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DOI

[10.1080/02626667.2018.1446213](https://doi.org/10.1080/02626667.2018.1446213)

Publication date

2018

Document Version

Accepted author manuscript

Published in

Hydrological Sciences Journal

Citation (APA)

Abdullah, A. D., Castro-Gama, M. E., Popescu, I., van der Zaag, P., Karim, U., & Al Suhail, Q. (2018). Optimization of water allocation in the Shatt al-Arab River under different salinity regimes and tide impact. *Hydrological Sciences Journal*, 63(4), 646-656. <https://doi.org/10.1080/02626667.2018.1446213>

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Optimization of water allocation in the Shatt al-Arab River under different salinity regimes and tide impact

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Abstract

Wastewater effluents from irrigation, domestic and industrial sectors have serious impacts in deteriorating water quality in many rivers, particularly in the area under tidal influence. There is a need to develop an approach that considers the impact of human and natural causes of salinization. The study uses a multi-objective optimization-simulation model to investigate and describe the interactions of such impacts in the Shatt al-Arab River, Iraq. The developed model was able to reproduce the salinity distribution in the river given varying conditions. Salinity regime in the river varies according to different hydrological conditions and anthropogenic activities. Due to tidal impacts salinity caused by drainage water is noticed to intrude further upstream into the river. The applied approach provides a way to obtain optimal solutions where both river salinity and deficit in water supply can be minimized. The approach is used for exploring the trade-off between these two objectives.

Keyword: salinity, water management, optimization, Shatt al-Arab River, drainage water, tidal influence

1. INTRODUCTION

Improving water allocation strategies for different water uses among different stakeholders is crucial for social and economic developments. Designing such strategies for multiple purposes is complex if water scarcity conditions are prevalent. Distribution of river water whether for irrigation, industrial or domestic use, requires a water quality standard. Seawater intrusion and increasing agricultural and domestic water demands result in salinity increase in many tidal rivers (e.g. the Shatt al-Arab, Nile, and Indus rivers). Managing freshwater inflows is one of the important control measures to maintain salinity fluctuations caused by salinity intrusion into river estuaries to a minimum. On the other hand, return flows from irrigation, industrial and domestic effluents increase salinity at their points of discharge and beyond in the downstream direction.

Various methods are now available to model water allocation in river basins. These methods lead to models which are classified into two categories: optimization and simulation models. The determination of an allocation policy is not trivial due to inflow uncertainty and conflicting demands on scarce water resources. Optimization techniques have the ability to deal with multiple conflicting objectives in complex water system.

Engineering optimization approaches are effective for planning purposes useful for real-time operation systems and complex optimization problems (e.g. Barros *et al.* 2003, Labadie 2004, Farthing *et al.* 2012, Kourakos and Mantoglou 2012, Singh 2012). In water resources, optimization models have capabilities, depending on their sophistication, to perform assessments of the natural, physical, and human-water components that characterize a complex river basin system. In particular, integrated hydrologic and

economic models are well equipped to find optimal water allocation strategies in river basins (Mckinney *et al.* 1999, Cai *et al.* 2006). For the task set in this paper, namely to minimize salinization as well as minimize the deficit for irrigation and domestic water supply in a river system, a hydrodynamic salt intrusion simulation model is required to evaluate the optimal water allocation strategies considering salinity variation under tidal influence.

Little is known about salinity management in general, when there is a combination of different salinity sources in a tidal river. There are however, few studies available, but these are limited in their scope and applicability and not applicable to the general multi-factors type problems of salinity in a tidal river affected by a combination of irrigation practices, industrial effluents and urban discharges (quantity and type), the quality and quantity of upstream river inflow, and seawater intrusion. Mayer and Munoz-Hernandez (2009) provide a state-of-the-art compilation of integrated models for water resource optimization, and identified the need for the inclusion of human and natural resources impacts of salinization due to wastewater return flows.

The objective of this study is to develop a multi-objective optimization-simulation model to identify efficient alternatives for water allocation for at the Shatt al-Arab River (SAR). Such a study is necessary in order to mitigate the impact of high salinity concentrations and fluctuations associated with different salinity sources due to water use along the river. The model is used to account for different upstream inflows and salinity concentrations. Furthermore, optimal water allocations and strategies for different upstream conditions are investigated for irrigation and domestic uses.

2. CASE STUDY

Water resources management comprises scenarios, plans and actions to manage the available water resources in an efficient and equitable manner for the present and the future. It should aim to satisfy current and projected water requirements and at the same time control any likely impacts of floods, droughts and water pollution (Koudstaal *et al.* 1992, Loucks *et al.* 2000). Understanding and monitoring water fluxes between upstream and downstream portions of a river basin is necessary for proper governance of water resources (Van der Zaag 2007). The Tigris-Euphrates basin, shared by Turkey, Syria, Iran, and Iraq, witnessed the construction of a number of water resources projects which are most often developed unilaterally. There are around 35 dams in operation, 8 under construction and 9 planned. These developments have altered both the water flow and water salinity patterns. The most affected region by the changes is the SAR (Abdullah *et al.* 2015). This tidal river is formed at the confluence of the Tigris and Euphrates rivers which eventually discharge into the Gulf.

Figure 1 shows the location of the SAR and its tributaries. Currently the Tigris is considered the main tributary to the SAR, while the water from the Euphrates is released into SAR only during the wet season when it has lower salinity. Before the construction

of major projects in the Tigris basin in 1988, the monthly average discharge into the SAR was around 200 m³/s, but it has since reduced significantly and was 50 m³/s in 2014. Upstream developments not only decreased river discharge but also increased salinity. At the most downstream station in the Tigris, the salinity increased threefold from 0.6 to 1.8 kg/m³ over the period 1980-2002 (Abdullah *et al.* 2015). The SAR salinity changes in space and time. The salinity ranged from 0.25 kg/m³ in the upstream to 40 kg/m³ in the estuary (Abdullah *et al.* 2016). This variation was associated with different salinity sources including irrigation return flows, domestic effluents, and seawater intrusion. Drainage water of irrigation and waste water of domestic sectors discharge directly into the river. Also the water draining from the surrounding marshes is saline. There are three major marshes in the region; Hawizeh, Hammar, and the central marshes connecting with the SAR through the Sweeb, Garmat Ali, and Euphrates Rivers, respectively (Fig. 1). The observed salinity in these marshes during 2014 ranged from 1.0 to 5.0 kg/m³ (Abdullah *et al.* 2016).

Increased water withdrawals upstream and along the river course resulted in further seawater intrusion. Combined with waste water inflow from several sources resulted in salinity levels that are highly unsteady (dynamic) and variable both at seasonal and daily time scales. As a result, large areas of Southern region of Iraq are facing persistent deficit in water availability; drinking water decline, with worsening prospects of increasing shortages. Salinity in the SAR will further lead to relinquishment of hitherto fertile farmland and colossal economic losses. More details about salinity of the SAR and contributing water bodies in upstream regions can be found in Abdullah *et al.* (2015), Al-Furaiji *et al.* (2015), and Brandimarte *et al.* (2015).

3. MODEL DEVELOPMENT

A multi-objective optimization model was coupled with an existing 1-D numerical simulation model to optimize water allocations in the SAR. Seawater intrusion, return flows, and upstream salinity are accounted to obtain optimized solutions to this class of problems in salinity dynamics. Simulations of different water management practices can be conducted individually or in combination to solve for scenarios leading to minimum impact from salt transport. The following section describe this approach.

3.1. Simulation model

Salinity variation on the SAR was simulated by a 1-D hydrodynamic and salt intrusion model, which is available for use. The set-up, calibration and validation of the model is presented in detail in Abdullah *et al.* (2017). The model is based on Delft3D and has been calibrated and validated with hourly time-series of the SAR water levels and salinity data collected during the year 2014. In 2014, for the first time, ten monitoring stations were

installed to monitor water level, salinity, and temperature along the SAR River and its estuary. This provided the opportunity to correlate salinity variations to the changes in hydrological conditions and water levels due to combined impacts of tide and river discharge (Abdullah *et al.* 2016))

The combined effects of anthropogenic activities and natural factors on the salinity regime are more dominant during irrigation season, when it is expected that water from return flows is at its maximum. Therefore in the present study the selected period for simulations is 26 January -1 April, which corresponds with the irrigation season. The interval range of 8 weeks is also reasonable for attaining management objectives. The boundary conditions during this interval were the river discharge at the upstream boundary and the hourly measured tidal elevation at the downstream boundary. Salinity at the upstream boundary was specified by the minimum and maximum observed river salinity, 0.25 and 1.5 kg/m³ respectively. At the downstream boundary salinity was averaged over the period and was 30 kg/m³. The water and salinity levels at the beginning of the simulation period were specified as the initial conditions. The model was developed with 56 observation points to extract the computed salinity (Fig. 2). Drainage water consists of irrigation return flows and industrial and domestic effluents discharging into the SAR, mainly along its upper portion. Observations in the field and data analysis showed that the maximum impact of the drainage water was at a station near the city of Basrah. This station is located in the midcourse of the river (Fig. 1). The drainage water is represented by an outfall point near Basrah, corresponding to observation point number 19 (Fig. 2). The average observed salinity at this station was used as the drainage water salinity (2.7 kg/m³). The flow rate of drainage water was estimated at 20 m³/s (Abdullah *et al.* 2017). This consists of 10 m³/s drainage from the marshes and domestic uses, and a further 10 m³/s from irrigation return flows. The later value corresponds to 25% of average consumption (40 m³/s), the minimum required drainage volume according to Iraqi standards.

Water withdrawals for both domestic and irrigation uses were represented by two extraction points at distances of 16 and 26 km from the upstream boundary, located at observation points 4 and 6 respectively (Fig. 2). These are the locations suggested by the local water resources authority to divert water for domestic and irrigation purposes.

3.2. Optimization model

The optimization technique was used to establish a tradeoff between the conflicting objectives of minimizing the water supply deficit and minimum salinity. This study aimed at managing the salinity variation along the SAR taking into account growing water demands and decreasing water inflows. Considering the drainage water components, salinity could be mitigated by releasing more water that would dilute and flush out saline water and also counteract seawater intrusion. Discharging more fresh water into the estuary deprive other sectors of their source of water. On the other hand, the salinization impact of drainage water could be extended further upstream driven by tidal influence.

Salinity in the upstream portion will be under combined effects: the upstream conditions of water quality and quantity and the downstream conditions of drainage water and seawater intrusion. Therefore, the optimization framework was developed as a multi-objective approach to reduce the impact of salinity changes on the ecosystem and water sectors (domestic and irrigation) under different prevailing conditions. The Monte Carlo technique was used as a computational algorithm for the optimization process coupled with the Delft3D simulation model. The Monte Carlo method is a computational algorithm mainly used for optimization, numerical integration, and probability distribution. The Monte Carlo optimization technique is used for mathematical programming problems, especially nonlinear systems of equations (Dickman and Gilman 1989), and in optimization (Sakalauskas 2000, and Guda *et al.* 2001).

Two objective functions were considered. The first objective was to minimize the river water salinity along its course, while the second objective tackled the deficit in water supply (for irrigation and domestic uses). The optimization problem can be mathematically posed as

$$\text{Min } (F_1, F_2) = [S_{ave}, D_{water\ supply}] \quad (1)$$

$$\text{Salinity objective } (F_1) = \min (S_i - S_{max}) \quad i \in \{1, 2, \dots, x\} \quad (2)$$

$$\text{Supply objective } (F_2) = \min [(A_i - DD) + (A_i - ID)] \quad i \in \{1, 2, \dots, x\} \quad (3)$$

Subject to: $x \in X$,

where S_{ave} is the average salinity along the river excluding its estuary; the salinity is averaged over the river stretch between observation points number one (the upstream end) and number 39 (at 65 km from the river mouth). This is to avoid high salinity levels caused by seawater intrusion as well as to maintain seawater intrusion at that limit. D is the deficit of water supply from two main water uses, irrigation and domestic. The vector of decision variables x lies in the feasible space X determined from the equity and inequity constraints (C) represented mathematically as

$$0 \leq ID \leq 50$$

$$0 \leq DD \leq 10$$

$$0 \leq S \leq 2.1$$

Where, the maximum irrigation demand (ID) is 50 m³/s, maximum domestic demand (DD) is 10 m³/s, and S for salinity. Water is not allowed for use for consumption if a salinity exceeds the target limit of 2.1 kg/m³ (De Voogt *et al.* 2000). For this reason an additional constraint is posed during the simulation in order to verify whether or not this condition is

fulfilled. The maximum irrigation demand considered in the present study is a combination between the one estimated by Water Resources Authority in Basrah considering the available agricultural lands; and the maximum domestic demand estimated by Water Treatment Department in Basrah based on current population of the region. The decision variable for the simulation model is the amount of water, A , to be allocated from the supply source to each water use, denoted A_i , where i designates the user. Available water is a function of the supply source, the season and the development scale. Although water availability varies from season to season and year to year depending on climatologic conditions, the river discharge was expressed equal to the low, average, and high observed monthly discharge over the last two decades. This is to find the optimal water allocation for different uses for each river flow condition.

3.3. Coupling of optimization and simulation models

The multi-objective model, written in MATLAB, links optimization with simulation. Figure 3 presents a framework of the general algorithm. This code contains a rewritten subroutine within the simulation part which contains decision variables. The decision variables are generated randomly in the optimization code. A multi-objective optimization routine runs the simulation model for each decision variable. Salinity dynamics is simulated by the Delft3D model. Consequently, the profile of salinity along the river is analyzed to evaluate the objective functions and the constraints, the maximum demands and maximum salinity levels. The optimization-simulation model was developed under different scenarios, in order to investigate the impact of salinity changes corresponding to different salinity and inflow levels in the upstream reaches of the SAR. According to the hydrological data obtained from Iraqi water resources authority, river discharge for the period from 1988 to 2010 ranges between 20 and 120 m³/s; and the upstream salinity for the year 2014 ranges from 0.25 to 1.5 kg/m³ (Abdullah *et al.*, 2015). The duration curve of the discharge for the period 1988-2010 is presented in Fig 4. In order to assess the sensitivity of the salinity regime in the river to the drainage water considering different upstream conditions, six scenarios were developed using high, average, and low river discharge, and maximum and minimum upstream salinity (Table 1).

4. RESULTS

4.1. Simulation-based optimization

Results of salinity distributions at two withdrawal points (for domestic and irrigation supply) and an outfall point (for drainage water) are presented in Figure 5. The optimization was used to minimize the average salinity along the river. Generally, average salinity increases in all scenarios but with different levels. Contrary to expectation, salinity was found to increase more in the case of minimum upstream salinity (0.25 kg/m³), but not with maximum salinity (1.5 kg/m³). Salinity interval ranges are bigger for both cases

of maximum and minimum upstream salinity values. However the amount of increase differs from one case to another. Hence, in case of a minimum salinity, S_{ave} increases in a ratio of 100%, 300%, and 700% more for the high, average, and low flow respectively; whereas, for the case of maximum salinity levels, S_{ave} increases by 10 %, 30 %, and 60 % with high, average, and low flow respectively. The different salinity ranges for different upstream condition could be attributed to dilution and mixing processes along the river.

Upstream conditions are more dominant at the withdrawal points during high and average flow scenarios (Sc_{1-1} - Sc_{2-2}). Despite increases in S_{ave} , salinity remains almost constant at both domestic and irrigation withdrawal points with slight increases during average flow. At the outfall point, however, salinity increases, but differently, during high and average flow in both minimum (0.25 kg/m^3) and maximum (1.5 kg/m^3) upstream salinity conditions. In the low flow scenarios (Sc_{3-1} and Sc_{3-2}) the differences are significant. S_{ave} at domestic, irrigation, and outfall points could exceed the allowable limit (2.1 kg/m^3). The gray domain in Fig. 5 represents the salinity where river water is not usable. The gray domain increases in downstream direction and extends further upstream with higher upstream salinity.

Figure 6 illustrates the salinity distribution at withdrawal and outfall points as a function of deficit in water supply. The results show that water demands can be satisfied during high flow conditions. Drainage water combined with tidal influences has no impact on the salinity levels in the upstream region. However, during average flow conditions, drainage water could only increase salinity in the upstream region with full water supply, while reduced water supply to domestic and irrigation uses by about $10 \text{ m}^3/\text{s}$ (16%), upstream salinity levels remain constant. During low flow conditions, there is no possibility to satisfy all water demands, with deficits of around $7 \text{ m}^3/\text{s}$ (12%) and $20 \text{ m}^3/\text{s}$ (33%) in scenarios Sc_{3-1} and Sc_{3-2} , respectively. Only if the supply deficit is at least 50 % there will be no increases in upstream salinity levels. On the other hand, salinity at the outfall point increases with increasing water supply in all scenarios (Fig. 6). During high flow scenarios, S_{ave} rise to 1.1 and 1.9 kg/m^3 with minimum and maximum salinity conditions, while it goes up to 2.5 kg/m^3 in the other scenarios.

The concentration ensemble of the simulations is presented in Fig. 7. Drainage water influences salinity in the downstream reaches under high river discharge. However, its impact extends to the upstream section with average river discharge and increases further with low river discharge. With minimum salinity levels (Sc_{1-1} , Sc_{2-1} , and Sc_{3-1}), the salinity regions in the river varies more widely compared to maximum salinity levels (Sc_{1-2} , Sc_{2-2} , and Sc_{3-2}). Seawater intrusion, on the other hand, varies according to river discharge and water supply. Consistent with expectation, seawater intrudes further upstream in case of low river discharge and high water withdrawals.

4.2. The optimal solution

In a multi objective optimization problem one cannot get a single optimal solution fulfilling both objective functions simultaneously. Therefore, the aim of multi objective optimization

is not to search for the best solution but to find an efficient solution that minimizes both objective functions. In fact there are infinite numbers of possible solutions (called the Pareto efficiency). A graphical presentation of the two objective functions in the selected criterion space is presented in Fig. 8. The feasible ranges of optimal solutions are bounded by the deficit of water supply at the upper left corner and the average river water salinity at the lower right corner, excluding the gray part. Considering water supply requirements, the gray part indicates that river salinity exceeds the maximum level for irrigation and domestic uses. Each corner represents the optimal benefit of its corresponding individual objective, while all other individual objectives are worse off. Moving from the lower right to upper left points on the convex efficiency front gives different weights to the two objective functions, which represent the tradeoff between water demand deficit and average salinity.

4.3. System performance

To evaluate the water system performance under different upstream conditions, the results of one optimal solution for each scenario are presented in Fig. 9. For that purpose, the middle point of the efficiency front has been chosen that gives equal weight to both objective functions. The figure indicates that the salinity region in the river is influenced by the combined effect of drainage water and seawater intrusion. Tidal influence on the river water salinity extended further upstream with minimum salinity levels under average and low flow conditions (Sc_{2-1} and Sc_{3-1}), whereas it has almost the same extent with high river discharge. Therefore, all seawater intrusion distances are almost the same in scenarios Sc_{1-1} and Sc_{1-2} , around 30 km. During average flow, the seawater intrusion distance corresponding to minimum and maximum salinity levels, increases from 40 km to 60 km, and during low flow increases from 80 km to 90 km, respectively. One of the main findings is that seawater intrusion in the upstream is greater for low salinity levels of the river as compared to higher level of salinity. This cause is considered to be due to the difference between salinity of the river water and seawater; higher salinity difference increases the flux of seawater and allows for longer intruded distance. Out of the seawater intrusion domain, the highest salinity are at the outfall location but this reduced in both upstream and downstream directions.

5. CONCLUSIONS AND RECOMMENDATIONS

A multi-objective optimization model was developed incorporating simulation and optimization to determine the impact of drainage water on the natural sources and water sectors under different scenarios. This approach was used to address the issue of river salinity changes considering the upstream salinity sources and the tidal influence downstream. Moreover, the water system performance was evaluated under different upstream conditions taking into account demand requirements and salinity variation. This

is to assist the decision making process for water resources management and development.

A Monte Carlo optimization algorithm was coupled to a Delft3D simulation model within a MATLAB environment. The optimizer code consisted of two objective functions to minimize deficit in water supply and manage the river water salinity to remain in the allowable range (below 2.1 kg/m^3). The simulation model was used to compute salinity results taking in account the quantity and quality of river and drainage water, water demands, and seawater intrusion. The results were then evaluated by the optimization code to produce an efficiency front of optimal solutions.

Limits of water availability for human uses were obtained in terms of their salinity. The model has been applied to the SAR case. Drainage into the SAR of saline water influences the salinity regime in the downstream and upstream reaches most significantly during low river flow. The range of water salinity variation is mainly governed by the salinity levels of the receiving water, where the impact of drainage water increases at lower salinity levels. Moreover, the impact of seawater extended further upstream at the low salinity levels of river water compared to the higher levels. These findings confirm the result of Abdullah *et al.* (2017) that sea water intrusion is highly correlated with river discharge, where the longer intrusion distance occurs during the dry period. Water demands can only be satisfied under high and average river discharge with salinity in the range $0.45\text{-}2.1 \text{ kg/m}^3$. However, under low flow conditions not all water demands can be met, a deficit of 12% and 33% correspond to minimum and maximum salinity levels of the upstream source. The results of Abdullah *et al.* (2017) simulation based approach show an increase of sea water excursion and salinity along the river associated with different scenarios of water withdrawals and drainage water. Therefore, an optimization based approach is required to determine the optimal water withdrawal and intrusion distance.

The presented approach can be used to explore and capture the impact of salinization sources on water sectors and the ecosystem, and is intended to provide an effective tool supporting water resources planning and management. Ideally, this is achieved by conserving computation time using a 1-D hydrodynamic model, reasonably sized grid and time intervals with sufficient resolution, as well as using the simplest Monte Carlo optimization algorithm. Water management of salinity related problems in rivers require proper understanding of the discharge-salinity intrusion relationships. Several studies have examined this relation such as the ones of Whitney (2010) and Becker *et al.* (2010). One important factor in all studies is the impact of freshwater inflow on the seawater intrusion. As pointed out by many researchers (see Vaz *et al.* 2009, Das *et al.* 2012), for effective water supply and water demand management an optimization-simulation approach provide better information about water quantity and water quality considering different hydrological conditions, tide impacts, water withdrawals, and drained water (Cai *et al.* 2015, Grygoruk and Okruszko 2015). To help find more complex patterns for sustainable management of water resources, the existing model can be extended to

include more dynamic conditions. For that purpose further work is required considering dynamic salinization sources such as varying drainage volumes and/or salinity levels, and several outfall points for drainage water. This could guide the decision process determining the optimal location of drainage water outfalls while minimizing river salinity and seawater intrusion.

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Table 1. Simulated scenarios (Sc) of salt concentration for different upstream conditions.

			Salinity of upstream inflow (kg/m ³)	
			0.25 (1)	1.5 (2)
Upstream river discharge (m ³ /s)	100	(1)	Sc ₁₋₁	Sc ₁₋₂
	50	(2)	Sc ₂₋₁	Sc ₂₋₂
	25	(3)	Sc ₃₋₁	Sc ₃₋₂

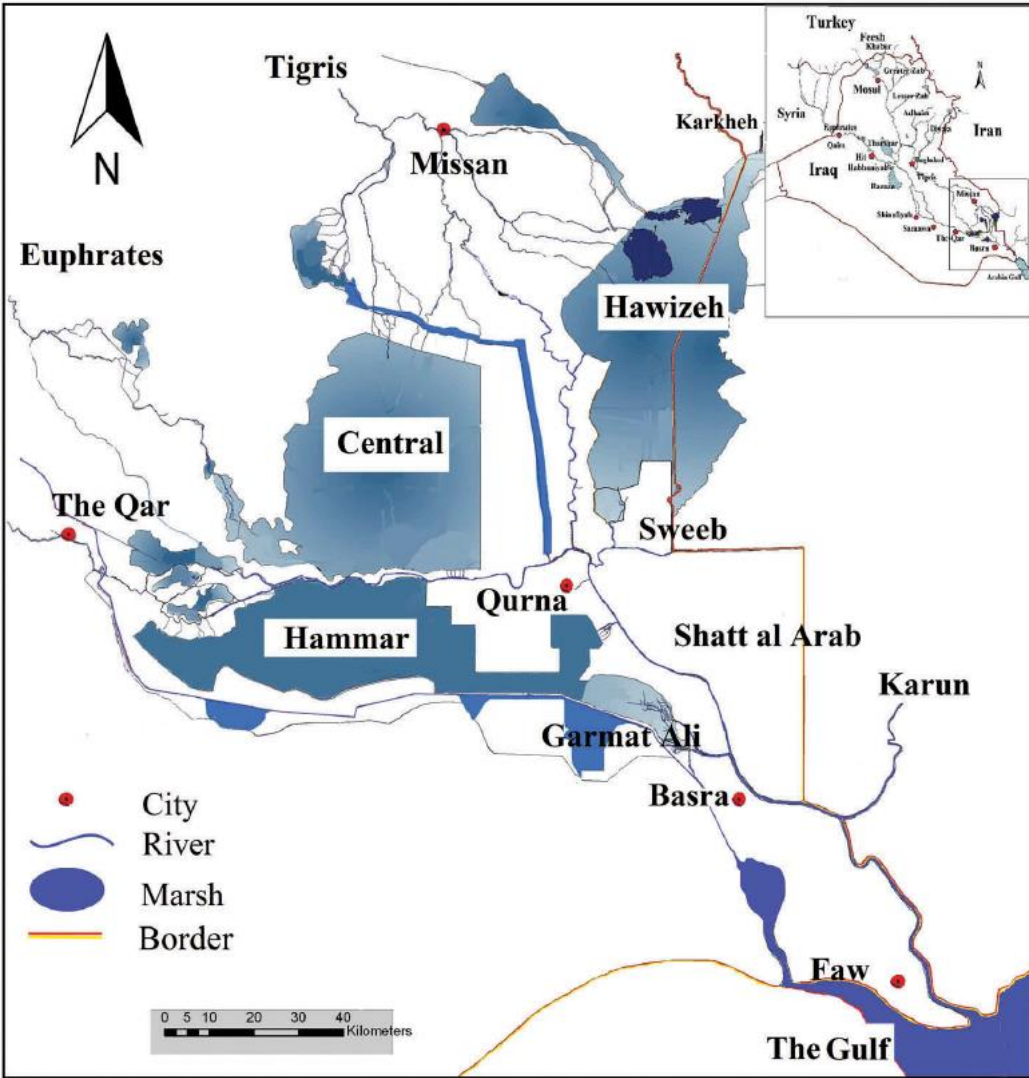


Fig. 1 The location of the Shatt al-Arab River and the main features of the system.

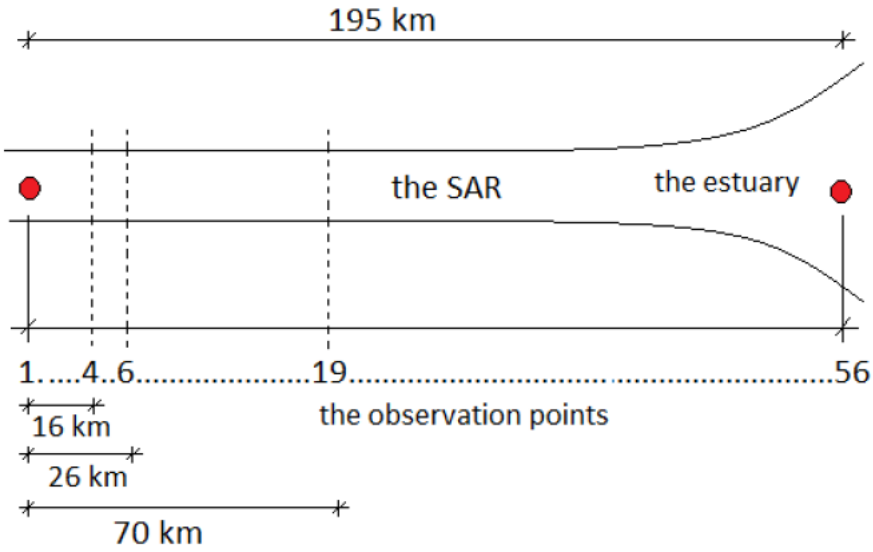


Fig. 2 Schematic presentation of observation points 1-56 showing domestic withdrawals (4), irrigation withdrawals (6), and drainage outfall (19) locations.

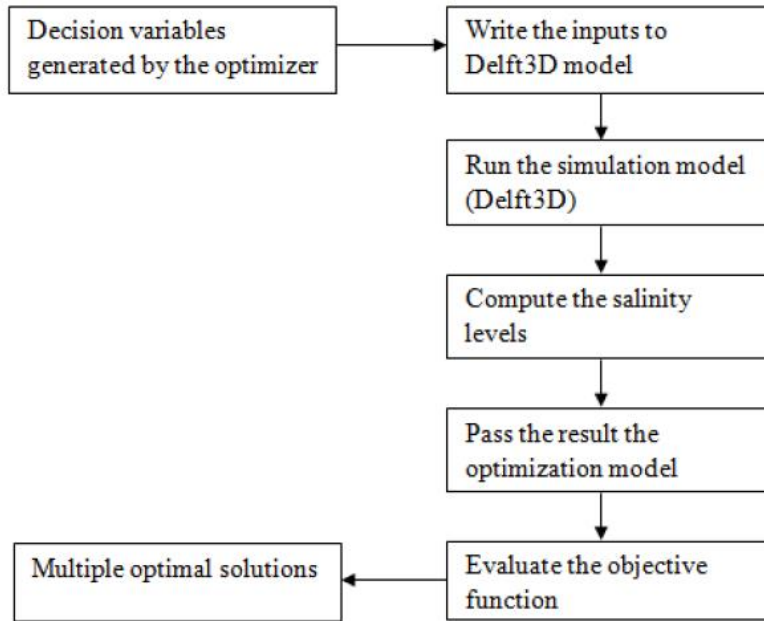


Fig. 3 General framework of the multi-objective optimization-simulation model.

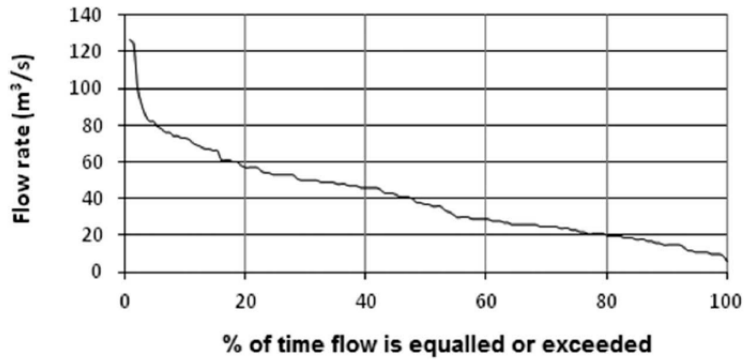


Fig. 4 Flow duration curve of the SAR based on 1988-2010.

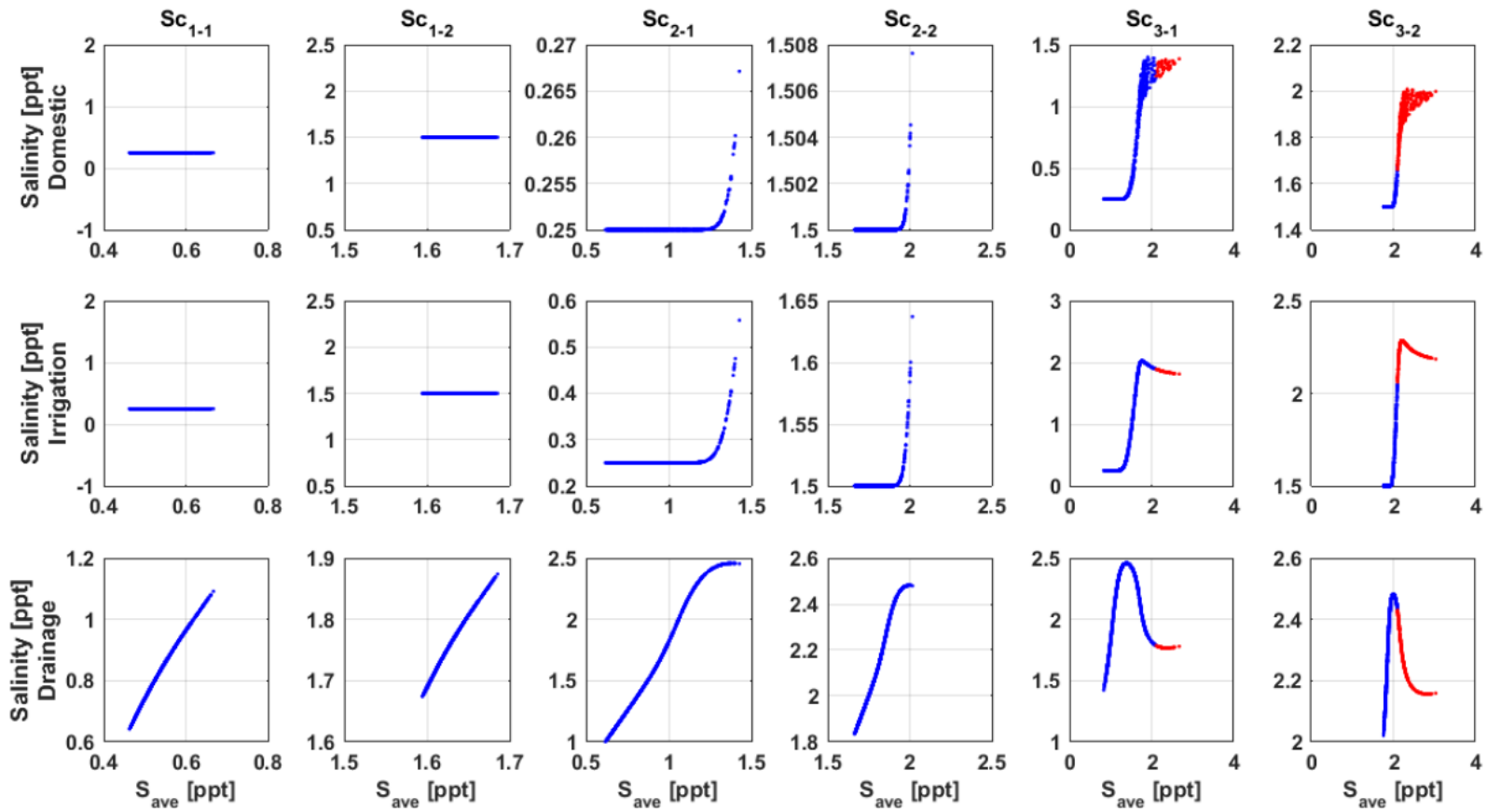


Fig. 5 Salinity at withdrawals and outfall points (see Fig. 2 for their locations) for the six scenarios as a function of river water salinity (note that the axes have different scales for the different conditions).

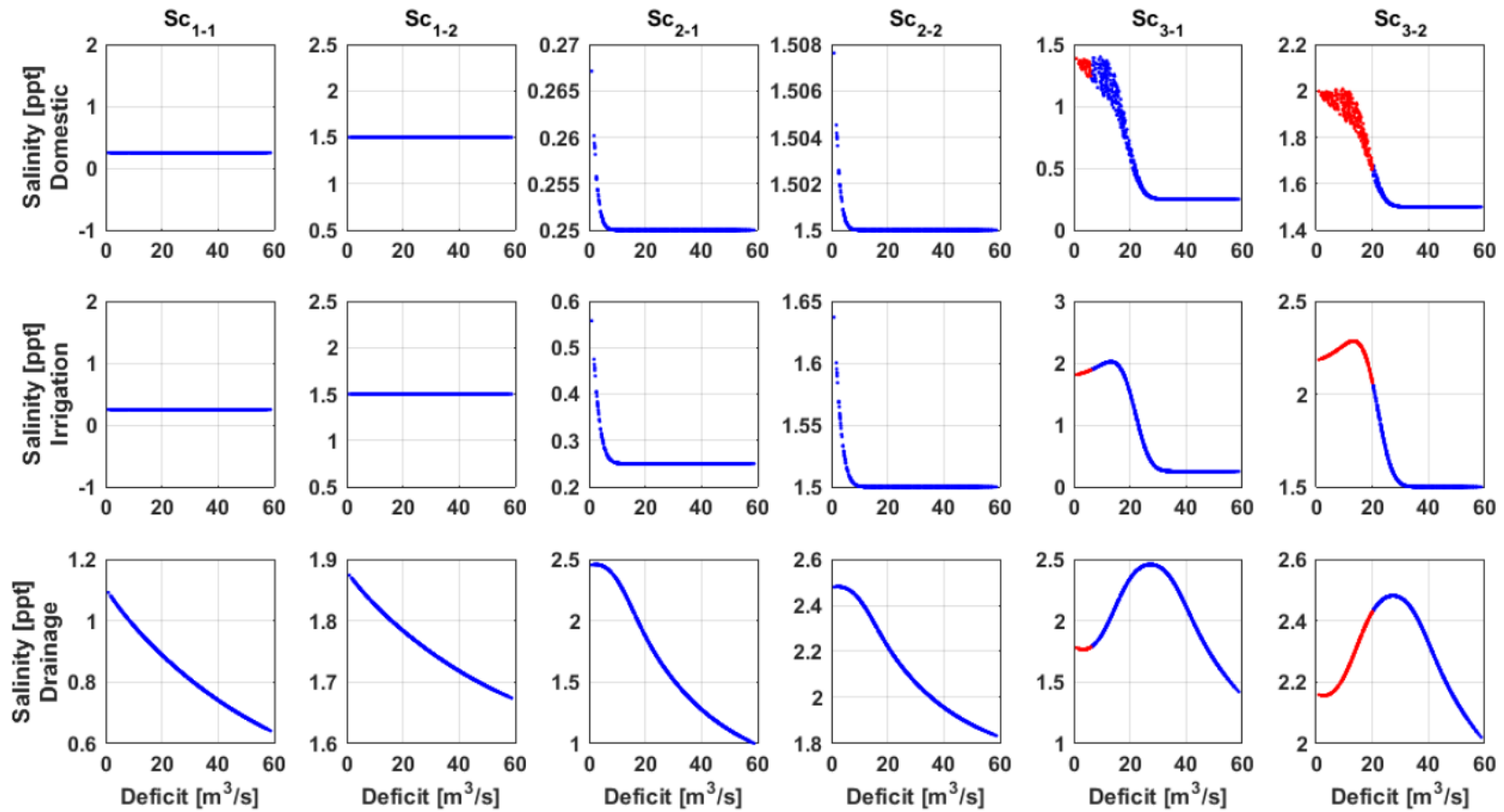


Fig. 6 Salinity at withdrawals and outfall points for six scenarios as function of water supply deficit (note that the salinity y-axes have different scales for the different conditions).

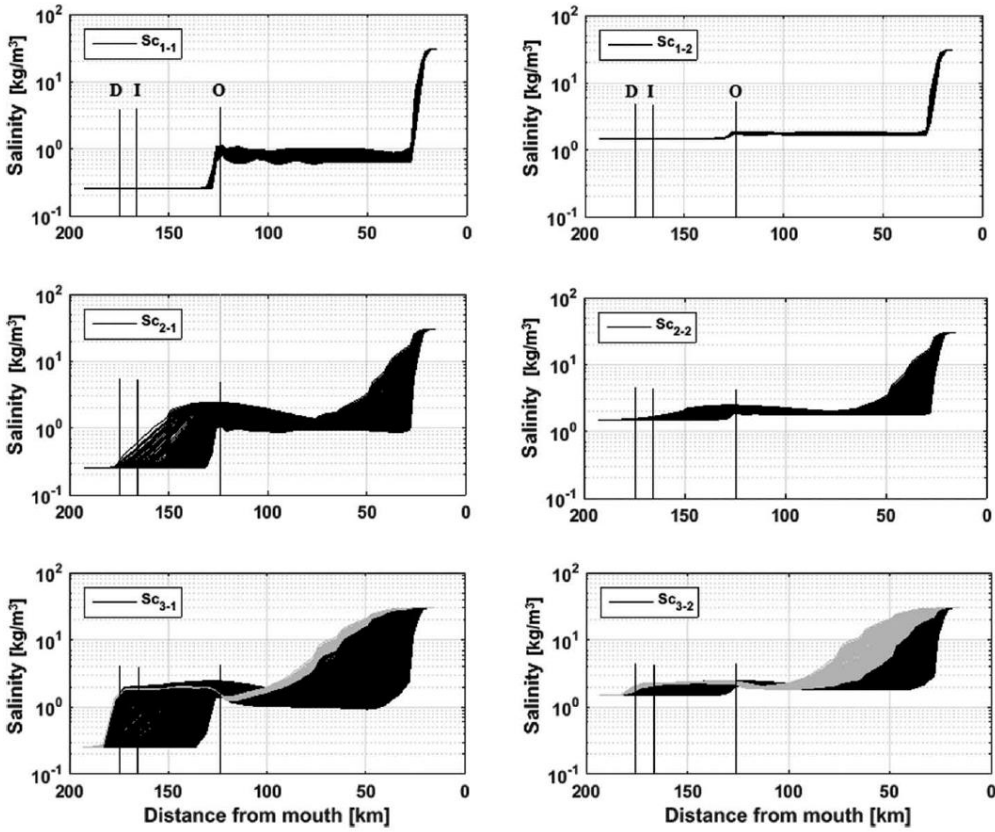


Fig. 7 Optimized salinity distribution along the SAR extracted from the 56 observation points (see Fig. 2). Points D, I, and O represent the locations of the withdrawals for domestic water supply, for irrigation water supply, and the outfall for drainage water respectively (in gray: unfeasible solutions, i.e. average river water salinity is larger than 2.1 kg/m³).

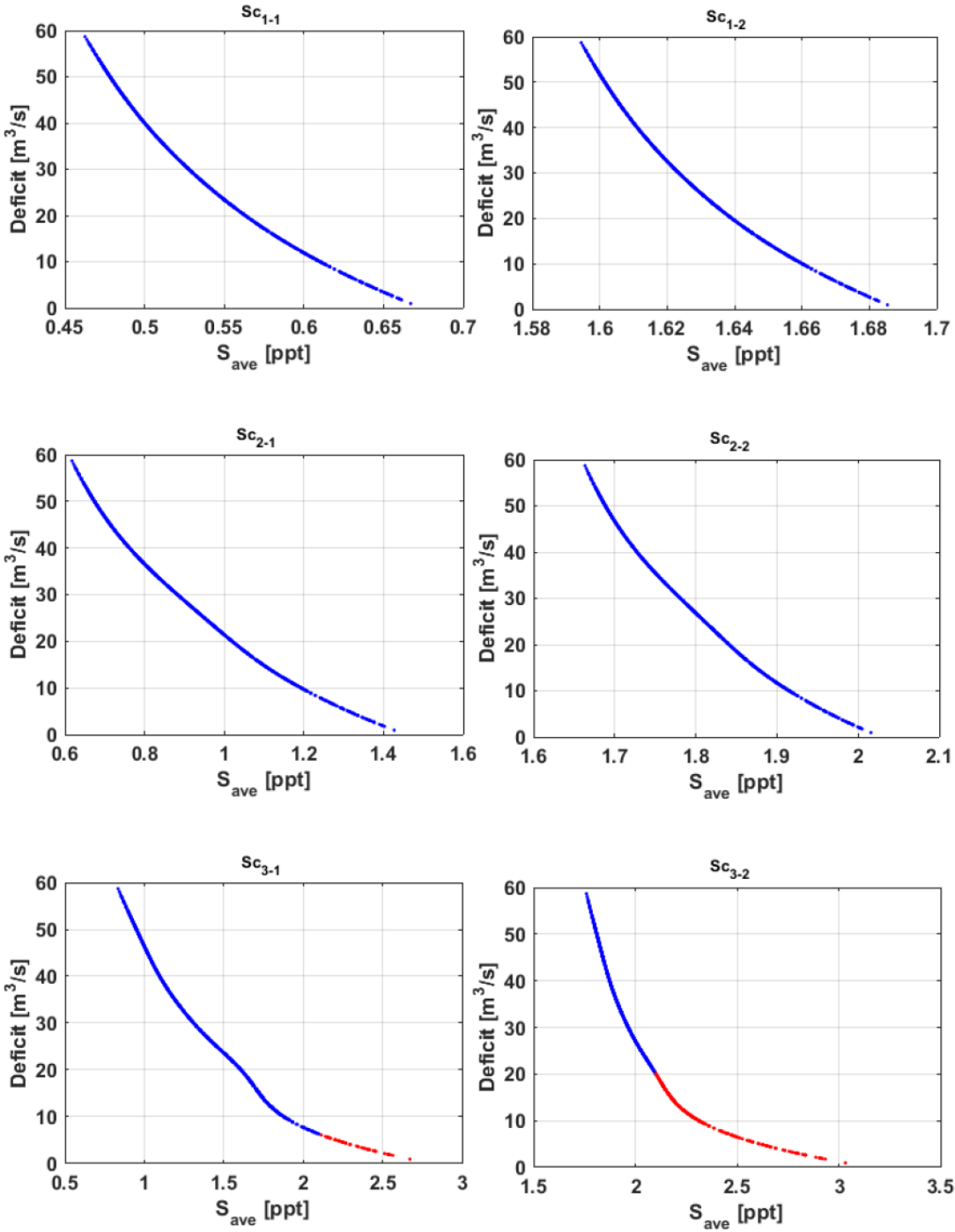


Fig. 8 The objective space of solutions for each of the six selected scenarios simulated 1000 times (in gray unfeasible solutions, i.e. average river water salinity is larger than 2.1 kg/m³).

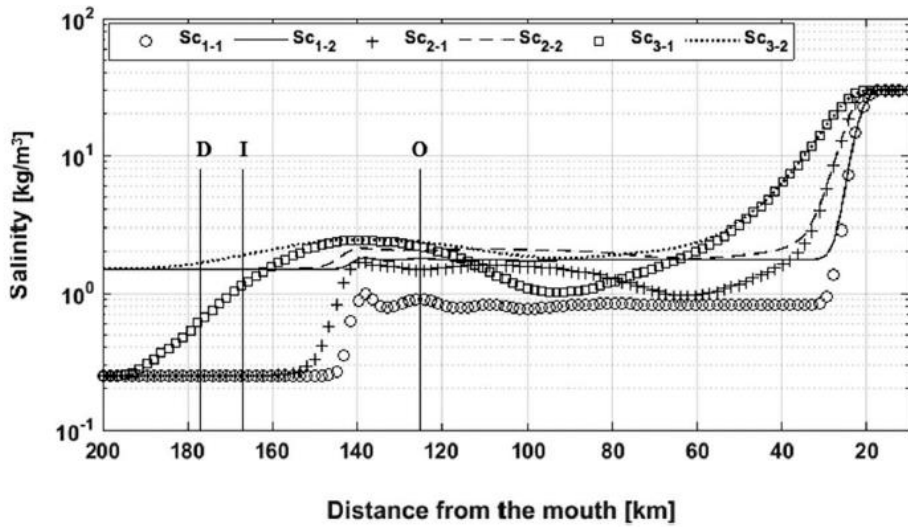


Fig. 9 Longitudinal salinity distribution considering different upstream conditions. Points D, I, and O represent the locations of the withdrawals for domestic water supply, for irrigation water supply, and the outfall for drainage water respectively.