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Management scenarios for the Jordan River salinity crisis

Efrat Farber [a], Avner Vengosh [a,*], Ittai Gavrieli [b], Amer Marie [c],
Thomas D. Bullen [d], Bernhard Mayer [e], Ran Holtzman [f], Michal Segal [f],
Uri Shavit [f]

[a] *Department of Geological and Environmental Sciences, Ben Gurion University, P.O. Box 653, Beer Sheva 84106, Israel*
[b] *Geological Survey of Israel, 30 Malkei Israel St., Jerusalem 95501, Israel*
[c] *Department of Applied Earth and Environmental Sciences, Al-Quds University, East Jerusalem, West Bank*
[d] *Water Resources Division, U.S. Geological Survey, MS 420, 345 Middlefield Rd., Menlo Park, CA 04025, USA*
[e] *Department of Geology and Geophysics, University of Calgary, 2500 University Drive NW, Calgary, Alta., Canada T2N 1N4*
[f] *Department of Civil and Environmental Engineering, Technion, Israel Institute of Technology, Haifa 32000, Israel*

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Abstract

Recent geochemical and hydrological findings show that the water quality of the base flow of the Lower Jordan River, between the Sea of Galilee and the Dead Sea, is dependent upon the ratio between surface water flow and groundwater discharge. Using water quality data, mass-balance calculations, and actual flow-rate measurements, possible management scenarios for the Lower Jordan River and their potential affects on its salinity are investigated. The predicted scenarios reveal that implementation of some elements of the Israel–Jordan peace treaty will have negative effects on the Jordan River water salinity. It is predicted that removal of sewage effluents dumped into the river (~13 MCM/a) will significantly reduce the river water's flow and increase the relative proportion of the saline groundwater flux into the river. Under this scenario, the Cl content of the river at its southern point (Abdalla Bridge) will rise to almost 7000 mg/L during the summer. In contrast, removal of all the saline water (16.5 MCM/a) that is artificially discharged into the Lower Jordan River will significantly reduce its Cl concentration, to levels of 650–2600 and 3000–3500 mg/L in the northern and southern areas of the Lower Jordan River, respectively. However, because the removal of either the sewage effluents or the saline water will decrease the river's discharge to a level that could potentially cause river desiccation during the summer months, other water sources must be allocated to preserve in-stream flow needs and hence the river's ecosystem.

1. Introduction

Management of cross-boundary rivers requires full cooperation between the riparian states. In many cases, the upstream country controls the river's flow rate (e.g., Euphrates, Nile, Colorado, Rio Grande, Danube and Mekong) and thus many conflicts arise due to uneven distribution or unilateral changes in water utilization. In addition to water quantity distribution, water quality has become an important factor determining the ability to utilize the river

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[*] Corresponding author.
E-mail address: avnerv@bgu.ac.il (A. Vengosh).

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water. This is due to the fact that the quality of many international rivers has deteriorated significantly over the last decades (Shmueli, 1999).

The problems involved in applying international treaties for international rivers include heterogeneities in drinking-water standards (e.g., the Danube River; Linnerooth, 1990), water laws, and management systems (e.g., the Rio Grande River; Schmandt, 2002) among the riparian states. The joint management of an international river requires a comprehensive scientific understanding of the processes that are controlling the degradation of the river's quality. In this paper, the Lower Jordan River system is used to demonstrate that scientific understanding of the hydrological system is the key for sustainable joint management between the riparian states.

The Lower Jordan River marks the international border between Israel and the West Bank on the west and the Hashemite Kingdom of Jordan on the east. Decades of diversion of upstream good-quality water and direct dumping of saline water and wastewater have severely damaged the river's ecological system. The salinity of the Lower Jordan River has risen significantly (up to 5400 mg Cl/L in summer 2001; Farber et al., 2004), endangering its capability to supply water, even to saline-resistant crops such as palms, which are one of the main agricultural products of the Jordan Valley. At the same time, the Jordan River is an important component of the Peace Treaty between Israel and Jordan (Israel–Jordan Peace Treaty, Annex II, 2004). The water issue is an essential aspect of the treaty and received the same level of attention as security and territorial issues. Concerning the Jordan River, it was agreed that (1) Jordan is entitled to an annual quantity equivalent to that of Israel, provided, however, that Jordan's use will not harm the quantity or quality of Israeli uses (Annex II, article 2); (2) Saline springs currently diverted to the Jordan River are earmarked for desalinization (Annex II, article 3); and (3) Israel and Jordan will each prohibit the disposal of municipal and industrial wastewater into the course of the Yarmouk River or the Jordan River before they are treated to standards allowing their unrestricted agricultural use (Annex II, article 3).

Although the peace treaty was signed a decade ago, none of the above items have been implemented. However, future development in the region will require dealing with these issues. The complexity of the hydrological system and the severe degradation of the water quality make future management schemes even more difficult to design. In this paper, the authors use their understanding of the hydrological and geochemical system of the Lower Jordan River (Farber et al., 2004; Holtzman et al., 2005) to show that implementation of the treaty is likely to lead to further degradation in water quantity and quality of the Lower Jordan River water. The relationships between surface inflows and groundwater discharge to the river are used in order to quantify the salt budget and hence the salinity of the Jordan River. Different management scenarios that are related to the implementation of the peace treaty are then simulated for prediction of the river flow rate and salinity.

2. The hydrological system of the Lower Jordan River

The total length of the Jordan River, from its origins in the Hermon Mountains in the north to its mouth at the Dead Sea, is approximately 250 km (aerial distance), but its meandering course increases its length to 330 km (Tahal, 2000). The River is located in a semiarid area and can be divided into two sections: the Upper Jordan River, from the Hermon Mountains, to the Sea of Galilee (Lake Tiberias), and the Lower Jordan River, from the Sea of Galilee to the Dead Sea. The latter section also marks most of the border between Israel, the West Bank and Kingdom of Jordan (Fig. 1). While the Upper Jordan River is a major source of high quality drinking water, the water that discharged from the Sea of Galilee into the Lower Jordan River were historically more saline and therefore of lower quality (Nissenbaum, 1969). The construction of two dams at the outlet of the Sea of Galilee has resulted in further deterioration of the water quality and quantity in the Lower Jordan River. Currently, there is no input of water from the Sea of Galilee to the Lower Jordan River Water. Water quantity has decreased from the historical volumetric discharge estimated around 1300 MCM/a (Salameh and Naser, 1999) to a recently measured and estimated base flow of 30–200 MCM/a (Holtzman et al., 2005 and Tahal, 2000, respectively) with rare high discharge ($\sim$600 m^3/s) flood events. Holtzman et al. (2005) measured the discharge under drought conditions (i.e., only base flow) while Tahal (2000) estimated the discharge including floods, which occur mostly during very rainy winters, when the dams over the Sea of Galilee and/or on the Yarmouk River are opened. The historical contributors included outlet from the Sea of Galilee (540 MCM/a),

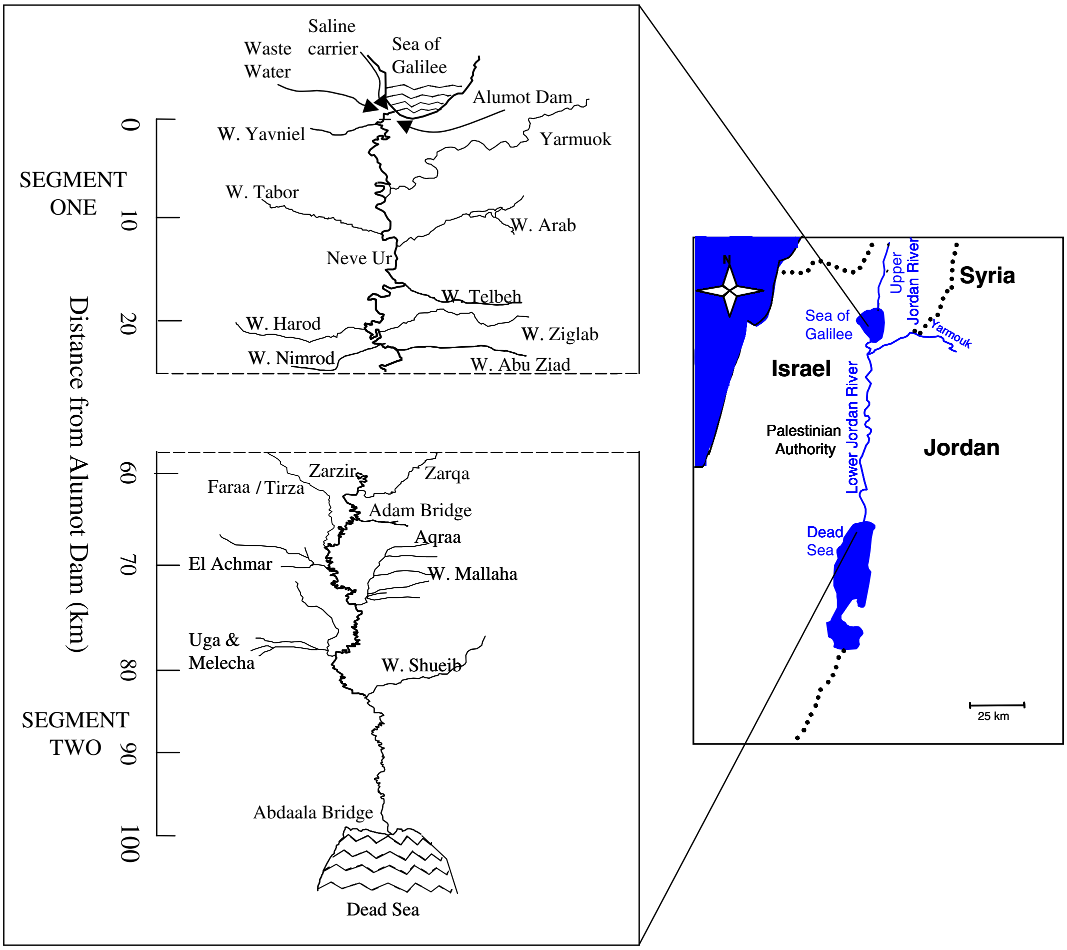

Fig. 1. Schematic map of the Lower Jordan River.

the Yarmouk River (480 MCM/a), local streams, and floods (Hof, 1998). Following the construction of water projects in Israel, Jordan and Syria, both the Sea of Galilee and the Yarmouk River have been dammed and no fresh surface water flows into the Lower Jordan River except for negligible contributions to the river's base flow and the above mentioned flood events. The base flow thus consists primarily of sewage effluents and diverted saline springs (see Section 4.1 for more details). Farber et al. (2004) identified 3 sections along the Lower Jordan River in terms of chemical composition (Fig. 2): (1) a northern section (up to 22 km downstream from the Sea of Galilee) in which the initial high Cl concentrations decrease and SO_4 concentrations increase downstream; (2) a central section (22–66 km) in which the variation in chemical composition is less significant and mimics the upstream composition; and (3) a southern section (66–100 km) in which the Cl and SO_4 concentrations increase downstream (Fig. 2). In this paper, the northern and the central sections will be combined and will be referred to a new division (Fig. 1): a northern segment ("Segment One", up to 66 km downstream from the Sea of Galilee) and a southern segment ("Segment Two"; from 66 to 100 km downstream from the Sea of Galilee).

3. Methodology

As shown in Farber et al. (2004) and Holtzman et al. (2005), the water balance of the Lower Jordan River is controlled by groundwater flow along different parts of the river. Hence, a mass balance equation of the water in the river can be given as

$$Q^{\mathrm{fi}} = Q^{\mathrm{in}} + \sum_{i=1}^{n} Q_i^{\mathrm{sw}} + \sum_{i=1}^{n} Q_i^{\mathrm{gw}}, \qquad (1)$$

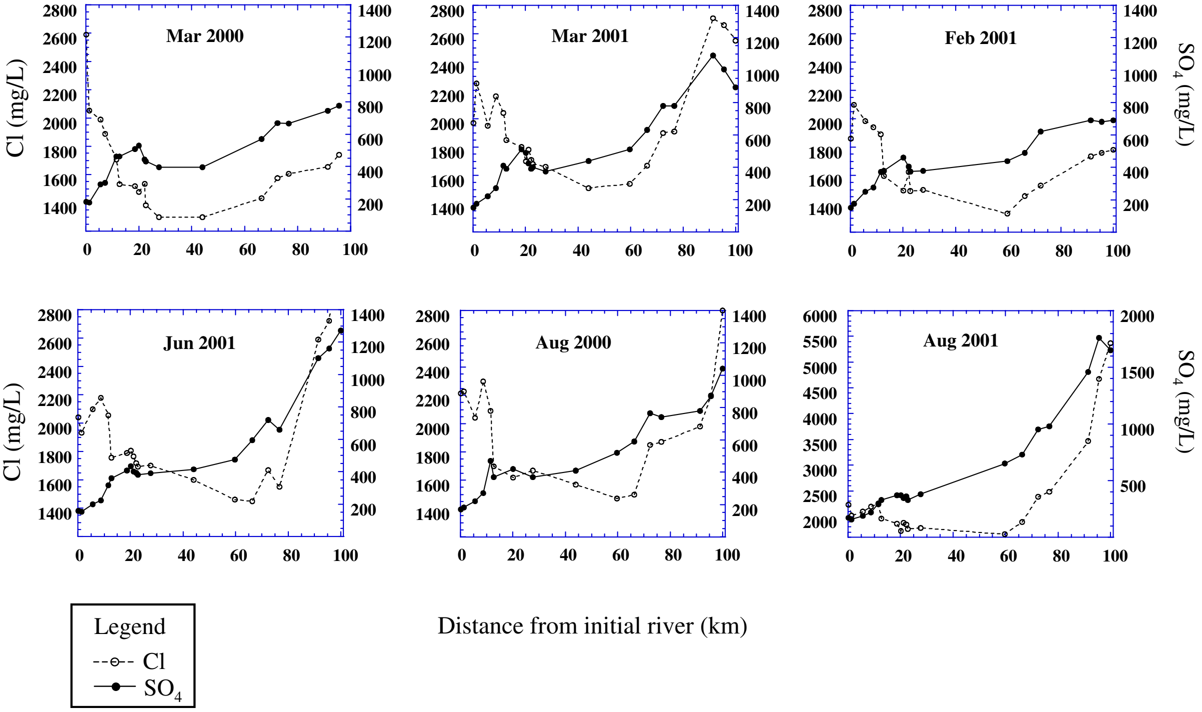

Fig. 2. The variation of Cl and SO_4 contents (in mg/L) with aerial distance along the Lower Jordan River as recorded during separate months. Note that the *y*-axis range was increased for the August 2001 results to include the high salinity peak.

where Q^{fi} is the total water discharge (L/s) at the end point of an investigated section, Q^{in} is the water discharge at the initial point of an investigated section, $\sum_{i=1}^{n} Q_i^{\mathrm{sw}}$ is the total discharge of several (n) surface water sources along the section, and $\sum_{i=1}^{n} Q_i^{\mathrm{gw}}$ is the total discharge of several (n) groundwater sources along the section. For the solute mass balance, the conservation of mass of that solute is added

$$C^{\mathrm{fi}}Q^{\mathrm{fi}} = C^{\mathrm{in}}Q^{\mathrm{in}} + \sum_{i=1}^{n} C_i^{\mathrm{sw}}Q_i^{\mathrm{sw}} + \sum_{i=1}^{n} C_i^{\mathrm{gw}}Q_i^{\mathrm{gw}}. \tag{2}$$

According to Eqs. (1) and (2), if one quantifies the groundwater flows into the river, it is possible to calculate the salinity of the river at any point along the river, following:

$$C^{\mathrm{fi}} = \frac{C^{\mathrm{in}}Q^{\mathrm{in}} + \sum_{i=1}^{n} C_i^{\mathrm{sw}}Q_i^{\mathrm{sw}} + \sum_{i=1}^{n} C_i^{\mathrm{gw}}Q_i^{\mathrm{gw}}}{Q^{\mathrm{in}} + \sum_{i=1}^{n} Q_i^{\mathrm{sw}} + \sum_{i=1}^{n} Q_i^{\mathrm{gw}}}. \tag{3}$$

Farber et al. (2004) and Holtzman et al. (2005) found that the contribution of the surface water and its solutes to the river water is negligible. Therefore, Eq. (3) can be reduced to the following form:

$$C^{\mathrm{fi}} = \frac{C^{\mathrm{in}}Q^{\mathrm{in}} + \sum_{i=1}^{n} C_i^{\mathrm{gw}}Q_i^{\mathrm{gw}}}{Q^{\mathrm{in}} + \sum_{i=1}^{n} Q_i^{\mathrm{gw}}}. \tag{4}$$

If, however, the flow rates are unknown, it is still possible to determine the relative mass contribution of the groundwater sources into the river. In a system where the groundwater contribution is homogeneous (i.e., a single groundwater source) the solute mass balance will be

$$C^{\mathrm{fi}} = C^{\mathrm{gw}}f^{\mathrm{gw}} + C^{\mathrm{in}}(1 - f^{\mathrm{gw}}) \tag{5}$$

and the relative contribution, f^{gw}, is defined as

$$f^{\mathrm{gw}} = \frac{(C^{\mathrm{fi}} - C^{\mathrm{in}})}{(C^{\mathrm{gw}} - C^{\mathrm{in}})}. \tag{6}$$

In the two segments of the Jordan River the groundwater flow and the salt mass-balance in the river under the current hydrological conditions are quantified. In the northern segment of the river the solute mass balance is used to determine the relative contribution of the groundwater salt flux (Eqs. (5) and (6)). In the southern segment of the river actual flow measurements and water quality in the river are used to quantify the relationships between river water and groundwater, and possible changes of the river salinity upon changing the parameters of river flow (Eqs. (4)).

4. Results and discussion

4.1. The northern segment of the Lower Jordan River

4.1.1. Current situation

The northern segment of the Lower Jordan River extends from Alumot Dam to Adam Bridge (Segment One- the upper 66 km; Fig. 1). The downstream side of the Alumot dam is the headwaters of the Lower Jordan River. The dam separates the Sea of Galilee from the headwaters of the Lower Jordan River (Fig. 3).

The base flow of the river begins at Alumot Dam and is composed of two principle components (Fig. 3): (1) *saline springs* that emerge along the western shore of the Sea of Galilee and are diverted to the Lower Jordan River via the so called "Saline Water Carrier" (SWC). This carrier is an artificial conduit, built to lower the natural salinity of the Sea of Galilee by draining the waters of several saline springs along the western shore of the Sea of Galilee to Alumot Dam. The saline water in the SWC is derived primarily from the Tabgha Springs and Tiberias Hot Springs (THS). (2) *Sewage effluents* derived from the municipal sewage water of Tiberias (drained directly into the SWC) and from regional agricultural and municipal sewage that is treated and drained through a separate pipeline ("Bitaniya" sewage; Fig. 3). The current average discharge of this combined base-flow is approximately 30 MCM/a (Holtzman, 2003; Fig. 3). Mixing between these two sources occurs at the initial point of the Lower Jordan River, at downstream of Alumot Dam.

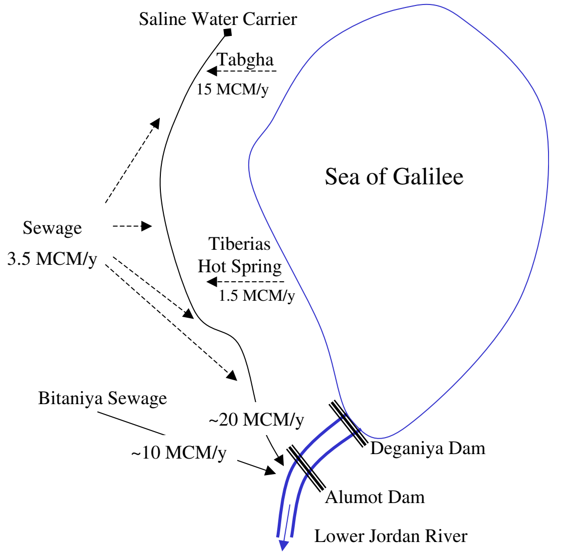

Fig. 3. Schematic map and annual discharge (MCM/a) of Bitaniya sewage and the Saline Water Carrier (data information from El-Ezra, Personel communication. Mekorot, Jordan Area, Personal communication).

The relative proportions of salt contents from the respective sources contributing to the river water at the beginning of the Lower Jordan River were determined using mixing Eqs. (5) and (6). Whereas the annual discharge of the Tabgha Springs is larger by an order of magnitude than that of THS (15 MCM/a versus 1.5 MCM/a), the salinity of THS ($Cl = 18$ g/L) is much higher (Tabgha Springs, $Cl = 3$ g/L). Consequently, the chemical composition of the mixed water in the SWC is mainly controlled by the higher saline component of the THS, although some contribution of Tabgha Springs is also identified (Fig. 4(a)). Given that the saline THS dominates the chemical composition of the water at the initial point of the Lower Jordan River, the salt contribution of the Tabgha Springs cannot be evaluated by using the chemical variations, and thus is neglected in the following calculations.

A salt mass-balance (Eq. (5)) between the Cl contents in the sewage and the saline (THS) components reveals that the saline water contribution to the initial base flow of the Jordan River varies from 6% to 10% of the total salt budget (Table 1). Here, the "*f*" value (Eq. (6)) refers to the relative salt contribution of the saline component. The variations of other dissolved constituents normalized to Cl (Na/Cl, SO_4/Cl, Ca/Mg, and Ca/SO_4 molar ratios; Fig. 5) reflect similar mixing relationships between the sewage and the saline components (i.e., about 10% of the salt budget of the initial river at Alumot Dam is derived from the saline component).

The chemical composition of the initial base flow of the Jordan River is changing along the first 22 km downstream from Alumot Dam. Farber et al. (2004) showed that the initial Ca–Cl composition (i.e., low Na/Cl and SO_4/Cl ratios) is gradually modified towards a Mg–Cl water type (higher Na/Cl and SO_4/Cl ratios). Given the unique chemical and isotopic compositions that were monitored along the Jordan River, Farber et al. (2004) suggested that the explanation lay in groundwater discharges into the river. Indeed, water with high Na/Cl and SO_4/Cl ratios was found in the saline Yarmouk River, downstream from Adassiya Dam in Jordan and was suggested to represent the composition of the

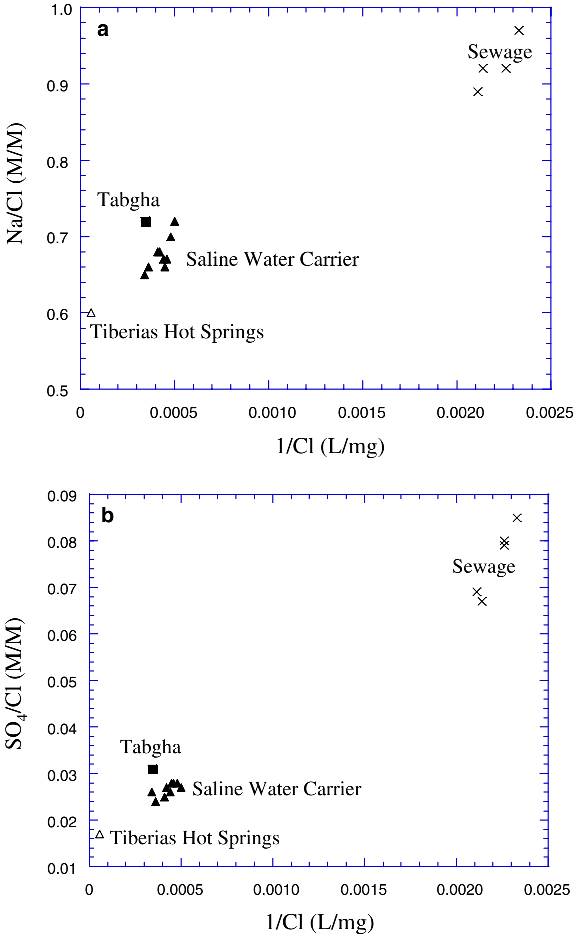

Fig. 4. Na/Cl (a) and SO_4/Cl (b) versus 1/Cl (L/mg) of the saline water springs (i.e., Tabgha and Tiberias Hot Springs) sewage water (as sampled at Bitaniya) and the Saline Water Carrier (SWC; as sampled below the Alumot Dam). Note that the salt content of the SWC is controlled by the chemical composition of the Tiberias Hot Springs and not the Tabgha Springs.

discharging groundwater. Holtzman et al. (2005) measured the flow rates in this river section and showed a significant contribution of groundwater flux to the Jordan River (i.e., a range of 20–80% of the river's measured discharge).

Following Eq. (5), the "*f*" value is defined as the relative contribution of the Mg–Cl groundwater, C^{in} as the SO_4 content in the initial base flow at Alumot Dam, C^{gw} as the SO_4 content in the saline Yarmouk River (represents the Mg–Cl groundwater in the area), and C^{fi} as the SO_4 content measured in different sites along Segment One of the Lower Jordan River. Table 2 presents the *f* (%) values of the Mg–Cl groundwater and Fig. 6(a) illustrates the variations of this value during two years of water quality monitoring. The results show an increase in the contribution of the Mg–Cl groundwater, particularly in the spring months (Fig. 6(a)). Since it is assumed that the groundwater chemical composition is constant during the year, the variations in the groundwater salt contribution indicate different rates of groundwater discharge to the river.

The variations in groundwater discharge could be the result of: (1) more irrigation of seasonal crops, which enhances agricultural return flows; and (2) more recharge in the winter months that resulted in increasing groundwater discharge. Fig. 6(b) presents the monthly flow volumes measured during 1990–2000 in Naharaim Hydrometric station, adjacent to the confluence of the Yarmouk and the Jordan Rivers (data from Israeli Hydrological Service, 2002). The increased flow rate during the winter months suggests that the overall discharge of surface and groundwater is seasonally controlled (i.e., option #2).

Given that the water quality in the northern segment (Segment One) of the Jordan River is controlled by 3 water components of (1) the saline end-member; (2) the sewage end-member derived from anthropogenic dumping into the river; and (3) shallow groundwater with Mg–Cl composition, in the following section the relative contributions of these 3 end-members is quantified.

Fig. 7 plots the calculated compositions (SO_4 and Cl) attained by mixing the 3 end-members and presents the relative contribution (%) of the shallow groundwater to the overall salt balance along Segment One. The 3 lines that connect the data points of the end-members' (forming a triangle) therefore describe the theoretical lines of mixing between the 3 end-members. The data points representing the initial river base flow (as sampled at Alumot Dam) lie on the line between the saline and sewage end-members. Downstream from Alumot Dam, the river data points plot towards the shallow groundwater end-member ("Mg–Cl"; Fig. 7). The data show differences in the relative contribution of the shallow groundwater; about 45% during September 1999 (Fig. 7(a)) and about 80% during December 2000 (Fig. 7(b)).

4.1.2. Future prediction and management

The current hydrological situation described above (i.e., mixture of 3 water sources) is used for predicting future scenarios. In the following discussion, possible changes in the river salinity that may be induced by changes in the relative contribution of the different water sources of the Jordan River are evaluated.

Table 1
Calculation of the mixing proportions (*f*) between the saline component (as sampled at Tiberias Hot Springs) and sewage component (average of samples from Bitaniya sewage) that composed the initial base flow of the Jordan River at Alumot Dam (in separate months)

Name	Date		Ca	Mg	Na	Cl	SO_4
Tiberias Hot Springs (THS)	Moise et al. (2000)	mg/L	3523	680	7042	18081	827
Bitaniya sewage	Average	mg/L	91	61	271	451	93
Alumot dam	01/02/01	mg/L	347	98	850	1860	150
THS		*f* (%)	7	6	9	8	8
Bitaniya sewage		*f* (%)	93	94	91	92	92
Alumot dam	01/03/01	mg/L	359	97	855	1970	150
THS		*f* (%)	8	6	9	9	8
Bitaniya sewage		*f* (%)	92	94	91	91	92
Alumot dam	01/04/01	mg/L	378	105	930	2070	160
THS		*f* (%)	8	7	10	9	9
Bitaniya sewage		*f* (%)	92	93	90	91	91
Alumot dam	01/06/01	mg/L	363	104	950	2040	158
THS		*f* (%)	8	7	10	9	9
Bitaniya sewage		*f* (%)	92	93	90	91	91

Calculations were made for different major elements.

Several major management scenarios are considered (Table 3): (1) desalination of the SWC and removal of all of the saline source from the SWC and the Lower Jordan River; (2) eliminating sewage dumping into the river; (3) differential removal of one of the saline sources from the SWC (i.e., Tabgha Springs or THS); and (4) eliminating both saline sources and sewage dumping into the river.

According to Holtzman et al. (2005), the groundwater flux to the river varies from 20% to 80% of the river flow rate. These values will be used as upper and lower constraints for the groundwater influence on river salinity.

Fig. 8(a) illustrates the mixing combination between different end-members that include sewage, Mg–Cl groundwater, and the two saline water sources: Tabgha Springs (marked as "T") and THS (data from Moise et al., 2000). Line A represents the mixing between sewage water and the saline THS. Line B represents the mixing between the sewage water and Tabgha Springs (T), line C represents the mixing between THS and the Mg–Cl groundwater as sampled at Yarmouk River, and line D represents the mixing between Tabgha Springs and the Mg–Cl groundwater.

Fig. 8(b) focuses on the gray zone in Fig. 8(a) and demonstrates the changes in the river salinity due to the following scenarios (arrows 2–6 in Fig. 8 and Table 3):

- All the saline water is removed such that the base flow at Alumot Dam is composed only of sewage effluents with low salinity. Although the downstream river salinity (arrow 2 in Fig. 8(b)) is expected to increase given the input of the saline groundwater, in this scenario the overall salinity will be significantly lower than that of the current situation.
- All sewage effluent is removed such that the initial river base flow at Alumot Dam will be solely composed of the saline sources. The downstream river salinity will evolve along arrow 3 (Fig. 8(b)). This is the only scenario in which the river salinity becomes much higher than it is at present. If, however, the sewage effluents are adequately treated and returned to the river, no major change in the river salinity will take place.
- The THS is selectively removed. The overall salinity of the base flow will be lower than today but the downstream river salinity will evolve to values similar to the current situation (arrow 4 in Fig. 8(b)).
- The Tabgha Springs is selectively removed. The volume of the base flow will significantly decrease but its salinity and the salinity of the downstream river (arrow 5 in Fig. 8(b)) will be only slightly lower than the current situation.
- The Tabgha Springs are desalinized at an efficiency of 50%, and the reject brine (i.e., 50% of the initial volume with twice the original salinity) is diverted into the Lower Jordan River. The salinities of the base flow and downstream river are expected to be slightly higher than the current situation (arrow 6 in Fig. 8(b)).
- All the current inputs that make up the base flow of the Jordan River (sewage effluents and saline springs in SWC) are eliminated. The downstream river salinity will therefore be controlled only by

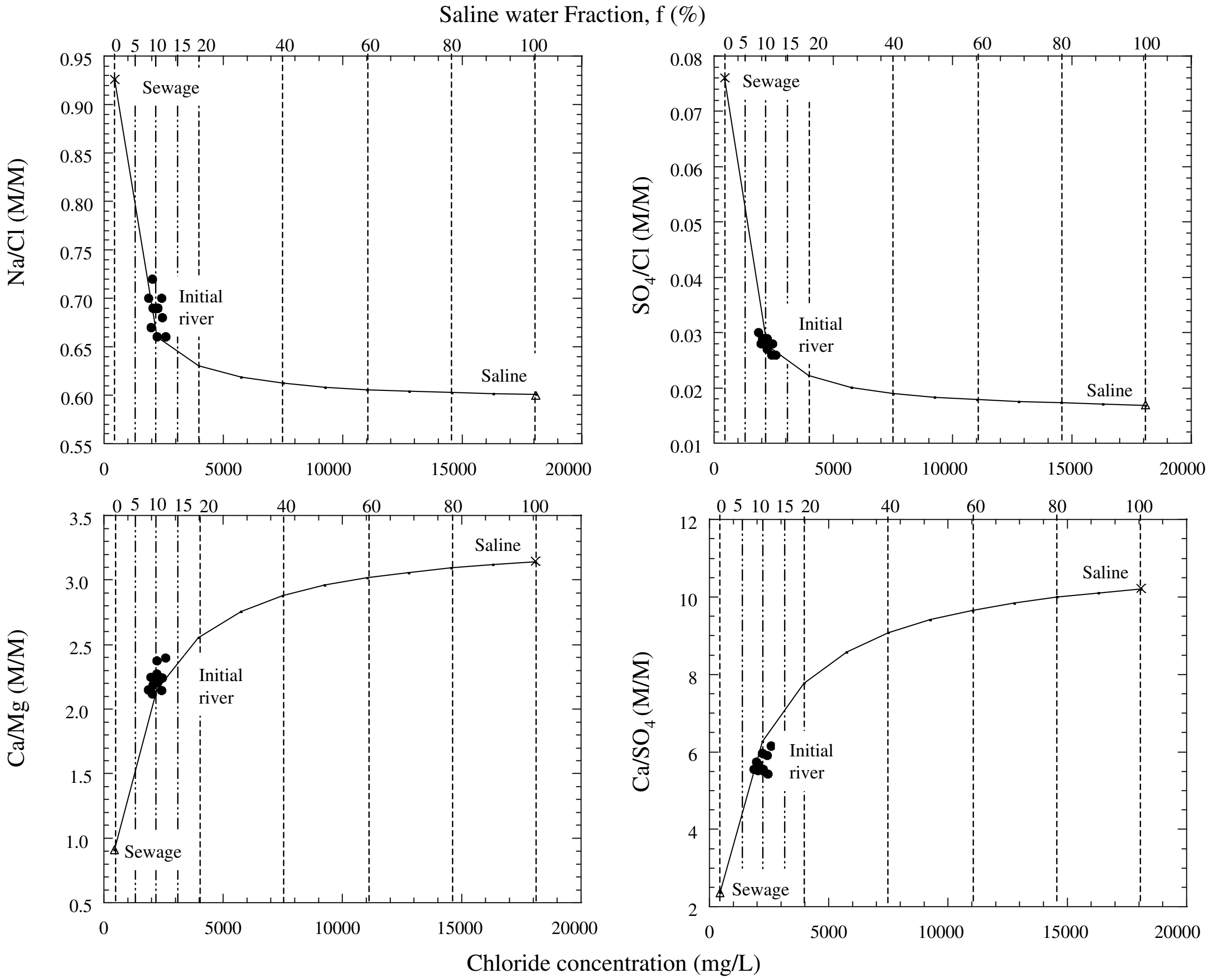

Fig. 5. Na/Cl, SO_4/Cl, Ca/Mg and Ca/SO_4 ratios versus Cl concentration (mg/L) of the origin of the water river, as sampled from below of Alumot Dam at different times. The measured data are compared to calculated mixing lines between sewage water (as sampled at Bitaniya) and the saline water end member (as sampled at Tiberias Hot Springs). Note that the river composition at Alumot Dam is determined by the mixing relationship between the sewage component (~90%) and the saline component (~10%).

Table 2
The contribution of Mg–chloride groundwater (as sampled at the Yarmouk River) to the river flow along the northern section

Date	Sampling location	Distance from Alumot (km)	Yarmouk fraction (%)
01/09/99	Sheich Hussein Bridge	22.7	48
01/03/00	Hamadiya South	20.1	87
01/05/00	Neve Ur South	12.7	58
01/08/00	Neve Ur North	11.6	44
01/12/00	Hamadiya South	20.1	82
01/02/01	Hamadiya South	20.1	85
01/03/01	Hamadiya North	18.6	51
01/04/01	Hamadiya North	18.6	50
01/06/01	Hamadiya South	20.1	30
01/08/01	Shif'a Station	27.7	9

The calculated results shown here (and in Fig. 6(a)) were obtained using Cl concentration.

the groundwater discharge. The gradual discharge of groundwater into the river will be most pronounced under this scenario, as the flow rate will increase down stream. The composition of the river will not change along the river and will be the Mg–Cl of the discharging groundwater. It is expected that after 12 km, the salinity of the river will be about 1150 mg Cl/L with a maximum flow rate of 24 MCM/a (assuming 80% groundwater discharging).

Overall, it seems that removal of the saline water is the preferred management scenario to have optimal effects on the river's ecology, whereas removal of the sewage effluents will have detrimental effects in term of the river salinity.

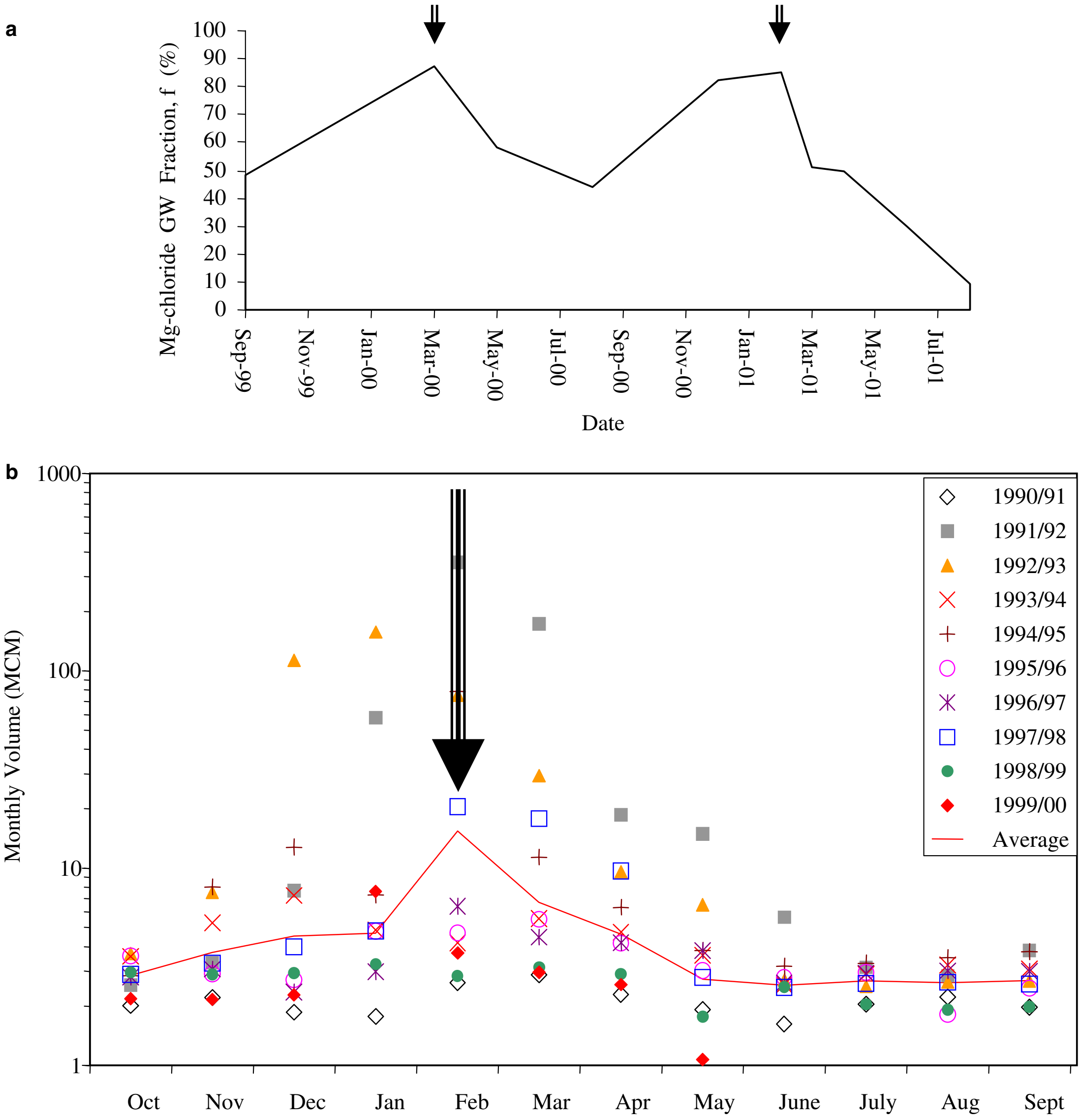

Fig. 6. (a) Mg–Cl groundwater (GW; as sampled at Yarmouk River) contribution to the Lower Jordan River's chemical composition along the northern section of the river, and (b) monthly flow volumes at the Naharaim hydrometric station (in the Yarmouk River), from 1990–2000 (Israeli Hydrological Service, 2002). Note the correspondence between the increases in the discharge of surface and groundwater during the fall and winter months, marked as arrows.

4.2. *The southern segment of the Lower Jordan River*

4.2.1. *Current situation*

The southern segment (Segment Two; 66–100 km from Alumot Dam; Fig. 1) of the Lower Jordan River is characterized by a downstream increase in salinity (Fig. 2). Historical data (Bentor, 1961; Neev and Emery, 1967) indicate that the Cl concentration of the most southern point of the Lower Jordan River at Abdalla Bridge was ~400 mg/L in 1925 and 1947. The present river Cl concentration is in the range of 1500–2500 mg/L during most of the year, but can reach up to 5400 mg/L at its most southern point during the summer months (Farber et al., 2004).

Until the 1950s, the estimated Jordan River discharge to the Dead Sea was approximately 1300 MCM/a (Klein, 1995, 1998; Hof, 1998). The current discharge is only 30–200 MCM/a (Holtzman et al., 2005; Tahal, 2000). The significantly reduced flow

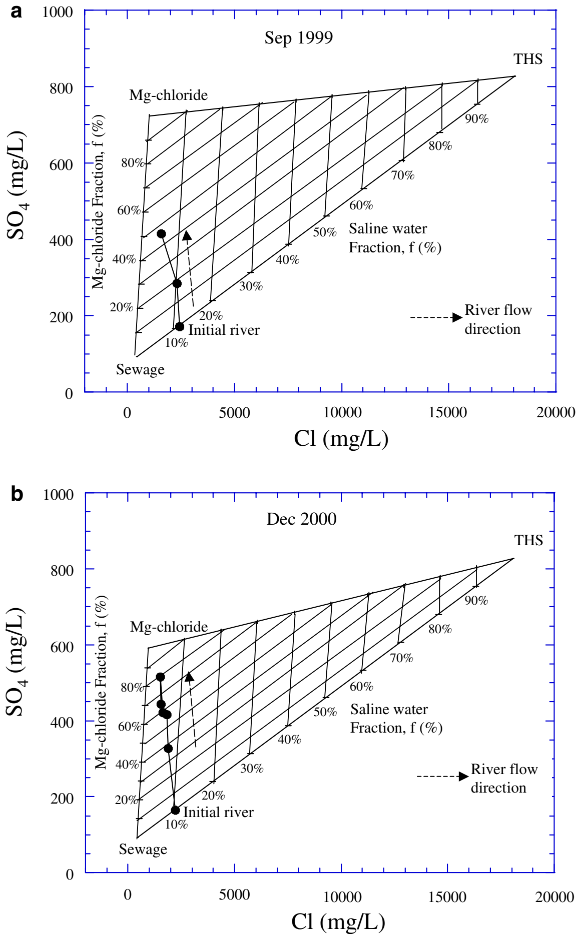

Fig. 7. Sulfate and Cl concentrations of river samples and an interpretation of the mixing processes occurring among the 3 end members (i.e., saline spring – as sampled at the Tiberias Hot Springs (THS), sewage – an average of Bitaniya water samples, Mg–chloride groundwater – as sampled at the Yarmouk River, and river water from the initial 20 km as sampled during September 1999 (a) and December 2000 (b)). Note that as the downstream distance from the lower river's origin increases, the river concentrations move towards the data point representing the shallow groundwater end member ("Mg–chloride"). The groundwater contribution to the water flow of the river varies in time (i.e., in December 2000 the groundwater discharge constituted ~80% of the river flow while in September 1999 it was only ~45%).

of the Lower Jordan River has resulted in lowering the Dead Sea water level by over 20 m in the last 50a (Gavrieli and Oren, 2004; Hassan and Klein, 2002).

To predict the water quality of the southern part of the Lower Jordan River under different water-management scenarios, the current hydrological situation must first be determined. Farber et al. (2004) investigated the chemical and isotopic compositions of river water in the southern section of the Lower Jordan River and the associated inflows and groundwater. The geochemical data indicated that the river's quality is largely controlled by non-point discharge of saline groundwater sources. It was demonstrated that the groundwater itself is a mixture of two end-members: (1) SO_4-rich saline groundwater; and (2) Ca–Cl Rift Valley brines. The SO_4-rich groundwater is characterized by high Na/Cl (0.81–1.0), SO_4/Cl (0.25–0.50), and low Br/Cl ($1–4 \times 10^{-3}$) molar ratios. In contrast, the brines have low Na/Cl (0.55–0.69), SO_4/Cl (0.02–0.04), and high Br/Cl ($5–9 \times 10^{-3}$) ratios. Farber et al. (2004) recognized seasonal variations in the intensity and locations of salinization of the Jordan River water. These variations are related to the differential contribution of the two end-member groundwater sources. It was shown that the SO_4-rich groundwater contribution predominates during the spring months in a particular river section A (70–80 km from the river's origin at Alumot Dam; Fig. 9), while the Ca–Cl brine source affects section B (>75 km; Fig. 9) mostly during the summer months. Farber et al. (2004) estimated Cl concentrations of ~9000 mg/L for the SO_4-rich groundwater that discharge to the river in section A and 18,700 mg/L for the brines that discharge to the river in section B.

The distinction of these two sections allows quantification of the groundwater discharge by assuming that: (1) groundwater contribution has a distinct discharge Q^{gw} and concentration C^{gw} in the two sections; (2) no sinks or additional sources exist in the two sections.

The chemical variations of the river are used to define the two sections during the spring (June) and summer (August) months. Section A and B are affected by the SO_4-rich groundwater and brines, respectively. In the spring (June) section A lies between Zarzir site (59.7 km downstream from Alumot Dam; Fig. 9) and the Baptism site (95.6 km; 35.9 km long section), and section B lies between the Baptism site and Abdalla Bridge (100 km; 4.4 km long section). In the summer (August), section A lies between the Zarzir and Gilgal sites (76.6 km; 16.9 km long section) and section B between Gilgal and Abdalla Bridge (23.4 km long section).

Following Eqs. (1) and (2) solute mass balances were conducted for the specific sections. For section A the solute mass-balance during the spring (June 2001) is

$$C^{bp}Q^{bp} = C^{zr}Q^{zr} + Q_1^{gw}C_1^{gw}, \qquad (7)$$

Table 3
Combinations of Lower Jordan River water quality (Cl concentration in meq/L and mg/L) and quantity (river discharge in MCM/a) at its origin and 17 km downstream under different management scenarios and with different groundwater (GW) contributions (i.e., 20%, 50% and 80%)

	Cl concentration (meq/L)	Cl concentration (mg/L)	Discharge (MCM/year)	Arrow No. in Fig. 8(b)
Tabgha	85	3000	15	
Tiberias Hot Springs (THS)	508	18,000	1.5	
Total sewage (MNM + Bitaniya)	13	450	13.5	
Total Initial River	73	Up to 2600	30	
Tabgha desalinization	170	6027	1.5	
Groundwater inflow (20%)	32	1150	6	
Groundwater inflow (50%)	32	1150	15	
Groundwater inflow (80%)	32	1150	24	
Initial River				
Present	73	Up to 2600	30	1
Removal of all saline water	13	450	13.5	2
Removal of Tabgha	62	2205	15	5
Tabgha desalinization	72	2552	16.5	6
Removal of THS	51	1792	28.5	4
Removal of sewage	123	4364	16.5	3
After 17 km (contribution of 20% GW)				
Present	67	2360	36	1
Removal of all saline water	19	665	19.5	2
Removal of Tabgha	54	1904	21	5
Tabgha desalinization	61	2178	22.5	6
Removal of THS	47	1680	34.5	4
Removal of sewage	99	3507	22.5	3
After 17 km (contribution of 50% GW)				
Present	60	2118	45	1
Removal of all saline water	23	818	28.5	2
Removal of Tabgha	47	1678	30	5
Tabgha desalinization	53	1885	31.5	6
Removal of THS	44	1571	43.5	4
Removal of sewage	80	2833	31.5	3
After 17 km (contribution of 80% GW)				
Present	55	1957	54	1
Removal of all saline water	25	898	37.5	2
Removal of Tabgha	44	1556	39	5
Tabgha desalinization	49	1721	40.5	6
Removal of THS	42	1499	52.5	4
Removal of sewage	69	2459	40.5	3

The right column correlates to the arrows in Fig. 8(b).

where C^{bp} and C^{zr} are Cl concentrations at the river's initial-point and end-point of section A (i.e., Baptism sites and Zarzir; 2720 and 1460 mg/L, respectively). C_1^{gw} is the we conducted-rich groundwater in section A (8863 mg/L; Farber et al., 2004), Q^{zr} is the actual river-discharge measurement carried out in June 2001 (1200 L/s; Holtzman, 2003), and Q_1^{gw} is the we conducted-rich groundwater discharge in section A. Using this data, the total discharge of river flow at the end-point of section A was calculated (i.e.,Q^{bp} at Baptism Site). This discharge is equal to the total discharges

$$Q^{\mathrm{bp}} = Q^{\mathrm{zr}} + Q_1^{\mathrm{gw}}. \tag{8}$$

For section B the solute mass balance during the spring (June 2001) is

$$C^{\mathrm{ab}}Q^{\mathrm{ab}} = C^{\mathrm{bp}}Q^{\mathrm{bp}} + Q_2^{\mathrm{gw}}C_2^{\mathrm{gw}}, \tag{9}$$

where C^{bp} and C^{ab} are the Cl concentrations at the river's initial-point and end-point of section B (i.e., at Baptism Site and Abdalla Bridge, 2720 and 3440 mg/L, respectively). C_2^{gw} is the brine component in section B (18,790 mg/L; Farber et al., 2004), Q^{bp} is the value that was calculated previously, $Q_2^{\mathrm{gw}}$is the

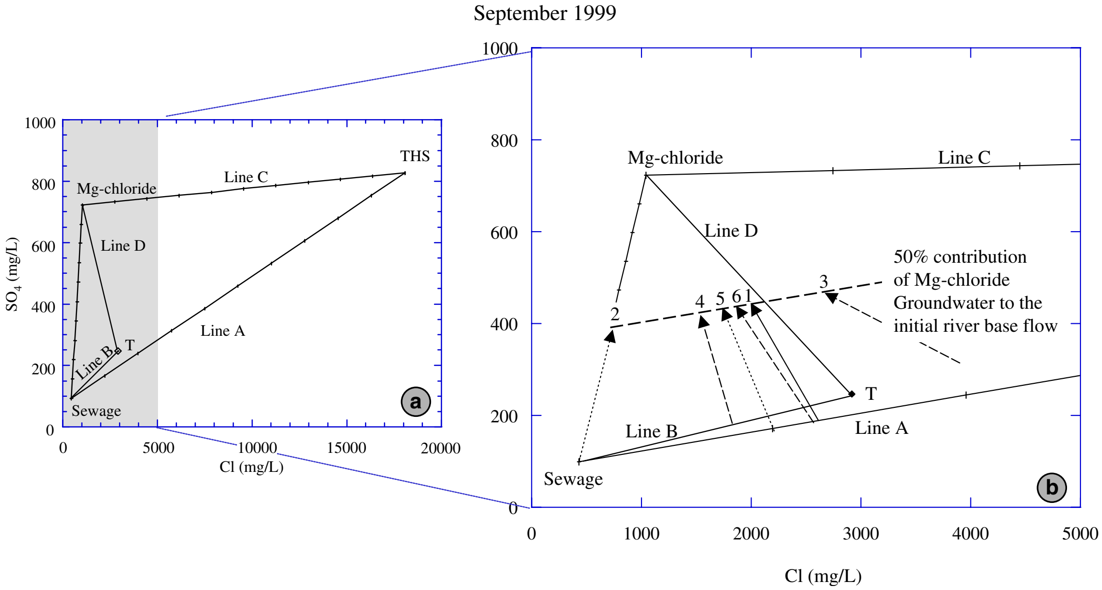

Fig. 8. (a) Mixing processes between different end members that include sewage, Mg–chloride groundwater, and two saline water sources assuming selective removal of one of them. "T" represents the composition of Tabgha Springs. "THS" represents the composition of Tiberias Hot Springs. Line A represents the mixing between sewage water and Tiberias Hot Springs (THS). Line B represents the mixing between sewage water and Tabgha Springs (T). Line C represents the mixing between THS and the Mg–chloride groundwater as sampled at Yarmouk River. Line D represents the mixing between Tabgha Springs and the Mg–Cl groundwater. Figure (b) focuses on the gray zone in figure (a); arrows 1–6 represent the variation trends in the river's chemical compositions currently (1) and as a result of the implementation of different scenarios: removal of all the saline water (2); removal of sewage (3); removal of THS (4); removal of Tabgha (5), and Tabgha desalinization (6). Note that the slope of dashed line is derived from the Holtzman et al. (2005) estimate.

Ca–Cl groundwater discharge in section B. Using this data, the total discharge of river flow at the end-point of section B was calculated (i.e., Q^{ab} at Abdalla Bridge). This discharge is equal to the total discharges

$$Q^{ab} = Q^{bp} + Q_2^{gw}. \tag{10}$$

In the same way the groundwater discharge for sections A and B during the summer was calculated (August 2001), as section A spans from Zarzir to Gilgal and section B from Gilgal to Abdalla Bridge. For these calculations, the actual river-discharge measurements carried out in August 2001 were used (300 L/s; Holtzman, 2003) and the Cl concentrations measured in the river during that period.

The results indicate that groundwater discharge rates in June 2001 were 246 and 68 L/s for sections A and B, respectively. In August 2001 the discharge rates were 39 and 73 L/s for section A and B, respectively. The data indicate that the groundwater flux (i.e., the discharge divided by the length of every section) is not constant around the year and the total flux in June was higher.

Following Eq. (4), the Cl concentration in Abdalla Bridge (i.e., the end-point of the river) can be calculated as follows:

$$C^{ab} = \frac{C^{zr}Q^{zr} + C_1^{gw}Q_1^{gw} + C_2^{gw}Q_2^{gw}}{Q^{zr} + Q_1^{gw} + Q_2^{gw}}, \tag{11}$$

where the indexes 1 and 2 refer to groundwater of sections A and B, respectively. Thus, the salinity in Abdalla Bridge is directly dependent on the relationships between the river flow, (Q^{zr}), the groundwater flow in the two sections (Q_1^{gw} and Q_2^{gw}), and their salinities. Based on Eq. (11) it is possible to evaluate how the salinity in Abdalla Bridge would change under different management scenarios.

4.2.2. Future prediction and management

The different management scenarios considered for Segment One of the Lower Jordan River (from Alumot Dam to Adam Bridge) are also applied to Segment Two. The final point of Segment One (66 km downstream from Alumot Dam) is used as a starting point for Segment Two. The Cl concentration, C^{ab}, at Abdalla Bridge was calculated for two

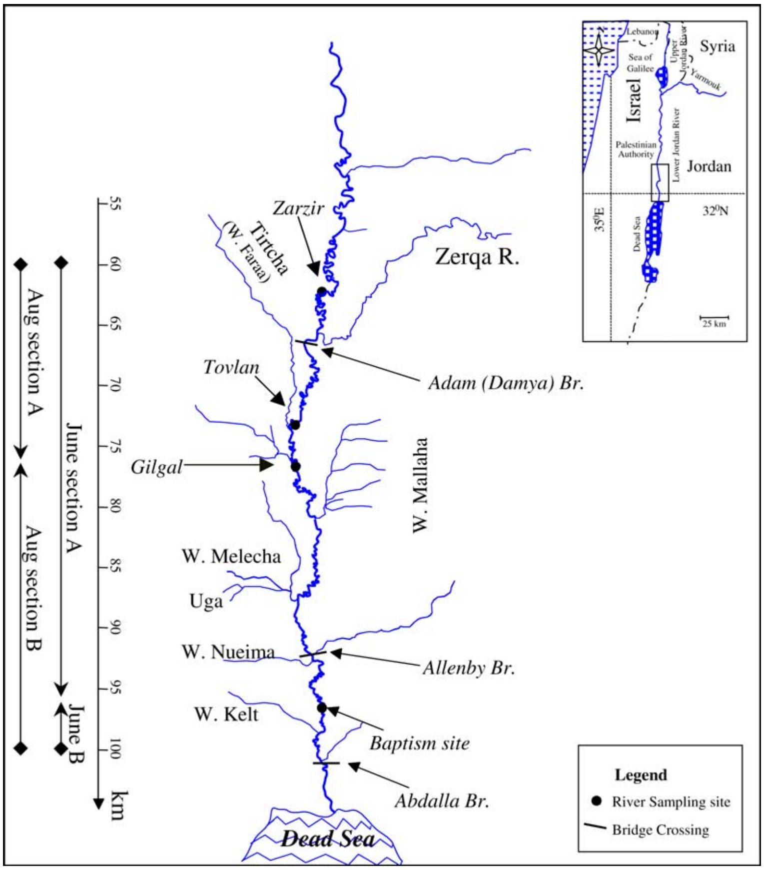

Fig. 9. Detailed map of the southern part of the Lower Jordan River, including river segments for June and August 2001.

different conditions: "August condition" and "June condition". The previously calculated groundwater discharges are used (i.e., 246 L/s in section A and 68 L/s in section B for "June condition"; 39 L/s in section A and 73 L/s in section B for "August condition"). The groundwater Cl concentrations for the SO_4-rich groundwater and for the Ca–Cl groundwater were 8863 and 18,790 mg/L, respectively (Farber et al., 2004). C^{zr} for the starting-point of Segment Two is the same as the Cl concentration of the end-point of Segment One, and varies according to the different management scenarios outlined in the previous section.

Table 4 summarizes the effects of the different scenarios on the salinity and the river discharge at Abdalla Bridge. The results of all but one (removal of THS) of the management scenarios indicate a significant reduction in the discharge flow of the river relative to the present situation (Table 3). Thus, the current ratio between the surface water and groundwater discharge is expected to decrease and the saline groundwater contribution will increase. Consequently, the salinity differences between the upstream river (before groundwater discharge) and downstream river will also increase and the effect of the saline groundwater discharge will be more significant leading to a further salinization of the downstream part of the Lower Jordan River.

The current flow of the Jordan River to the Dead Sea is approximately 30–200 MCM/a (Holtzman et al., 2005; Tahal, 2000). According to Table 3, most of the future management scenarios will cause a reduction of 14–16 MCM/a. Thus, it is predicted that implementation of these management scenarios will cause a further decrease of the river flow to the Dead Sea.

Table 4 summarizes the Cl concentrations of the river under different management scenarios, based on the discharge values measured in June and August 2001. During these two months, the Cl concentration at Abdalla Bridge was 3440 and 5370 mg/L, respectively. According to the "June calculations", removal of all of the saline water from the Lower Jordan River would reduce the Cl concentration

Table 4
Combinations of Lower Jordan River water quality (Cl concentration in mg/L) and quantity (river discharge in L/s) under different management scenarios and groundwater (GW) contributions

June-2001	Q_i (L/s)	C_i (mg/L)	Q_1 (L/s)	C_1 (mg/L)	Q_2 (L/s)	C_2 (mg/L)	Q_3 (L/s)	C_3 (mg/L)	August-2001	Q_i (L/s)	C_i (mg/L)	Q_1 (L/s)	C_1 (mg/L)	Q_2 (L/s)	C_2 (mg/L)	Q_3 (L/s)	C_3 (mg/L)
	1200	1461	246	8863	68	18,790	1514	3439		300	1659	39	8863	73	18,790	412	5371
After 17 km (contribution of 20% GW)																	
Removal of all saline water	1080	674	246	8863	68	18,790	1394	2999	Removal of all saline water	270	674	39	8863	73	18,790	382	4966
Removal of Tabgha	1080	1914	246	8863	68	18,790	1394	3961	Removal of Tabgha	270	1914	39	8863	73	18,790	382	5844
Tabgha desalinization	1080	2163	246	8863	68	18,790	1394	4153	Tabgha desalinization	270	2163	39	8863	73	18,790	382	6019
Removal of Tiberias Hot Springs (THS)	1200	1666	246	8863	68	18,790	1514	3602	Removal of Tiberias Hot Springs (THS)	300	1666	39	8863	73	18,790	412	5376
Removal of sewage	1080	3510	246	8863	68	18,790	1394	5197	Removal of sewage	270	3510	39	8863	73	18,790	382	6972
After 17 km (contribution of 50% GW)																	
Removal of all saline water	1080	815	246	8863	68	18,790	1394	3109	Removal of all saline water	270	815	39	8863	73	18,790	382	5066
Removal of Tabgha	1080	1666	246	8863	68	18,790	1394	3769	Removal of Tabgha	270	1666	39	8863	73	18,790	382	5668
Tabgha desalinization	1080	1879	246	8863	68	18,790	1394	3933	Tabgha desalinization	270	1879	39	8863	73	18,790	382	5818
Removal of THS	1200	1560	246	8863	68	18,790	1514	3518	Removal of THS	300	1560	39	8863	73	18,790	412	5299
Removal of sewage	1080	2836	246	8863	68	18,790	1394	4675	Removal of sewage	270	2836	39	8863	73	18,790	382	6496
After 17 km (contribution of 80% GW)																	
Removal of all saline water	1080	886	246	8863	68	18,790	1394	3164	Removal of all saline water	270	886	39	8863	73	18,790	382	5116
Removal of Tabgha	1080	1560	246	8863	68	18,790	1394	3686	Removal of Tabgha	270	1560	39	8863	73	18,790	382	5593
Tabgha desalinization	1080	1737	246	8863	68	18,790	1394	3823	Tabgha desalinization	270	1737	39	8863	73	18,790	382	5718
Removal of THS	1200	1489	246	8863	68	18,790	1514	3461	Removal of THS	300	1489	39	8863	73	18,790	412	5247
Removal of sewage	1080	2446	246	8863	68	18,790	1394	4373	Removal of sewage	270	2446	39	8863	73	18,790	382	6220

Calculated values are based on June and August 2001 discharge measurements, and the different scenarios refer to the present situation and removal one of the river's initial end-member sources. Q_i is the river discharge at the initial sample site (Zarzir Station), C_i the river Cl concentration at the initial sample site (Zarzir Station), Q_1 the GW discharge at segment 1, C_1 the GW Cl concentration at segment 1, Q_2 the GW discharge at segment 2, C_2 the GW Cl concentration at segment 2, Q_3 the river discharge at the final sample site (Abdalla Bridge), and C_3 the river Cl concentration at the final sample site (Abdalla Bridge).

to 3000 mg/L, whereas removal of the sewage from the lower river's origin would increase the Cl concentration to ~5000 mg/L at Abdalla Bridge. According to the "August calculations", removal of all the saline water from the lower river's origin would reduce the Cl concentration to 5200 mg/L and removal of the sewage from the lower river's origin would increase the Cl concentration to ~7000 mg/L at Abdalla Bridge. Therefore, the ability to utilize the river water in the future depends on the river's management at the initial point of the Lower Jordan River at Alumot Dam. Removal of the upstream saline water would have the most beneficial effect on the river's ecological system, whereas removal of the sewage water would have detrimental effects in term of the river salinity.

5. Conclusions

This paper aims to predict the future salinity variations of the Lower Jordan River under several different management scenarios that are included in the peace treaty between Israel and Jordan. The predictions are based on the authors' understanding of the relationships between shallow groundwater and surface water flow in the Jordan River. For the calculations of the future scenarios, differential removal of the water sources (sewage and saline waters) that composed the initial flow of the Jordan River have been considered. Removal of sewage effluents and saline water are the principal elements that are mentioned in the peace treaty between Israel and Jordan concerning future joint management activities.

While the data on actual discharge flow in the Jordan River is limited (Holtzman et al., 2005), recently published geochemical data (Farber et al., 2004) were used to quantify the relationships between groundwater flux and river flow.

The salinity of the initial river (at Alumot Dam) is currently up to 2600 mg Cl/L, and depends primarily on the relationships between natural saline water and sewage effluents that are dumped into the river. The calculations show that removal of the sewage effluents from the Lower Jordan River will increase its salinity (to ~4400 mg Cl/L), whereas removal of the saline component will reduce it (to ~450 mg Cl/L) at Alumot Dam. Current shallow groundwater discharge to the northern section (Segment One) of the Lower Jordan River buffers river quality and reduces river salinity. The river salinity decreases downstream from 2360 to 2000 mg Cl/L (with 20–80% groundwater contribution, respectively) about 20 km downstream of Alumot Dam. Removal of the sewage component will cause a downstream increase in river salinity (to ~3500 mg Cl/L), whereas removal of the saline component will cause a downstream reduction in salinity (to ~665 mg Cl/L). Our predictions indicate that the northern part (Segment One) of the Lower Jordan River could turn into a low-saline river if the current saline component is removed. In this case, the river will be suitable for almost all types of agricultural applications (but will have limited water for this purpose due to decrease in the river flux). In contrast, the salinity of the Lower Jordan River could increase upon removal of the sewage effluents and thus its suitability for different agricultural crops would be further limited.

The different management scenarios that are applied to the northern area of the Lower Jordan River are also valid to the southern part ("Segment Two"; 66–100 km downstream from Alumot Dam). For this part of the river, we based our estimation on two discharge measurements that were carried out in June and August 2001 at Zarzir Station (66 km downstream from Alumot Dam; Holtzman et al., 2005) and solute mass balance assuming that groundwater discharge is the major source of salinization of the river in this section (Farber et al., 2004). The current salinity of the most southern point of the Lower Jordan River at Abdalla Bridge is 3440 and 5370 mg Cl/L (June and August 2001, respectively). The calculations indicate that removal of the saline component at the initial point of the river in Alumot Dam would cause only a small change in the downstream river's salinity (decrease from 3440 to 3000 mg Cl/L in June and 5370 to 5000 mg Cl/L in August), given the large contribution of the saline groundwater. However, selective removal of the sewage component would cause a significant increase in the downstream river's salinity. Under this scenario, the river salinity at Abdalla Bridge would increase to 5200 mg Cl/L (in June), 7000 mg Cl/L (in August).

Overall, the predictions indicate that the future of the Lower Jordan River depends directly on the different management activities suggested by the peace treaty between Israel and Jordan. Two opposite trends are shown upon elimination of the saline water or sewage effluents from the river. The continuation and possible increase in sewage drainage into the river, combined with elimination of saline water discharge into the river, will significantly reduce river water salinity and will increase its suitability for different agricultural uses. In contrast, selective removal of the sewage component will reduce the surface flow, increase the contribution of the saline groundwater in the southern part of the river, and consequently, will increase the river's salinity. It is concluded that the sewage inflow into the Jordan River is a vital component in maintaining and even reducing the river's salinity. Nonetheless, discharge of sewage effluents might contribute organic contaminants. The authors, therefore, recommend im-proving the treatment of sewage effluents being discharged into the river in order to improve other elements of river quality.

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