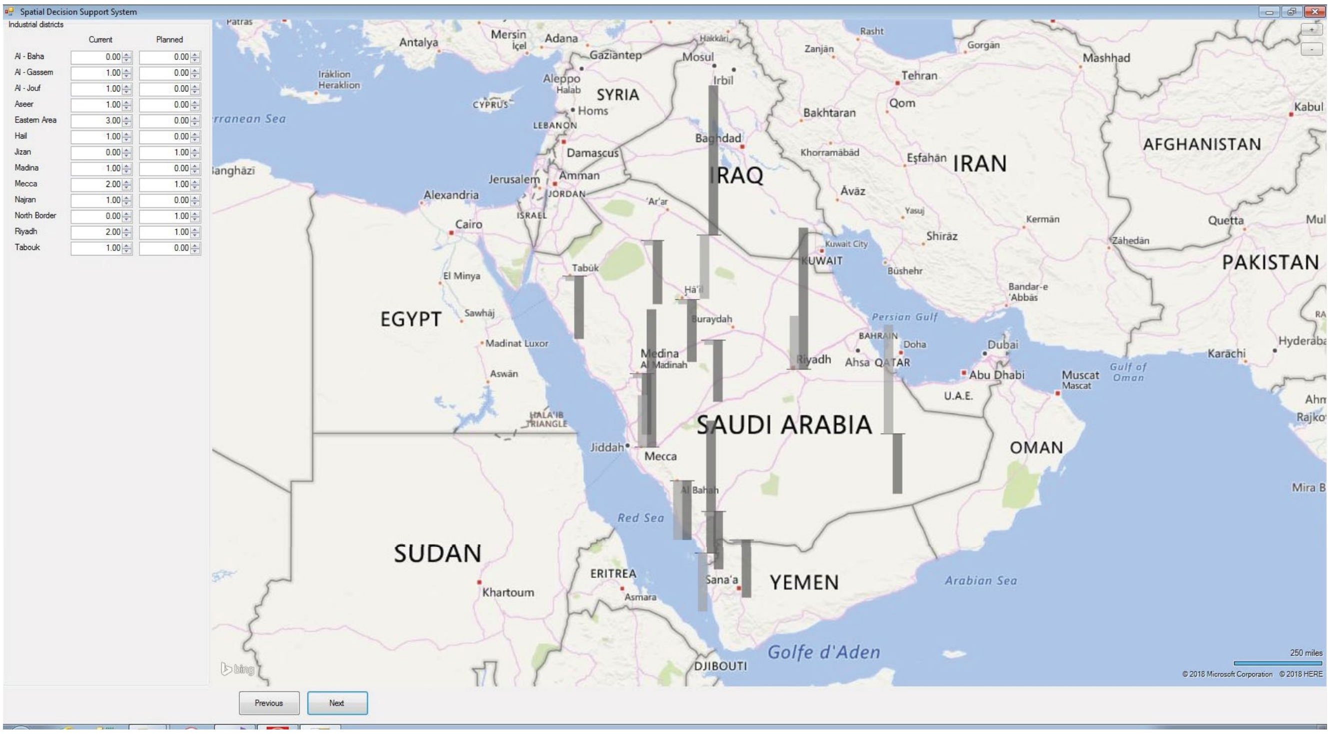

Fig. 4. Input of current and planned locations of industrial districts. The two bars for each of the 13 provinces represent the differences (%) with respect to the national average for the current (light grey) and planned (dark grey) industrial districts.

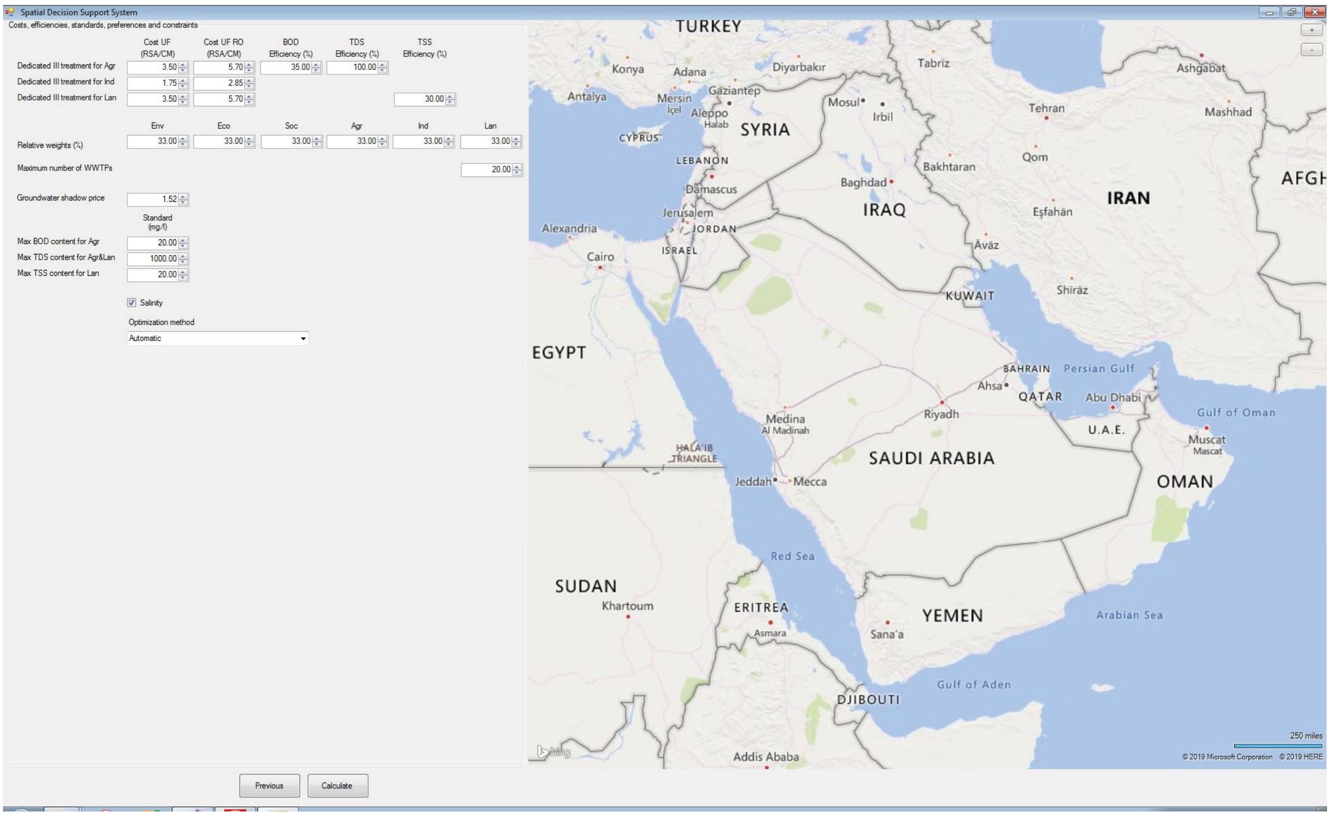

Fig. 5. Input of treatment costs and efficiencies, water quality standards, preferences (relative weights attached to sectors and features), focus (salinity issue and future groundwater depletion), calculation methods, and constraints.

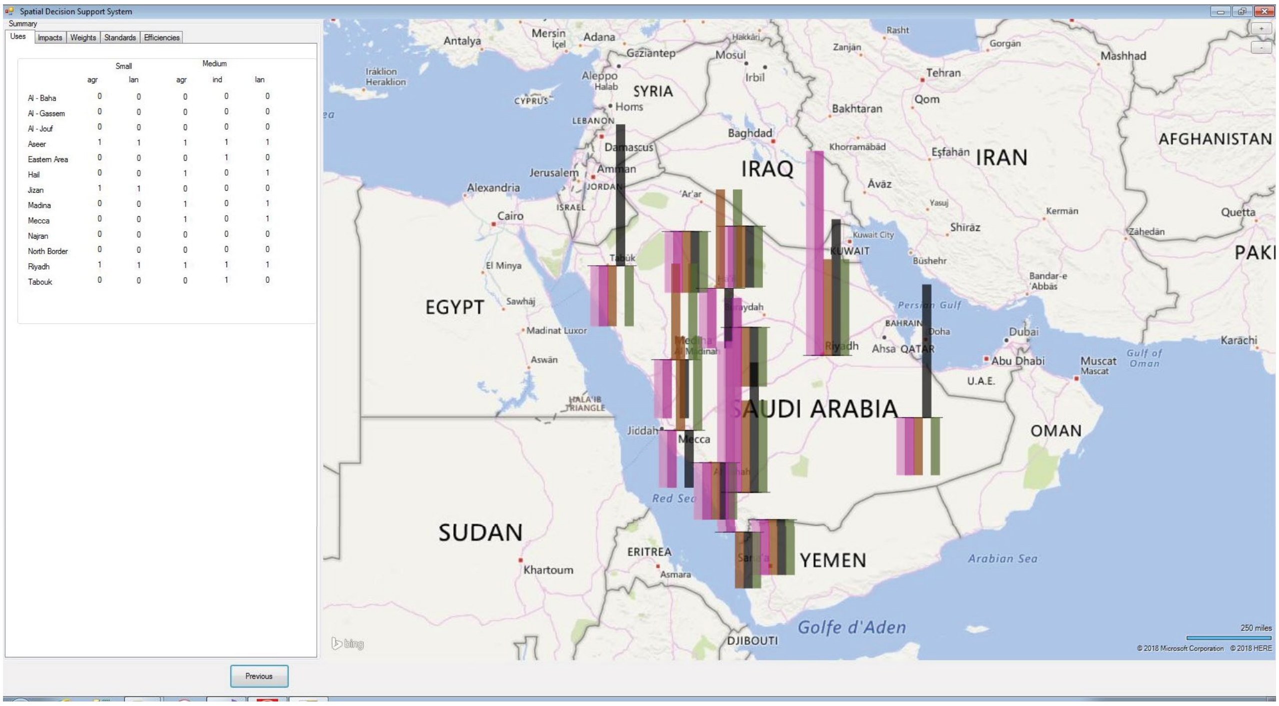

Fig. 6. Optimal sectoral uses of water (agr: agricultural irrigation; ind: industrial recycling and reuse; lan: landscape irrigation) in small and medium cities (1 for use, 0 for no use). The five bars for each of the 13 provinces represent the differences (%) with respect to the national average for agriculture uses in small cities (light violet), landscape uses in small cities (violet), agriculture uses in medium cities (magenta), industry uses in medium cities (black), and landscape uses in medium cities (grey).

- Reuse in the agricultural sector is almost always suggested (i.e., Aseer in small and medium cities, Hall in medium, Jizan in small, Medina in medium, Mecca in medium, Riyadh in small and medium) (Fig. 6).
- Reuse in the industrial sector is not always suggested in provinces with current or planned industrial districts (i.e., Aseer, Eastern Area, Riyadh, Tabuk) (Fig. 6).
- Landscape reuse is always coupled with agricultural reuse (Fig. 6).
- In terms of welfare, the overall score was 71, vs. a value of 83 with no WWTPs. A score below 100 means better status, on average, with respect to the economic, social and environmental opportunity costs or standards, and this suggests that implementation of 20 WWTPs would improve welfare significantly (by around 15%, on average), although the most significant improvements were observed for economic features (an average score of 61) and environmental features (an average score of 71), with social features relatively neglected (an average score of 88) (Fig. 7).
- In terms of equity, values of the Gini index suggest that satisfactory equity (i.e., a Gini index close to 0) is achieved for all three sectors, although small cities in general and social features in particular should be monitored carefully to ensure that equity does not decrease in the future (Fig. 7).

5.2. Sensitivity analyses for the spatial DSS

The previous section suggested the importance of exploring the sensitivity of the chosen WWTP locations to variations in preferences, guidelines, and expectations. Understanding this sensitivity will facilitate the process of setting preferences and linking of the uncertainties in the results to the uncertainties in the different function parameters. Here, we chose a variation of ±10% in the overall welfare score if all possible WWTPs are implemented to identify the range of welfare scores. Fig. 8 through 10 show the results.

Stakeholders are often unsure about how to quantify their preferences. To demonstrate the sensitivity of the model to this uncertainty, we analyzed the stability of the results to changes in the weights attached to the criteria by exploring potential trade-offs between conflicting criteria. In particular, we visualized a set of relative weights that support the chosen WWTP locations by providing a two-dimensional contour plot, in which w_{env} and w_{soc} represent the relative weights attached to environmental and social features, respectively, where the economic weight $w_{eco} = 1 - w_{env} - w_{soc}$ (Fig. 8). In this plot, the level curve at the welfare score in the chosen scenario is specified, together with a ±10% range of this value: a large non-white area means that the chosen WWTP location is supported by a large range of relative weights specified on the w_{soc} and w_{env} axes, whereas a large white area has the opposite meaning. The level curve is linear and decreasing: an increase in either w_{env} or w_{soc} will increase welfare, and an increase of w_{soc} by 0.01 must be compensated by a decrease in w_{env} by 0.247 (i.e., w_{env} decreases by 24.7% per 1.0% increase of w_{soc}): in other words, environmental features are more important (i.e., the welfare score is more sensitive to changes in environmental features).

Note that a survey with stakeholders and/or experts could be performed by applying alternative methodologies

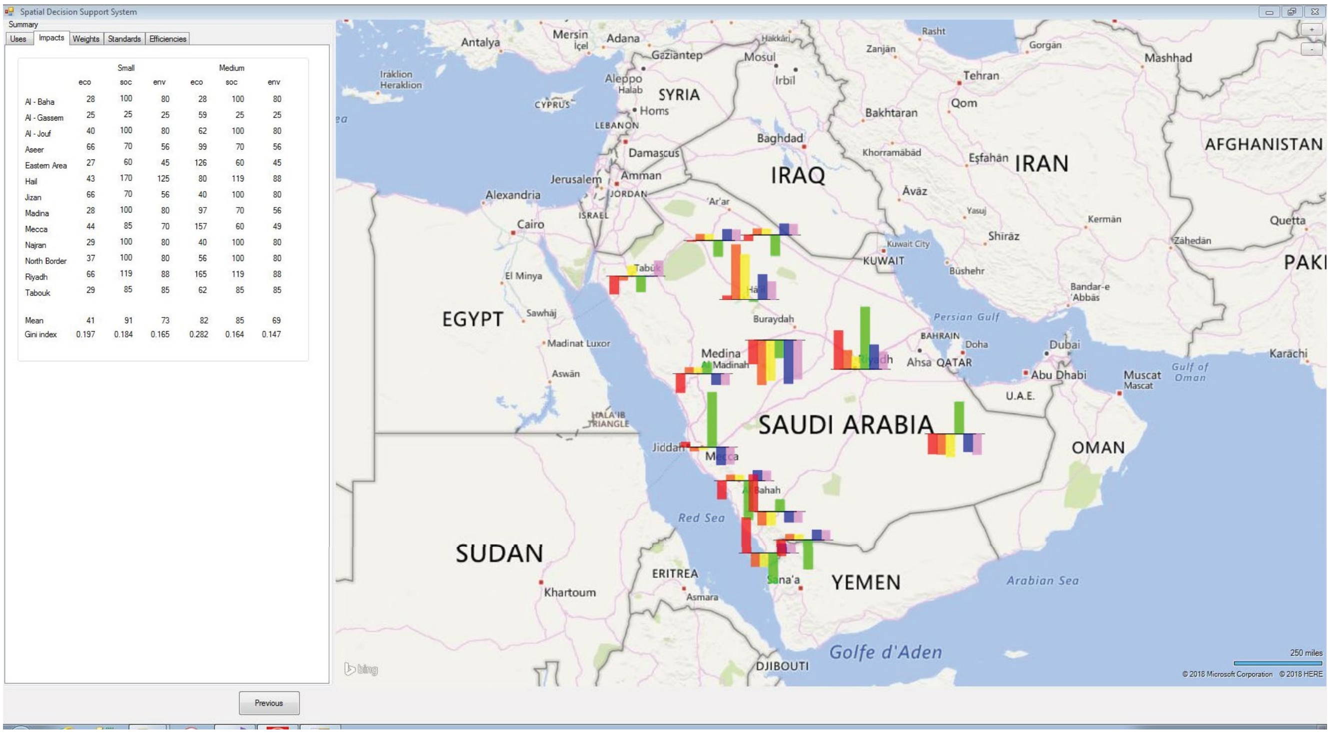

Fig. 7. Optimal sectoral impacts (eco: economic; soc: social; env: environmental) for small and medium cities. The six bars for each of the 13 provinces represent the differences (%) with respect to the national average for economic impacts in small cities (red), social impacts in small cities (orange), environmental impacts in small cities (yellow), economic impacts in medium cities (green), social impacts in medium cities (blue), and environmental impacts in medium cities (violet).

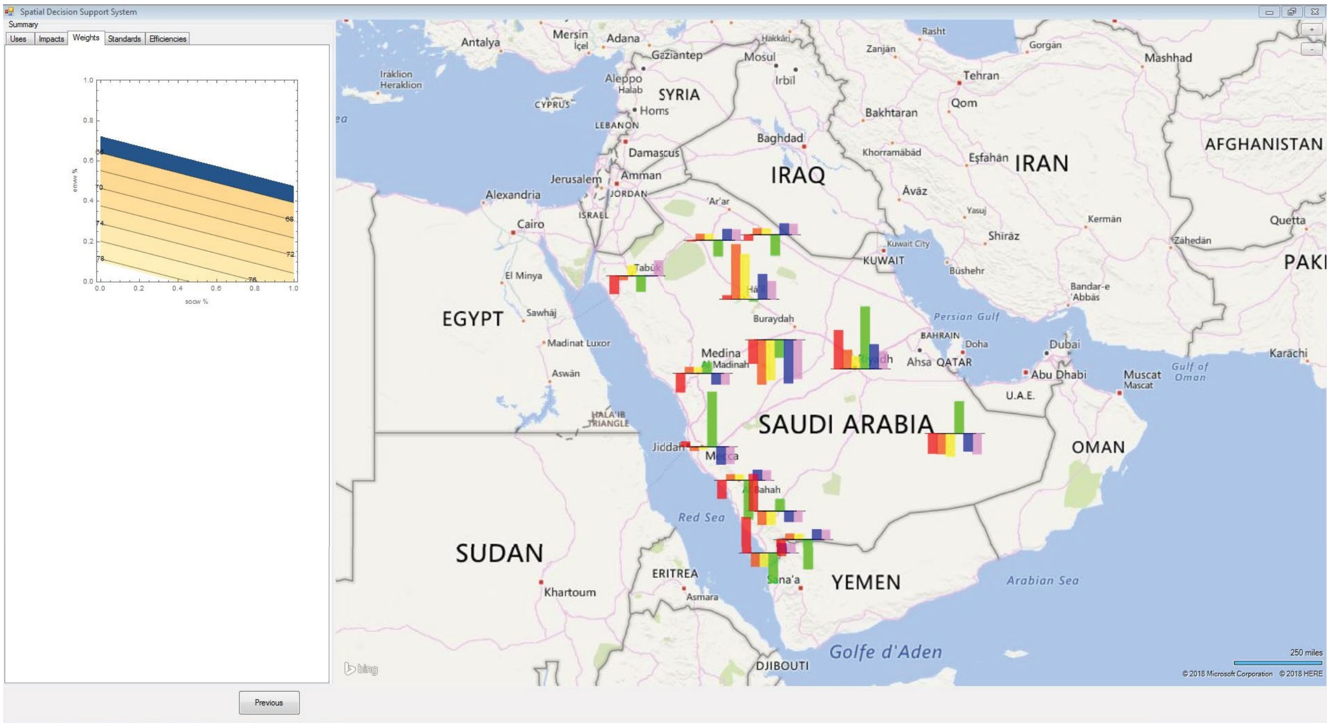

Fig. 8. Sensitivity analysis based on changes in the relative weights of social, economic, and environmental features. The non-white areas of the graph represent the ranges of feasible solutions. The smaller the white area, the greater the robustness of the results. Blue and yellow areas refer to +10% and –10% of the welfare score, respectively. Potential substitutions between relative weights are linear because they sum up to 1.

[20,21] to check whether the elicited relative weights belong to the range of feasible solutions (i.e., the estimated couple (w_{env}, w_{soc}) is plotted in non-white areas in Fig. 8).

Moreover, determining the values of the water quality standards is a difficult task: although international standards could be compared to show the range of possibilities (i.e., some nations will have more strict standards, and other nations less strict standards), standards often represent a policy compromise between health and environmental status, on one side, and economic interests, on the other side. To demonstrate the effects of these values, we examined the stability of the results with respect to changes in the parameters that represent water quality. In particular, we visualized the set of standards that support the chosen WWTP location by providing a two-dimensional contour plot, in which we used BOD and TSS to represent the water quality standards that must be satisfied for agricultural and landscape uses (Fig. 9). In this plot, the level curve at the welfare score in the chosen scenario is specified, together with a ±10% range of this value: a small non-white area means that the chosen WWTP location is sensitive to small changes in standards along the TSS and BOD axes. The level curve is non-linear and decreasing: an increase in either BOD or TSS will increase welfare, and an increase of TSS by 1 mg/L at the chosen couple of standards (i.e., TSS at 20 mg/L and BOD at 20 mg/L) must be compensated for by a decrease in BOD of 0.798 mg/L; that is, BOD is more important (i.e., the welfare score is more sensitive to changes in BOD standards).

Finally, predicting future values of treatment efficiency is difficult. To demonstrate the effects of these changes, we examined the sensitivity of the results with respect to changes in the treatment efficiencies. In particular, we visualized the set of treatment efficiencies that support the chosen WWTP location by providing a two-dimensional contour plot, in which the percent reduction in BOD and TSS represents the water quality improvements in dedicated treatments for agriculture and landscape uses (Fig. 10). In this plot, the level curve at the score in the chosen scenario is specified, together with a ±10% range of this value: a large non-white area means that the chosen WWTP location is supported by a large range of treatment efficiencies along the BOD and TSS treatment efficiency axes, whereas a large white area has the opposite meaning. The level curve is linear and decreasing: an increase in either BOD or TSS efficiencies increases welfare, whereas an increase of the TSS % reduction by 1% must be compensated for by a decrease of the BOD % reduction by 1.284%; that is, BOD is more important (i.e., the welfare score is more sensitive to changes in treatment efficiency in terms of BOD water quality improvements).

6. Discussion

The main scientific contribution of the present study is our development of an original approach to optimally locating WWTPs based on a spatially explicit DSS in the context of MCA with a non-linear optimization algorithm. In particular, we improved on the system of Vasiloglou et al. [22], which in turn improved on the system of Molinos-Senante et al. [23] with a DSS, by adding optimization and GIS support. We updated Hidalgo et al. [24], Zarghami et al. [25],

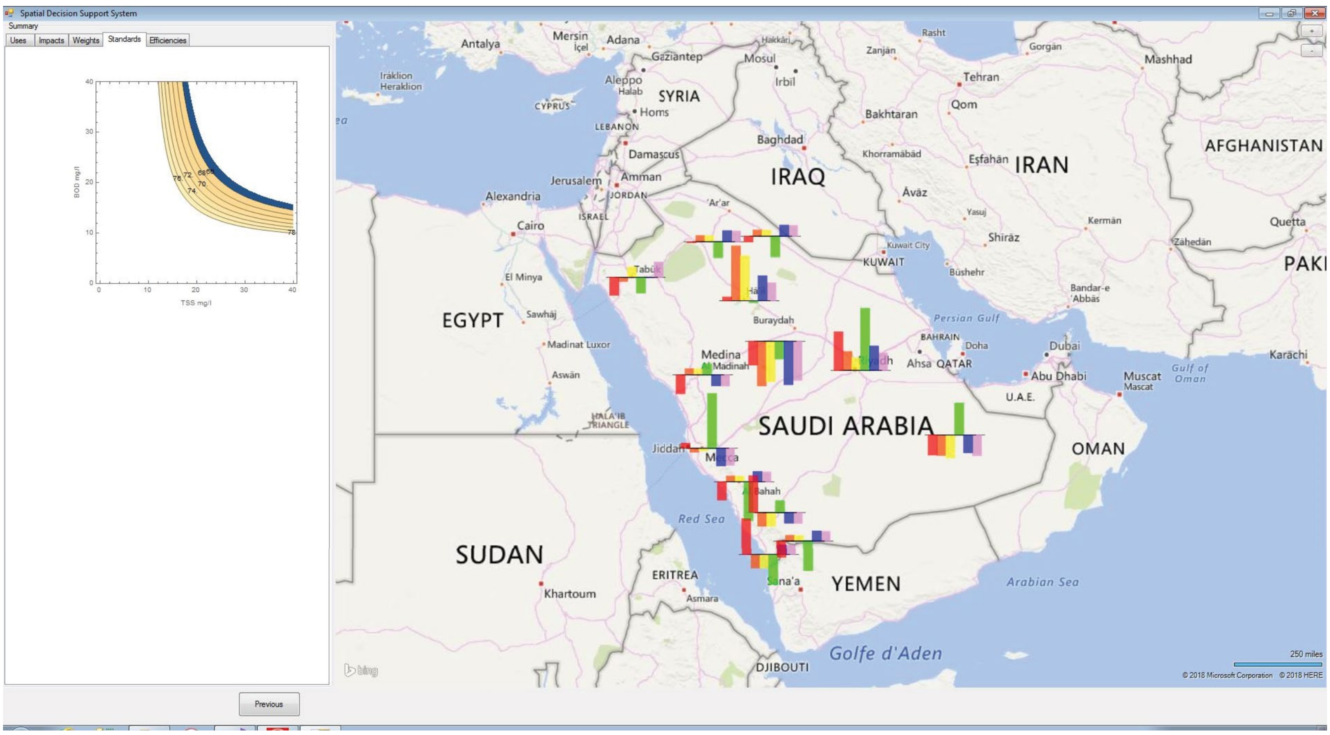

Fig. 9. Sensitivity analysis based on changes in water quality standards. The smaller the white area, the greater the robustness of the results. Blue and yellow areas refer to +10% and –10% of the welfare score, respectively. Since allocating money to improve one standard subtracts that money from the amount available to implement the standard for another pollutant, potential non-linear substitutions between quality standards are observed.

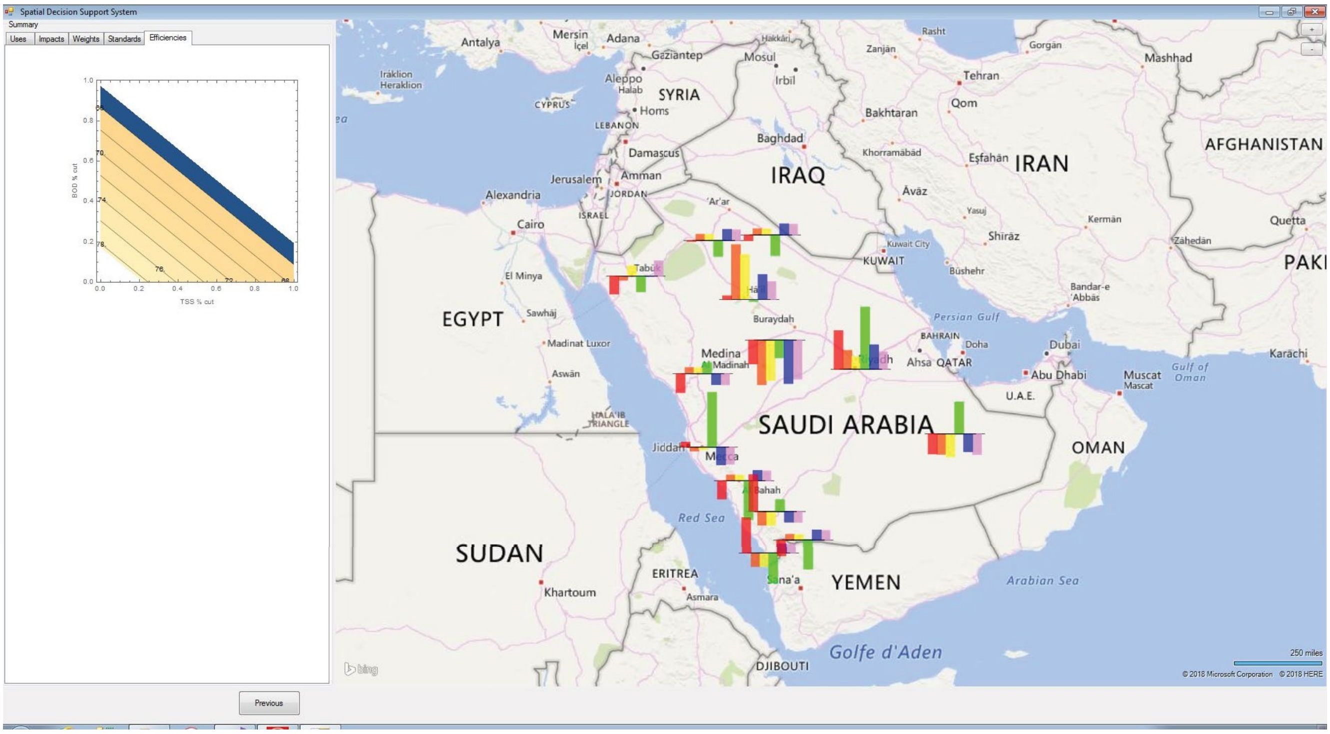

Fig. 10. Sensitivity analysis based on changes in tertiary treatment efficiency. The smaller the white area, the greater the robustness of the results. Blue and yellow areas refer to +10% and –10% of the welfare score, respectively. Since allocating money to improve one standard subtracts that money from the amount available to implement the standard for another pollutant, potential linear substitutions between treatment efficiencies are observed.

and Zeferino et al. [26] by implementing a spatial DSS. We updated Makropoulos et al. [27] and Zeng et al. [28] by implementing and optimizing DSS. We improved on the systems of Ahmadi and Merkley [29] and Dubber et al. [30] by applying an optimizing MCA. We improved on the systems of Neji and Turki [31] and Pedrero et al. [32] by developing a DSS and improved on the system of Anagnostopoulos and Vavatsikos [33] by adopting optimization. Moreover, we implemented some unique features from previous models: sensitivity analyses for many parameters, unlike the single parameter considered by Zeferino et al. [34] but like the approaches of Udias et al. [35] and Abdulbaki et al. [36], to deal with multi-dimensional uncertainty; an opportunity cost approach, without the assumptions made by Molinos-Senante et al. [23], to estimate overall social welfare; and alternative weighting and transfer functions, as in the approach of Massei et al. [37]. Finally, we introduced some innovative features: equity indicators based on the spatial distribution of the WWTP investments, and an overall score that summarized the average national achievement in a multi-attribute decision-making context.

Our approach has five main weaknesses. First, the analysis was based on a representative volume of available water per capita rather than on potential water needs or demands. However, alternative approaches were not feasible due to a lack of reliable data. The policy recommendations presented in this paper could change if the water needs or water demands could be reliably quantified. For example, an analysis based on water shortages could increase the need to rely on wastewater reuse in agriculture. Similarly, an analysis based on an unwillingness to pay could prevent wastewater reuse in the industry. Second, each farm is expected to pay the bill for its water use, and to avoid the creation of new wells or the depletion of old wells to preserve the groundwater stock. This may be unfeasible in practice. Third, each firm is assumed to pay its sectoral treatment costs, and to control its specific treatment processes, due to its unique characteristics. In practice, water treatment may need to be applied simultaneously to the effluents produced by all industries in a given area, suggesting that it may be necessary to use a single cost for all industries. Forth, each municipality is expected to pay the bill for its water use, and to avoid the creation of new wells or the depletion of old wells to preserve the groundwater stock. This may be unfeasible in practice. Fifth, the policy recommendations presented here could change if different or additional information could be used to support our analysis. For example, a detailed expansion plan for an industrial district could specify the specific treatment costs, rather than applying a general average cost. Similarly, a detailed agricultural plan could specify the specific treatment process for each cropping pattern, rather than applying an RO process for salt-tolerant crops.

Our approach has eight main strengths. First, we solved the problem of incompatibility between the datasets used in a GIS representation and linear programming, as highlighted by Lei et al. [38], by developing an interface based on the .NET framework. We also promoted participation by performing sensitivity analyses for changes in stakeholder preferences, water quality standards, and treatment efficiencies. Second, we tackled the issue of aggregation of partial achievements and efficiency of overall recommendations in designing a multi-criteria spatial DSS, as was stressed by Ferretti and Montibeller [39], by allowing users to dynamically change their preferences. We also avoided the black box effect, in which algorithms are complicated and cannot be understood by the user or preferences are fixed and cannot be changed by the user, by using a GUI, with user-modifiable settings, to ensure the transparency of the model. Third, modifying the relative weights attached to agriculture, industry, and the environment can support the development of an overall water tariff policy. On the one hand, this could lead to an optimal distribution of the total treatment costs to achieve the greatest overall social welfare; on the other hand, this could make wastewater reuse a competitive alternative to the current water sources (i.e., to relieve pressure on the groundwater stock). For example, the industry could be charged more and agriculture could be charged less by subsidizing agricultural reuse. Forth, by considering three alternative but interconnected uses (agriculture, industry, and environment), our approach can support the development of an integrated water management system. On the one hand, this could solve the problems of groundwater depletion and salinity at a lower cost; on the other hand, this could benefit all economic and social sectors. For example, the assumed TDS standard of 1,000 mg/L could dissuade water users from agricultural and landscape reuse in favor of industrial uses. Fifth, as in the analysis by Molinos-Senante et al. [23], we provided an overall score that provides a proxy for an overall welfare index based on a cost–benefit analysis. Sixth, as in the analysis by Ahmadi and Merkley [29], we accounted for population growth. In particular, the estimated population dynamics in small and medium cities from 2020 to 2035 differ among the provinces, although an overall increase is expected (from 17,207,110 people in 2020 to 20,163,887 in 2035). Numerical simulations with the estimated population distribution in 2035 (data for medium and small cities, respectively: Al-Bahah, 190,945, 206,097; Al-Qassim, 1,115,412, 488,088; Al-Jouf, 386,190, 138,070; Aseer, 1,444,884, 784,568; Eastern Area, 2,981,769, 1,036,253; Hail, 833,642, 75,751; Jizan, 515,938, 1,552,837; Medina, 2,546,298, 281,153; Makkah, 977,136, 491,711; Najran, 587,378, 202,437; North border, 221,898, 148,096; Riyadh, 391,364, 1,261,237; Tabuk, 979,997, 324,740) suggest the same WWTP location, with a slight worsening of the overall score from 71.232 to 71.469. Seventh, as in the analysis by Ahmadi and Merkley [29], we were able to distinguish between short-run and long-run decision-making. However, no value could be directly attached to the groundwater stock, so we inferred this value by considering only the short-run extraction costs; alternatively, groundwater recharge could be taken into account in the long run by estimating an additional cost (e.g., 20%) imposed as a safeguard against possible failure of the groundwater resource [40]. This could be combined with water production costs from seawater desalination or treated wastewater. Numerical experiments with groundwater evaluated at 5.370 riyals/m^3 (the highest current cost) as opposed to 1.518 riyals/m^3 (the average current cost) suggest increased agricultural and landscape reuse in the medium cities of the Eastern Area, coupled with a reduction in agricultural and industrial reuse in the medium cities of Riyadh, with a significant worsening of welfare, from 71 to 78. Needless to say, if we accounted for the secondary treatment costs, the value attached to groundwater would increase. Eighth, as in the analysis by Kalbar et al. [41], alternative decision-making scenarios can be considered. In particular, treatment costs for industrial reuse can range from 0 riyals/m^3 if water produced by secondary treatment is used without further treatment, with costs of 3.5 and 5.7 riyals/m^3 if additional complicated processes must be implemented, in the presence and absence of salinity problems, respectively. However, water quality requirements differ enormously among crops and industries; for example, the average treatment cost for industrial reuse depends on a region's industrial structure. Numerical simulations with industrial treatment costs of 5.7 and 3.5 riyals/m^3 (the highest current costs, with industries demanding high-quality water) as opposed to 2.85 and 1.75 riyals/m^3 (the average current costs, for any symmetric frequency of costs below and above these average costs) suggest an increase in agricultural and landscape uses in the small cities of Makkah province, and an increase in agricultural uses in the medium cities of Tabuk province, coupled with a reduction in industrial uses in Asser province, the Eastern Area, and Riyadh province, with a significant improvement of welfare, from 71 to 66.

A final remark on the numerical stability of the obtained solutions is noteworthy. In the case study under consideration, data on treatment costs, number of plants, water quality indicators, population, current and planned location of industrial districts are taken from other sources and assumed to be unaffected by measurement errors. Thus, in addition to risk measures and scenario analyses, two main alternative methods have been suggested in the literature [42] to check for the numerical instability of solutions, possibly arising from uncertainty on the measurement of the remaining parameters (i.e., relative weights attached to features, water quality standards, and the tertiary treatment efficiency): fuzzy sets and data assimilation techniques [43,44]. However, in order to estimate the measurement errors, a specific distribution of measurement noise must be assumed (e.g., white and Gaussian) to implement fuzzy sets, and a system dynamics (e.g., linear) and an interpolation process (e.g., averages) must be assumed to produce fictitious observations by using data assimilation techniques. This is particularly problematic for relative weights attached to features, since errors could arise from the specific methodologies applied to elicit these weights, but also from individual or group psychological biases, which might again depend on the specific methodologies applied: a uniform distribution of relative weights (and of other parameters) seemed to be the best assumption, since we did not specify any value of relative weights (and of other parameters). Note that there is no process noise in our context, since parameters suggested by stakeholders, experts and authorities are applied, within an MCA based on the opportunity cost approach, to produce an optimal solution. In other words, the choice of the maximization method applied by Mathematica (i.e., Automatic, Differential Evolution, Nelder Mead, Random Search, and Simulated Annealing), together with the performed sensitivity analyses (i.e., risk is measured by the proportion of white vs. non-white areas, and scenarios are presented as solutions derived for the whole parameter domains with uniform distributions), highlighted the instability of numerical solutions, by avoiding assumptions on error distributions, the system dynamics and the interpolation processes.

7. Conclusions

The spatial DSS developed in the present study was designed primarily to demonstrate a new approach rather than as a comprehensive tool to support sustainable regional planning. For our system to become a practical tool, more parameters should be examined and a more detailed and complex set of criteria should be used. Despite its limitations, two main characteristics of the spatial DSS approach should be emphasized.

First, by providing an interactive visual tool (i.e., a DSS) that facilitates the identification of spatial relationships (i.e., via a GIS) and the communication of optimal results (i.e., optimization), while also permitting sensitivity analyses, the suggested spatial DSS does not so much attempt to find a solution as to facilitate the learning process for decision-makers. Indeed, the suggested approach teaches stakeholders and experts about their perspectives: stakeholders are involved in defining the preferences and standards, whereas experts are expected to provide insights about standards and expectations. Both are involved in specification of the problem characteristics, and in identification of the WWTP locations to be implemented. In other words, the suggested spatial DSS provides an effective way of accounting for alternative perspectives [45] by identifying crucial issues to support MCA. Indeed, it is useless for stakeholders to argue about non-essential impacts of regional planning.

Second, by providing an interactive visual tool (i.e., a DSS) that combines efficiency (i.e., optimization) with division of the crucial features into criteria and sub-criteria (i.e., MCA), along with calculation of the spatial distribution of equity indexes, the suggested spatial DSS does not so much attempt to find an answer as to promote the participation process for decision-makers. Indeed, the suggested approach allows both experts and stakeholders to discuss and share different perspectives, knowledge, and perceptions. The welfare scores attached to economic, social, and environmental features, as well as the average indexes and their distribution within the study area, favour a balance between the perspectives of stakeholders and experts. In other words, the suggested spatial DSS is a step towards the implementation of strategic environmental assessment, which has been defined as "a systematic, participatory decision-making support process undertaken to ensure that key factors relating to the environment and sustainability are taken into account in the development of policies, plans, and programs" [46]. This is achieved by synthesizing alternative judgments into a consensus set of parameter values. Indeed, stakeholders need to find an agreeable compromise between the conflicting impacts that result from regional sustainability planning.

Two possible future enhancements of the suggested approach can be identified. First, users should be able to switch from an MCA framework to cost–benefit analysis as an alternative method to combine several features where impacts can be evaluated by experts in monetary terms. Second, a generalizable version of the system could be developed to allow modification of the numbers and types of model parameters (including criteria and water quality standards) to permit application of our system to different contexts, whenever spatially explicit sustainability planning is pursued.

References

[1] O.K.M. Ouda, Treated wastewater use in Saudi Arabia: challenges and initiatives, Int. J. Water Resour. Dev., 32 (2016) 799–809.

[2] World Bank, Middle-East and Northern Africa Water Outlook, 2011.

[3] E. Aleisa, W. Al-Zubari, Wastewater reuse in the countries of the Gulf Cooperation Council (GCC): the lost opportunity, Environ. Monit. Assess., 189 (2017) 553.

[4] M.R. Jumat, N.A. Hasan, P. Subramanian, C. Heberling, R.R. Colwell, P.-Y. Hong, Membrane bioreactor-based wastewater treatment plant in Saudi Arabia: reduction of viral diversity, load, and infectious capacity, Water, 9 (2017) 534.

[5] AQUAREC, Handbook of Feasibility Studies for Water Reuse Systems, EESD Program, European Commission, Zamudio, Spain, 2006.

[6] N. Al-Jassim, M.I. Ansari, M. Harb, P.-Y. Hong, Removal of bacterial contaminants and antibiotic resistance genes by conventional wastewater treatment processes in Saudi Arabia: Is the treated wastewater safe to reuse for agricultural irrigation?, Water Res., 73 (2015) 277–290.

[7] T.M. Missimer, R.G. Maliva, N. Ghaffour, T. Leiknes, G.L. Amy, Managed aquifer recharge (MAR) economics for wastewater reuse in low population Wadi Communities, Kingdom of Saudi Arabia, Water, 6 (2014) 2322–2338.

[8] I. Al-Saleh, R. Elkhatib, T. Al-Rajoudi, G. Al-Qudaihi, Assessing the concentration of phthalate esters (PAEs) and bisphenol A (BPA) and the genotoxic potential of treated wastewater (final effluent) in Saudi Arabia, Sci. Total Environ., 578 (2017) 440–451.

[9] U.N.E. Programme, Sick Water? The Central Role of Wastewater Management in Sustainable Development: A Rapid Response Assessment, UNEP/Earthprint, Nairobi, Kenya, 2010.

[10] S.R. Weijers, J. de Jonge, O. van Zanten, L. Benedetti, J. Langeveld, H.W. Menkveld, A.F. van Nieuwenhuijzen, KALLISTO: cost effective and integrated optimization of the urban wastewater system Eindhoven, Water Pract. Technol., 7 (2012), doi: 10.2166/wpt.2012.036.

[11] N. Mahjouri, E. Pourmand, A social choice-based methodology for treated wastewater reuse in urban and suburban areas, Environ. Monit. Assess., 189 (2017) 325.

[12] L. Jing, B. Chen, B. Zhang, P. Li, A hybrid stochastic-interval analytic hierarchy process approach for prioritizing the strategies of reusing treated wastewater, Math. Prob. Eng., 2013 (2013) 10 p, http://dx.doi.org/10.1155/2013/874805.

[13] C. Masciopinto, M. Vurro, V.N. Palmisano, I.S. Liso, A Suitable tool for sustainable groundwater management, Water Resour. Manage., 31 (2017) 4133–4147.

[14] O.S. Aburizaiza, G.A. Mahar, Degree of wastewater treatment versus types of reuses: case study, Saudi Arabia, Global NEST J., 18 (2016) 569–581.

[15] S. Sipala, G. Mancini, F.G.A. Vagliasindi, Development of a web-based tool for the calculation of costs of different wastewater treatment and reuse scenarios, Water Sci. Technol. Water Supply London, 3 (2003) 89–96.

[16] World Bank, Benchmarking the Kingdom of Saudi Arabia's Water and Sanitation Utilities, World Bank, Washington, D.C., United States, 2006.

[17] WHO, Guidelines for the Safe Use of Wastewater, Excreta and Greywater, World Health Organization, Geneva, Switzerland, 2006.

[18] D.D. Mara, S. Cairncross, Guidelines for the Safe Use of Wastewater and Excreta in Agriculture and Aquaculture: Measures for Public Health Protection, World Health Organization, United Nations Environment Programme, Geneva, Switzerland, 1989. Available at: https://apps.who.int/iris/handle/10665/41681 (accessed September 9, 2019).

[19] V. Ferretti, I. Pluchinotta, A. Tsoukiàs, Studying the generation of alternatives in public policy making processes, Eur. J. Oper. Res., 273 (2019) 353–363.
[20] S. Santoro, I. Pluchinotta, A. Pagano, P. Pengal, B. Cokan, R. Giordano, Assessing stakeholders' risk perception to promote Nature Based Solutions as flood protection strategies: the case of the Glinščica river (Slovenia), Sci. Total Environ., 655 (2019) 188–201.
[21] F. Zagonari, Choosing among weight-estimation methods for multi-criterion analysis: a case study for the design of multi-purpose offshore platforms, Appl. Soft Comput., 39 (2016) 1–10.
[22] V. Vasiloglou, F. Lokkas, G. Gravanis, New tool for wastewater treatment units location, Desalination, 248 (2009) 1039–1048.
[23] M. Molinos-Senante, F. Hernández-Sancho, R. Sala-Garrido, Cost–benefit analysis of water-reuse projects for environmental purposes: a case study for Spanish wastewater treatment plants, J. Environ. Manage., 92 (2011) 3091–3097.
[24] D. Hidalgo, R. Irusta, L. Martinez, D. Fatta, A. Papadopoulos, Development of a multi-function software decision support tool for the promotion of the safe reuse of treated urban wastewater, Desalination, 215 (2007) 90–103.
[25] M. Zarghami, A. Abrishamchi, R. Ardakanian, Multi-criteria decision making for integrated urban water management, Water Resour. Manage., 22 (2008) 1017–1029.
[26] J.A. Zeferino, M.C. Cunha, A.P. Antunes, Adapted optimization model for planning regional wastewater systems: case study, Water Sci. Technol., 76 (2017) 1196–1205.
[27] C.K. Makropoulos, E. Argyrou, F.A. Memon, D. Butler, A suitability evaluation tool for siting wastewater treatment facilities in new urban developments, Urban Water J., 4 (2007) 61–78.
[28] S. Zeng, J. Chen, P. Fu, Strategic zoning for urban wastewater reuse in China, Water Resour. Manage., 22 (2008) 1297–1309.
[29] L. Ahmadi, G.P. Merkley, Planning and management modeling for treated wastewater usage, Irrig. Drain. Syst., 23 (2009) 97–107.
[30] D. Dubber, F. Pilla, D. Smyth, N. Qazi, T. McCarthy, L.W. Gill, Development of a geographic information system-based decision support toolset to assess the feasibility of on-site wastewater treatment and disposal options in low permeability subsoils, Water Sci. Technol., 70 (2014) 464–471.
[31] H.B.B. Neji, S.Y. Turki, GIS – based multicriteria decision analysis for the delimitation of an agricultural perimeter irrigated with treated wastewater, Agric. Water Manage., 162 (2015) 78–86.
[32] F. Pedrero, J.J. Alarcón, M. Abellán, P. Perez-Cutillas, Optimization of the use of reclaimed water through groundwater recharge, using a geographic information system, Desal. Wat. Treat., 57 (2016) 4864–4877.
[33] K. Anagnostopoulos, A. Vavatsikos, Site suitability analysis for natural systems for wastewater treatment with spatial fuzzy analytic hierarchy process, J. Water Resour. Plann. Manage., 138 (2012) 125–134.
[34] J.A. Zeferino, M.C. Cunha, A.P. Antunes, Robust optimization approach to regional wastewater system planning, J. Environ. Manage., 109 (2012) 113–122.
[35] A. Udías, R. Efremov, L. Galbiati, I. Cañamón, Simulation and multicriteria optimization modeling approach for regional water restoration management, Ann. Oper. Res., 219 (2014) 123–140.
[36] D. Abdulbaki, M. Al-Hindi, A. Yassine, M. Abou Najm, An optimization model for the allocation of water resources, J. Cleaner Prod., 164 (2017) 994–1006.
[37] G. Massei, L. Rocchi, L. Paolotti, S. Greco, A. Boggia, Decision support systems for environmental management: a case study on wastewater from agriculture, J. Environ. Manage., 146 (2014) 491–504.
[38] T.L. Lei, R.L. Church, Z. Lei, A unified approach for location-allocation analysis: integrating GIS, distributed computing and spatial optimization, Int. J. Geo-Inf. Sci., 30 (2016) 515–534.
[39] V. Ferretti, G. Montibeller, Key challenges and meta-choices in designing and applying multi-criteria spatial decision support systems, Decis. Support Syst., 84 (2016) 41–52.
[40] M.S. Al-Sheriadeh, S.A. Barakat, M.S. Shawagfeh, Application of a decision making analysis to evaluate direct recharging of an unconfined aquifer in Jordan, Water Resour. Manage., 13 (1999) 233–252.
[41] P.P. Kalbar, S. Karmakar, S.R. Asolekar, Selection of an appropriate wastewater treatment technology: a scenario-based multiple-attribute decision-making approach, J. Environ. Manage., 113 (2012) 158–169.
[42] R. Pelissari, M.C. Oliveira, A.J. Abackerli, S. Ben-Amor, M.R.P. Assumpção, Techniques to model uncertain input data of multi-criteria decision-making problems: a literature review, Int. Trans. Oper. Res., 25 (2018) 1695–1706.
[43] M. Berardi, A. Andrisani, L. Lopez, M. Vurro, A new data assimilation technique based on ensemble Kalman filter and Brownian bridges: an application to Richards' equation, Comput. Phys. Commun., 208 (2016) 43–53.
[44] P.V. Gorsevski, P. Jankowski, An optimized solution of multi-criteria evaluation analysis of landslide susceptibility using fuzzy sets and Kalman filter, Comput. Geosci., 36 (2010) 1005–1020.
[45] J. Hodgkin, V. Belton, A. Koulouri, Supporting the intelligent MCDA user: a case study in multi-person multi-criteria decision support, Eur. J. Oper. Res., 160 (2005) 172–189.
[46] P.J. Posas, Exploring climate change criteria for strategic environmental assessments, Prog. Plann., 75 (2011) 109–154.
[47] M. Molinos-Senante, F. Hernández-Sancho, R. Sala-Garrido, Economic feasibility study for wastewater treatment: a cost–benefit analysis, Sci. Total Environ., 408 (2010) 4396–4402.
[48] M. Molinos-Senante, T. Gómez, M. Garrido-Baserba, R. Caballero, R. Sala-Garrido, Assessing the sustainability of small wastewater treatment systems: a composite indicator approach, Sci. Total Environ., 497–498 (2014) 607–617.
[49] M. Molinos-Senante, T. Gómez, R. Caballero, F. Hernández-Sancho, R. Sala-Garrido, Assessment of wastewater treatment alternatives for small communities: an analytic network process approach, Sci. Total Environ., 532 (2015) 676–687.
[50] D. Joksimovic, J. Kubik, P. Hlavinek, D. Savic, G. Walters, Development of an integrated simulation model for treatment and distribution of reclaimed water, Desalination, 188 (2006) 9–20.
[51] O.E. Demesouka, A.P. Vavatsikos, K.P. Anagnostopoulos, Spatial UTA (S-UTA) – a new approach for raster-based GIS multicriteria suitability analysis and its use in implementing natural systems for wastewater treatment, J. Environ. Manage., 125 (2013) 41–54.
[52] Q.K. Tran, K.A. Schwabe, D. Jassby, Wastewater reuse for agriculture: development of a regional water reuse decision-support model (RWRM) for cost-effective irrigation sources, Environ. Sci. Technol., 50 (2016) 9390–9399.

Supplementary information

Some papers have combined a geographical information system (GIS) with multi-criteria analysis (MCA) by considering several criteria (e.g., costs, levels of organic, and metallic pollutants) to deal with strategic location of wastewater treatment plants (WWTPs) at a national level for safe reuse of wastewater, but they did not develop an optimizing decision support system (DSS). For example, Zeng et al. [28] divided mainland China into 342 research regions, with each region having a large-scale or medium-scale central city, and sorted the regions into five types of strategic development zone (i.e., preferential imperative development, state-supported development, self-supported development, waiting for development, and non-mandatory development) by applying cluster analysis based on three upper-level indexes and seven lower-level indicators. However, they did not develop a DSS and did not analyze dedicated and safe reuse. Similarly, Makropoulos et al. [27] created suitability maps by applying multi-criteria decision analysis, and obtained a combined suitability index; they then used fuzzy logic to introduce the decision-maker's attitude towards risk. However, they did not develop a spatial DSS, and did not analyze dedicated reuse; instead, they focused on centralized vs. decentralized WWTPs. Note that Massei et al. [37] applied alternative weighting and transfer functions to check the robustness of their results.

Some researchers have combined DSS and MCA, but did not include GIS nor optimization. For example, Vasiloglou et al. [22] suggested a DSS based on MCA applied to environmental objectives (general, land-use planning, geomorphological, hydrogeological, and specialized), financial features, and technical features to rationally select a site for WWTPs. However, they did not implement an optimization algorithm for alternative uses at a national scale, and did not account for crucial thresholds for each criterion or the relative importance of the criteria.

Some papers have optimized the system for safe wastewater reuse using an MCA approach, but they did not develop a DSS within a GIS context to account for location criteria at national or regional levels. For example, Zeferino et al. [34] compared three optimization approaches (stochastic optimization, min-max, and robust optimization) to plan and design a regional wastewater system based on setup and operation costs as well as water quality parameters; they did this within an MCA framework, with penalties for failing to meet target water quality goals. However, they did not develop a DSS, and river flows were the only source of uncertainty. Zeferino et al. [26] extended their 2012 analysis to account for additional sources of uncertainty, but not in the form of a true DSS. Alternatively, Zarghami et al. [25] applied a multi-objective decision-making model by minimizing costs, maximizing the water supply, and minimizing social hazards, but they did not analyze wastewater reuse within a spatial DSS; instead, they investigated the integration of several demand management resources such as leakage detection within the water distribution network, water metering, by accounting for and solving problems with low water volumes as well as the integrated use of surface and groundwater resources. Similarly, Molinos-Senante et al. [23,47] applied the shadow price concept within a cost–benefit analysis context to estimate the economic costs and environmental benefits of alternative WWTP designs. Although they provided a net benefit score for each alternative, they did not develop a spatial DSS and relied on the assumption that all treated water could be sold at the market price. Molinos-Senante et al. [48,49] extended their 2010 analysis to account for the sustainability of alternative WWTPs, but not in the form of a spatial DSS. Alternatively, Hidalgo et al. [24] identified the most efficient solutions in terms of safety for agricultural reuse, but they did not suggest a spatial DSS; instead, they performed the analysis at the municipality level. Note that Udias et al. [35] performed stochastic simulations to test for sensitivity under alternative combinations of environmental uncertainties by assuming peculiar impact distributions.

Two papers developed a DSS based on GIS but did not use MCA nor optimization. Ahmadi and Merkley [29] developed a GIS-based model for planning and managing the reuse of treated wastewater for irrigation of agricultural fields and natural vegetation by accounting for health criteria, water quality, and the short- and long-term effects on soils and crops. However, they did not develop an optimizing DSS, although they did consider urban and population growth. Dubber et al. [30] suggest a GIS-based DSS for appropriate location of alternative treatment and disposal options by ranking locations and options in terms of environmental sustainability and costs, but they did not apply an optimization algorithm within an MCA framework. Note that Joksimovic et al. [50] provided a DSS for optimal location of wastewater reuse based on many criteria, but they did not try to support regional planning based on MCA within a GIS framework.

A single paper developed a DSS by combining GIS and MCA to tackle location criteria. Anagnostopoulos and Vavatsikos [33] applied a fuzzy spatial analytic hierarchy process to obtain suitability maps using qualitative variables to localize decentralized natural systems of wastewater treatment, but they did not optimize their system.

Two papers optimized the authors' system by using a GIS and MCA approach to determine safe reuse. Neji and Turki [31] applied a compromise programming method to optimize wastewater reuse (i.e., to reduce irrigated areas) according to farmer demands, aspirations, and aims, but they did not develop a DSS. Pedrero et al. [32] developed a model for the optimal spatial distribution of aquifer recharge based on GIS within a MCA framework, but they did not provide a DSS for alternative uses.

Note that Abdulbaki et al. [36] developed a model for optimal spatial distribution of water resources among alternative uses within a cost–benefit analysis framework (i.e., minimization of treatment, distribution, and environmental costs) by applying sensitivity analyses, but they did not provide a DSS within a GIS framework. Moreover, Demesouka et al. [51] applied the additive utility norm and linear programming techniques to GIS within an MCA framework to rank alternative sites for implementing natural systems (e.g., wetlands) for wastewater treatment. Finally, Tran et al. [52] developed a model for cost-effective wastewater treatment for a single-use (i.e., crop irrigation), but they did not provide a DSS within a GIS framework.