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Journal of Marine Systems 47 (2004) 109–120
JOURNAL OF MARINE SYSTEMS
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Groundwater discharge into the Aral Sea after 1960

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Received 7 May 2003; accepted 31 December 2003

Available online 8 March 2004

Abstract

The dramatic shrinkage of the Aral Sea that has occurred after 1960 has affected also groundwater resources in the region, and this effect needs to be clarified and quantified because groundwater is essential for meeting freshwater demands in the area. We determine upper and lower limits for the groundwater discharge into the Aral Sea after 1960, by use of water balance expressions, treating the groundwater as a fitting parameter and considering the uncertainty of the dominant evaporation term in the Aral Sea water balance equation. We also independently analyze, from a pure groundwater hydraulic perspective, the relative effects of the on-going sea surface lowering since 1960 on the hydraulic gradient and thereby also the groundwater discharge into different regions of the Aral Sea. These independent analyses yield consistent results in terms of the total groundwater discharge into the Aral Sea being equal or greater than in 1960, with some relevant scenario results yielding increased groundwater discharge up to about 200% of the 1960 value. In terms of regional groundwater discharge distribution, the present (2002) discharge into the southeast part of Large Aral is not greater than it was 1960; analyses of about 3000 different and relevant parameter combinations show that this prediction is robust with respect to uncertainty in parameter values. The groundwater discharge into the northwest part of Large Aral and into the Small Aral, however, should have increased due to the on-going sea level lowering. Furthermore, for an unchanged absolute groundwater discharge, its relative importance for the Aral Sea(s) has increased dramatically, from being about 12% of the total river discharge in 1960 to about 100% of total river discharge presently, and constitutes now a critical factor for the fate of the present lake system.

Keywords: Aral Sea; Water balance; Salt balance; Groundwater; Discharge; Evaporation; Bathymetry

1. Introduction and objectives

The present state of the Aral Sea and surrounding land constitutes one of the worst environmental disasters seen in the modern world. Changes following the 1960s have lead to desiccation of the Aral Sea, and desertification and pollution of the region at large, accompanied by detrimental changes in its ecosystem. These changes are at least partly due to failed mega-hydrological-agricultural engineering, leading to severe water mismanagement and pollution (Glantz, 1999; Lindahl Kiessling, 1999). Presently, the Aral Sea is reported to continue to shrink and is not expected to come back to its former natural state in the foreseeable future.

Groundwater flow in the region must also have been affected by the dramatic shrinkage of the Aral Sea and these effects need to be clarified and quantified because groundwater is essential for meeting freshwa-

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doi:10.1016/j.jmarsys.2003.12.013

ter demands in the area. From a scientific viewpoint, the large sea level changes and impacts on the water and salt balances of the Aral Sea may also provide useful field data for our general understanding of large-scale, long-term hydrological cause and effect relationships regarding surface and subsurface, freshwater and seawater interactions, and thereby contribute to the further development of modelling tools for both subsurface and surface flow and solute transport within and out from a catchment (e.g., Destouni and Graham, 1997; Destouni and Prieto, 2003; Lindgren et al., 2004; Simic and Destouni, 1999).

The main objectives of this study are (i) to determine limits for the *total* groundwater contribution to the overall water balance of the Aral Sea, during its period of continuous decrease after 1960, and (ii) to obtain robust estimates of the *relative* changes in groundwater discharges during this period, into *different regions* of the Aral Sea. We address objective (i) by use of water balance expressions, treating the groundwater inflow as a fitting parameter, and considering the uncertainty of other dominant parameters to obtain upper and lower limits for the possible groundwater contribution to the present Aral Sea water balance. We address objective (ii), from a pure groundwater hydraulic perspective, quantifying the relative effects of the on-going sea surface lowering since 1960 on the hydraulic gradient and thereby also the groundwater discharge into the Aral Sea. The use of these two different analysis approaches also provides a basis for comparison between totally independent groundwater discharge estimates. If independent estimates are consistent, there can be greater confidence in their validity; if they are inconsistent, this inconsistency can guide the direction and focus of subsequent groundwater studies.

2. Methods

Fig. 1 shows water balance changes and salt content changes in a lake with decreasing volume. Particularly, Fig. 1a illustrates that the water balance equation, applied to a lake that is subject to a volume change ΔV over a time interval Δt, can be expressed as:

$$P + R + \mathrm{GW} - E = \Delta V \quad (1)$$

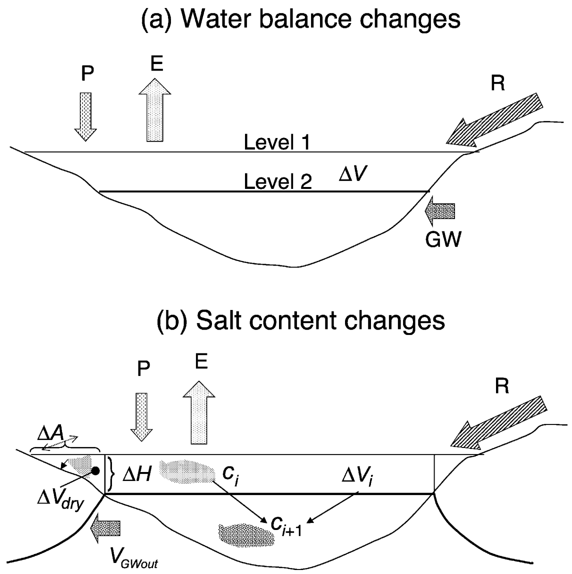

Fig. 1. Illustration of (a) water balance changes, and (b) salt content changes in a lake with decreasing volume.

where P is the cumulative precipitation on the lake, R is the cumulative surface water runoff into the lake, GW is the cumulative groundwater flow into the lake and E is the cumulative evaporation from the lake, which all represent cumulative quantities over the time interval Δt. Eq. (1) implies that GW can be determined once the other parameters are quantified. For the Aral Sea and its basin, there are historical records of R and ΔV. However, P and E can only be estimated indirectly and are therefore subject to uncertainty, with the evaporation E being the dominant quantity of the two, on average a factor of six greater than P in the Aral Sea. In the following, we will therefore consider different scenarios for E, as reported in different studies. Considering the different scenarios, we will then treat the groundwater inflow as a fitting parameter for fulfilling the equality of Eq. (1), and thereby obtain upper and lower limits for the total groundwater discharge into the Aral Sea.

Furthermore, we will estimate the salt content changes that result from the volume reduction of the Aral Sea as quantified by Eq. (1) with the fitted GW term, and compare these with measured data. This exercise provides an independent means of checking the consistency of reported data and scenario assumptions used in the above explained procedure for groundwater discharge estimations. The changing salt contents are illustrated in Fig. 1b and can be estimated through the mass balance equation:

$$c_i = \frac{(V_{i-1} - \Delta V_{\mathrm{dry}} - V_{\mathrm{GWout}})c_{i-1}}{V_i} \quad (2)$$

where V and c denote sea volume and mineral concentration, respectively, with index i and $i-1$ denoting their values at the end and the beginning of a considered time period i, respectively; the extent Δt of time period i and the total sea volume change $\Delta V = V_i - V_{i-1}$ connect the water and salt balance equations (Eqs. (1) and (2)). Furthermore, ΔV_{dry} is the part of total sea water volume change ΔV over the period Δt, which leaves dry sea bottom at the end of the period (the salt contained in this water then stays on the dry sea bottom and does not increase the mineral content of the sea), and V_{GWout} is the possible cumulative groundwater outflow from the Aral Sea over the period, i.e., $V_{\mathrm{GWout}} = \mathrm{GW}$ for $\mathrm{GW} < 0$ and $V_{\mathrm{GWout}} = 0$ for $\mathrm{GW} \geq 0$, with GW given from fitting Eq. (1); this groundwater volume V_{GWout} then carries with it some of the mineral content of the sea. The quantity ΔV_{dry} was estimated roughly as $\Delta V_{\mathrm{dry}} = \Delta A \Delta H/2$ where ΔA and ΔH are the sea area decrease and the sea depth decrease over the period, respectively (see Fig. 1b). Hence, we here consider two main processes that remove salt from the Aral Sea. Direct observations of large salt deposits on exposed sea bottom in the vicinity of the Aral Sea provide evidence of the importance of the first considered process (evaporation-caused salt-depositing on the drying sea bottom). Furthermore, the second process (i.e., salt being transported with outflowing groundwater) is supported by observations of saline groundwater in the vicinity of the Aral Sea; in this context, we note that the increasing salt content and water density of the Aral Sea implies an increased potential for density-driven seawater intrusion into surrounding aquifers.

As an independent, complementary way to estimate changes in groundwater discharge, we consider the possible changes in different regions of the Aral Sea. Specifically, the effects on regional hydraulic gradients and regional groundwater flow of the changed hydrologic conditions caused by the on-going Aral Sea level lowering are illustrated in Fig. 2. We consider aquifers that are well connected hydraulically with the Aral sea,

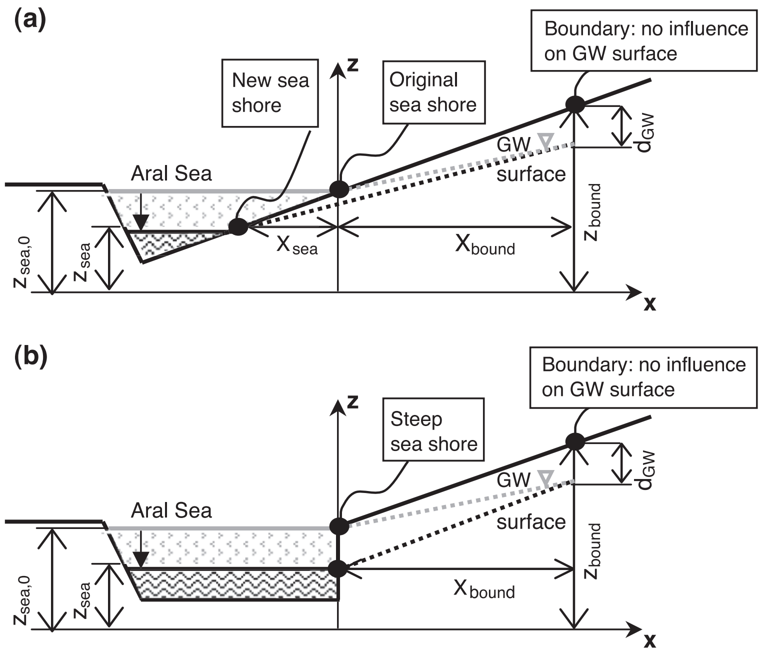

Fig. 2. Effects on regional groundwater (GW) surface slope of the changed hydrologic conditions caused by the on-going Aral Sea level lowering, for (a) shallow shore bathymetry, and (b) steep shore bathymetry.

and assume linear flow conditions and a finite influence zone, with its upstream boundary corresponding to the model boundary, $x = X_{\mathrm{bound}}$, where the groundwater table will be relatively unaffected by sea surface lowerings. The original sea level (with elevation $z = z_{\mathrm{sea},0}$), corresponding to the pre-1960 conditions, is illustrated by the grey line in Fig. 2. The corresponding groundwater table is illustrated by the dashed grey line. The changing, post-1960, sea level is shown by a solid, black line in Fig. 2, and the corresponding groundwater table is shown by a dashed black line. The depth to the groundwater table from the ground surface at the upstream boundary (with elevation $z = z_{\mathrm{bound}}$) is assumed to be d_{GW}, and the groundwater table coincides with the sea level at the sea shore, as also shown in Fig. 2. Fig. 2a illustrates schematically conditions at a location where the shore bathymetry is relatively shallow, with X_{sea} being the sea shore retreat, or the horizontal distance between the original sea shore and the changed (post-1960) sea shore, following the main direction of groundwater flow. Under these conditions, the mean regional hydraulic gradient i_0, corresponding to the conditions of 1960, is:

$$i_0 = \frac{z_{\mathrm{bound}} - d_{\mathrm{GW}} - z_{\mathrm{sea},0}}{X_{\mathrm{bound}}} \qquad (3)$$

Furthermore, the hydraulic gradient i, corresponding to the post-1960 conditions, is:

$$i = \frac{z_{\mathrm{bound}} - d_{\mathrm{GW}} - z_{\mathrm{sea}}}{X_{\mathrm{bound}} + X_{\mathrm{sea}}} \qquad (4)$$

Finally, since the specific groundwater discharge (i.e., groundwater flow per cross-sectional area, also denoted Darcy velocity and bulk velocity) is proportional to the hydraulic gradient through Darcy's law, we have $q/q_0 = i/i_0$, and hence:

$$q/q_0 = \frac{X_{\mathrm{bound}}(z_{\mathrm{bound}} - d_{\mathrm{GW}} - z_{\mathrm{sea}})}{(X_{\mathrm{bound}} + X_{\mathrm{sea}})(z_{\mathrm{bound}} - d_{\mathrm{GW}} - z_{\mathrm{sea},0})} \qquad (5)$$

where q_0 is the specific groundwater discharge for the original (pre-1960) conditions and q is the specific discharge for the changing conditions after 1960.

Fig. 2b shows the limiting case of a very steep shore bathymetry, which is essentially such that $X_{\mathrm{sea}} = 0$ in Eqs. (4) and (5). In this case, the change in hydraulic gradient from the original groundwater table (dashed gray line) to the new groundwater table (dashed black line) is considerably greater than in the case of a shallow shore (Fig. 2a), which shows the importance of shore bathymetry effects on the regional hydraulic gradients and associated groundwater flow. In order to quantify this influence, and the influence of other hydrogeological parameters that in many cases are uncertain, we analyze the effect of about 10,000 plausible parameter value combinations of X_{sea}, X_{bound}, d_{GW} on the value of q/q_0, considering the hydrogeological conditions of different parts of the Aral Sea basin (see further Section 4).

3. Overall water balance changes in the Aral Sea

Considering the Aral Sea, Table 1 shows estimates of the terms ΔV (the sea volume change), R (the cumulative river runoff into the Aral Sea), and P (the cumulative precipitation on the Aral Sea), and their sum. This sum, plus the cumulative groundwater input, must according to the water balance equation (Eq. (1)), correspond to the remaining cumulative net output from the Aral Sea for the same period, i.e., the cumulative evaporation E. By considering different limiting evaporation scenarios that are detailed below, we will use Eq. (1) to delimit the possible magnitude of groundwater discharge during the considered period. In Table 1, ΔV, R and P for the period 1960–1989 are derived from data given by Björklund (1999). Cumulative precipitation is based on average sea area over the considered period and a specific precipitation of 150 mm/year (Björklund, 1999; consistent also with the precipitation magnitude of 150–200 mm/year, given

Table 1
Estimated scenario-independent water balance terms from reported hydrologic data for 1960–1996

Period	Period length, Δt (years)	Sea volume change, ΔV (km^3)	River runoff, R (km^3)	Precipitation, P (km^3)	Sum of ΔV, R and P (km^3)
1960–1965	5	−60	178	49	287
1965–1970	5	−60	160	47	267
1970–1975	5	−130	110	44	284
1975–1980	5	−170	28	41	239
1980–1985	5	−200	0	36	236
1985–1989	4	−130	10	24	164
1990–1996	6	−93	15	26	134

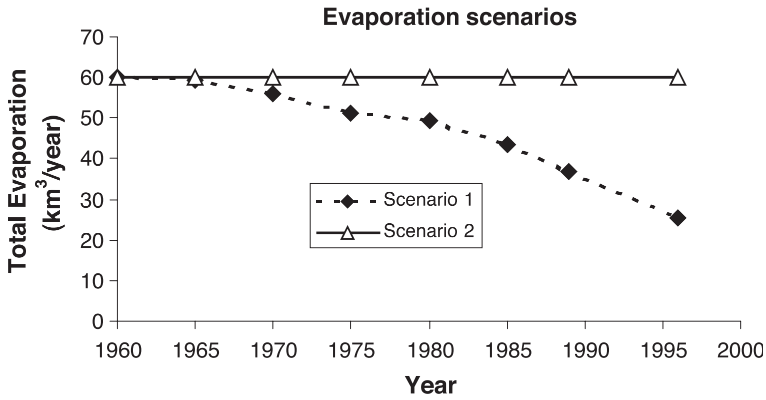

Fig. 3. The two considered evaporation scenarios.

by the Central Asian States, 2000). Data for 1990–1996 are for the Large Aral Sea, as derived from the data given by Björklund (1999) for the end of 1989, implying that its volume was then 310 km^3 and its area 33.5 thousand km^2, with changes in these quantities until 1997 being derived from the relative changes in sea area and volume reported by the Central Asian States (2000). The estimate of cumulative river runoff for 1990–1996 was based on the value of 5 km^3/year given by Björklund (1999) for the year 1989 and the relative changes until 1996 reported by the Central Asian States (2000). Cumulative precipitation was based on average sea area during the period and the specific precipitation value of 150 mm/year (Björklund, 1999; Central Asian States, 2000).

Fig. 3 shows the two limiting evaporation scenarios considered. *Scenario one* assumes unchanged climatic conditions, such that the specific evaporation rate remains essentially unchanged in the period 1960–1996 (900 mm/year, as reported by Björklund, 1999), in analogy with reported unchanged specific precipitation rate (compare value of 150mm/year by Björklund, 1999, to the range of 150–200 mm/year given by the Central Asian States, 2000). This scenario thus implies decreasing total evaporation over the period, which here was estimated based on the decreasing sea area. *Scenario two* assumes an unchanged total evaporation of about 60 km^3/year[1] (as reported by the Central Asian States, 2000), thus implying an increasing specific evaporation rate, over the period 1960–1996. At the end of the period considered (1996), the specific evaporation rate reaches, in this scenario, a value of 1640 mm/year, which is consistent with the value of 1700 mm/year reported by the Central Asian States (2000). Although the physical grounds for scenario two can be questioned, increasing specific evaporation rates as such are physically plausible. The scenario two assumption of unchanged total evaporation puts a reasonable upper bond to the magnitude of such increases.

These two basic evaporation scenarios do not include the effect of increasing salinity in the Aral Sea on the evaporation rates. Because salinity increases are associated with decreasing specific evaporation rates (see, e.g., Oroud, 1999, addressing the conditions for the Dead Sea), the evaporation may be somewhat lower than suggested by scenarios 1 and 2. Compared to the plausible effects of the dramatic changes in sea surface area on evaporation, we expect that the effects are relatively small of the change in Aral Sea salinity from 10.5 g/l in 1960, to approximately 32 g/l in 1996 (implying a density change of 2%). For instance, Stanhill (1994) linked empirically a 1% change in density of the Dead Sea to a 1.5% change in annual evaporation, and Asmar and Ergenzinger (1999) provide an empirical relation suggesting a 1.5% decrease in evaporation rate, given the salt concentration values corresponding to the reported Aral Sea values for 1960 and 1996, respectively. Although the ambient conditions differ considerably between the Aral Sea and the Dead Sea, the result of Stanhill (1994) and Asmar and Ergenzinger (1999)

[1] For the period 1990–1996, we consider only the Large Aral Sea, reported by Björklund (1999) to cover 92% (33.5 thousand km^2) of the total sea area (36.5 thousand km^2). We therefore use an evaporation value of $0.92 \times 60 = 55$ km^3/year for this time period.

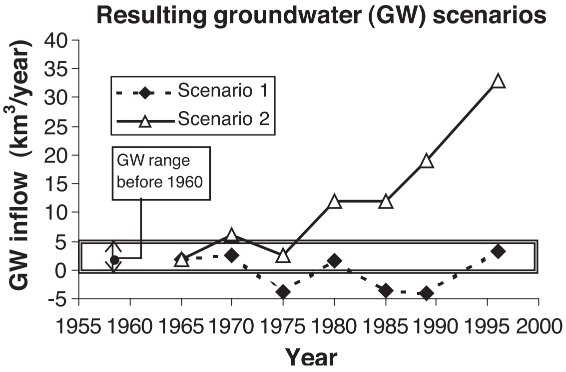

Fig. 4. Resulting groundwater scenarios, and the groundwater range before 1960.

indicate the order-of-magnitude by which changes in salinity can affect evaporation; these results are also consistent with the results of Bendhun and Renard (2004), specifically addressing the Aral Sea. Furthermore, since evaporation decreases with increasing salinity, the conclusion that scenario 2 provides an upper bond to the possible evaporation from the Aral Sea holds true.

Fig. 4 shows the resulting two scenarios for the total groundwater discharge into the Aral Sea, corresponding to the two evaporation scenarios of Fig. 3 and calculated using Eq. (1), with ΔV, R and P as in Table 1. In scenario 1 of Fig. 4 (dashed line), the total groundwater discharge into the Aral Sea ranges from essentially no change on the average, with even occasionally decreased values, as compared with the groundwater range before 1960 (illustrated with a box in Fig. 4). In scenario 2, the total groundwater discharge increases significantly up to about 30 km^3/year. Since this scenario can be considered an upper limiting case in terms of evaporation (see the paragraph above), the actual groundwater discharge into the Aral Sea during the considered period is likely to be somewhere in between the discharges given by scenarios 1 and 2. Furthermore, a comparison between the total cumulative river discharge for 1960 of 40 km^3 and the corresponding cumulative groundwater discharge value of up to 5 km^3, shows that the river flow dominated greatly over the groundwater flow at that time. However, for 1995, the reported cumulative river flow of 5 km^3 is the same as the scenario 1 groundwater discharge value, and much smaller than the scenario 2 groundwater discharge value (see Fig. 4), showing that the groundwater flow component has become increasingly important for the overall water budget, and is now a controlling factor for the fate of the Aral Sea.

Fig. 5 shows the resulting two salt content scenarios, corresponding to the two evaporation and groundwater scenarios of Figs. 3 and 4. The calculations were performed using Eq. (3), with an initial mineral content in 1960 of 10 g/l (reported by Björklund, 1999; Mikhailov et al., 2001), groundwater outflow

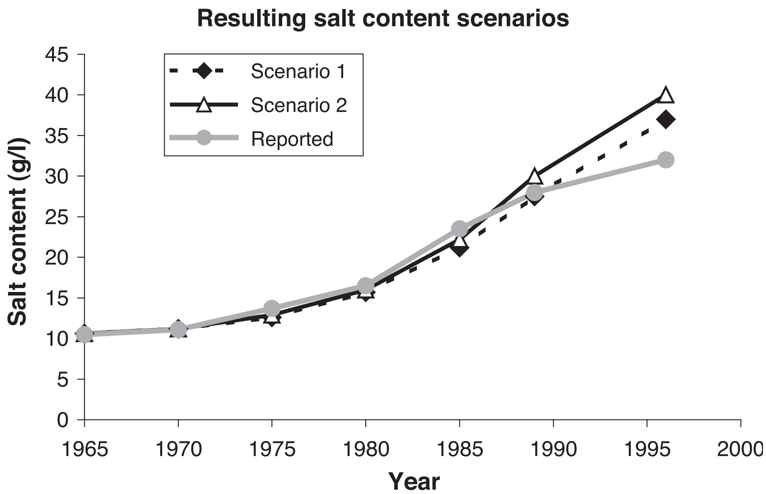

Fig. 5. Resulting salt content scenarios. Reported values for the period 1965–1989 are taken from Björklund (1999), and the value for 1996 is taken from Central Asian States (2000).

values V_{GWout} from Fig. 4, and the same basic volume and area change data as used in the water balance analysis. Fig. 5 also shows previously reported salt contents in the Aral Sea (grey line). Reported salt content values in Fig. 5 are for the period 1965–1989 taken from Björklund (1999); these values are consistent with those reported by Mikhailov et al. (2001) and Central Asian States (2000). The results for both evaporation scenarios are quite consistent with the reported salt content values for 1965–1989, after which the time data series of Björklund (1999) and Mikhailov et al. (2001) end. The discrepancies between the two evaporation scenarios and shown reported data increase for the period 1990–1996, with reported data for the year 1996 (Fig. 5) taken from Central Asian States (2000); this choice was made because the preceding data series reported by Central Asian States (2000) were consistent with the reports from both Björklund (1999) and Mikhailov et al. (2001), in contrast to other data sources. Zavialov et al. (2003) report a salt content in Large Aral (Western part) of about 90 g/l for the year 2002, which indicates a continuing salinisation also after 1996. However, the period 1996 to 2002 is outside the time period of the reports shown in Fig. 5, because there are no corresponding data for sea volume, area, and river inflow decreases from 1996 to 2002, which is needed for the scenario calculations. Regardless of the incon-

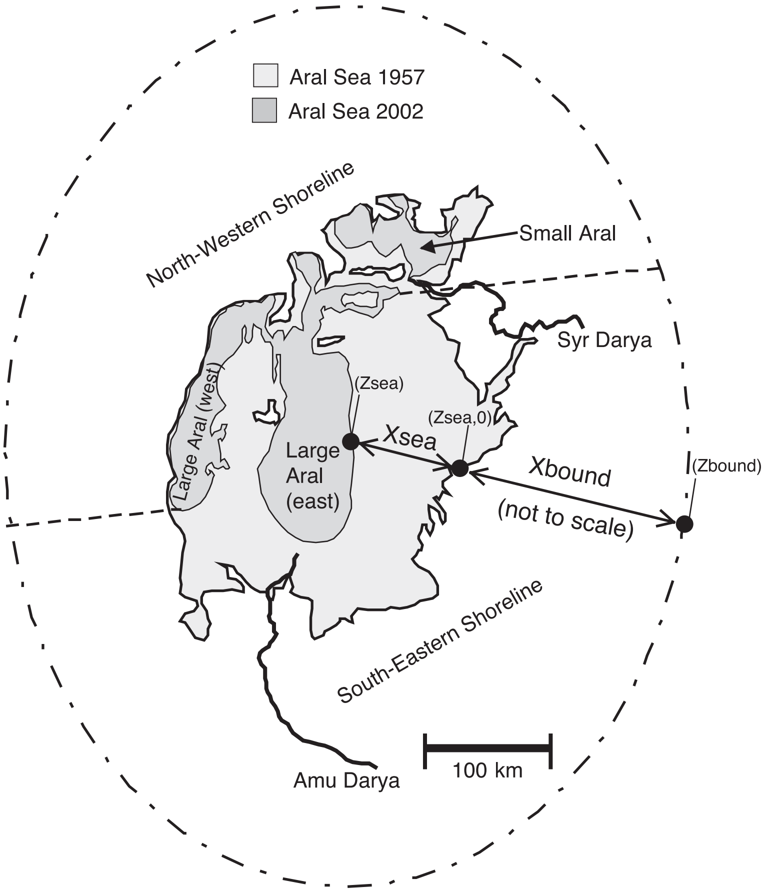

Fig. 6. Illustration of the distances: X_{sea} between the original (pre-1960) shoreline at elevation $z_{sea,0}$ and the shoreline of 2002 at elevation z_{sea} (see Fig. 2); and X_{bound} between the original shoreline and an upgradient location at which the groundwater table is no longer influenced by the lowering of the sea surface (dash-dotted line; ground elevation z_{bound}, see Fig. 2). The dashed borderlines illustrate the division between the southeastern shoreline and the northwestern shoreline. The basic features of the map were digitalised after Cans (1994), and the 2002 shoreline was obtained from the NOAA satellite image of the 25th September 2002.

sistencies in different salt content reports, which put into question the data accuracy, particularly during the 1990's, Fig. 5 shows that, for the given sea volume, area and river inflow changes, both groundwater scenarios of Fig. 4 (resulting, in turn, from the two evaporation scenarios in Fig. 3) can produce corresponding salt content scenarios that are consistent with reported data.

4. Relative changes in regional hydraulic gradients

The lowering of the Aral sea level by more than 20 m since 1960 influences the slope of the groundwater table and the groundwater flow conditions in the Aral Sea basin, as shown by Eq. (5) and Fig. 2. The horizontal sea shore retreat X_{sea} is then one of the parameters that determines and limits the magnitude of this influence. Fig. 6 illustrates the distance X_{sea} between the original (pre-1960) Aral sea shoreline and the shoreline of 2002, at some arbitrary location on the eastern part of the Large Aral. Considering the full southeastern (SE) shoreline, Fig. 6 also shows that X_{sea} takes on values between 50 and 130 km. By contrast, in most parts of the northwestern shoreline, X_{sea} is very small due to the steep near shore bathymetry. The largest value of X_{sea} in this region is around 10 km, as also shown by Fig. 6, where the dashed line shows the border between the relatively shallow SE shore and the much steeper northwestern (NW) shore.

Furthermore, Fig. 6 shows schematically the distance X_{bound} between the original (pre-1960) shoreline and the upgradient location (at the model boundary), at which the groundwater table is no longer influenced by the lowering of the sea-surface. This boundary distance must be defined, both in analytical and numerical groundwater models, however, this task is not trivial, in particular since X_{bound} is affected by both engineered (such as irrigation networks) and natural (e.g., aquifer hydrogeology) water system functioning and conditions. Hence, the boundary may exhibit a much more irregular pattern than shown schematically by the dash-dotted line in Fig. 6. Therefore, we will in the following investigate the sensitivity of the model results with respect to X_{bound}, using a wide range of possible X_{bound}-values (between 10 and 500 km).

In order to use Eq. (5), we must also know the elevation z_{bound} at the model boundary (at distance X_{bound} from the original seashore; see Fig. 2). Generally, the topographic slope of the SE Aral Sea basin (that includes both the Syr Darya and Amu Darya rivers), and also major parts of the Small Aral catchments, is very uniform and equals 1:5000 (see, e.g., Akmansoy and MCKinney, 1997). This implies that both for the SE part of Large Aral and Small Aral, the same expression $z_{bound} = 0.0002X_{bound} + 54.25$ m.a.s.l. (which is consistent with the 1:5000 slope with X_{bound} and z_{bound} given in meters), can be used for quantification of the elevation z_{bound}. For exam-

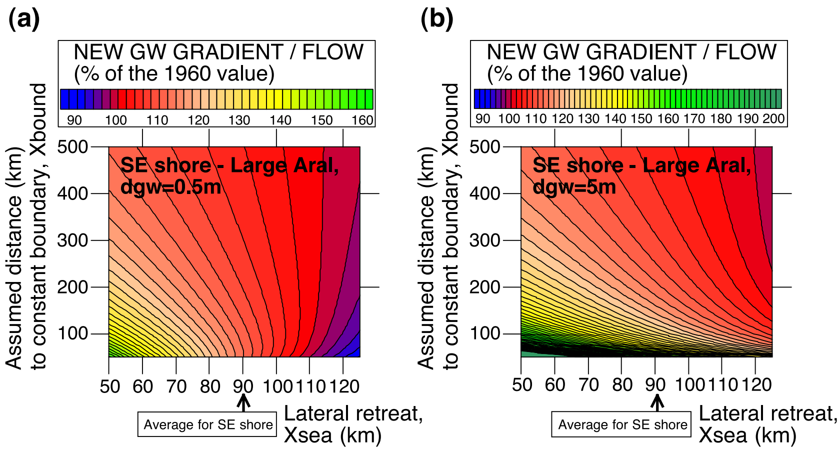

Fig.7. Changes in groundwater gradients/flows at the *SE shore of the Large Aral*, assuming a depth to the groundwater surface at the boundary of (a) 0.5 m, and (b) 5 m.

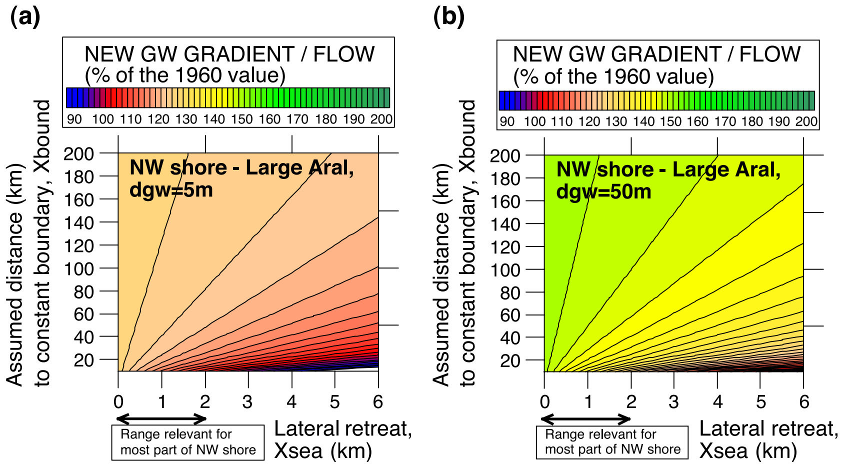

Fig. 8. Changes in groundwater gradients/flows for the *NW shore of Large Aral*, assuming a depth to the groundwater surface at the boundary of (a) 5 m, and (b) 50 m.

ple, the coefficient of correlation R^2 between this relation and a 700 km long elevation profile to the east of the Aral Sea, extracted from the GTOPO30 data set (USGS, 1996), is as high as 0.96. By contrast, to the west of Large Aral, there is a large plateau with an elevation between 100 and 200 m.a.s.l., and mostly around 150 m.a.s.l. Therefore, for quantification of the elevations to the west of Large Aral, we used the relation $z_{\mathrm{bound}} = 150$ m.a.s.l. Furthermore, the pre-1960 sea shore elevation $z_{\mathrm{sea},0}$ was 53 m.a.s.l., and the 2002 sea shore elevation z_{sea} was 30 m.a.s.l. for Large Aral and 40 m.a.s.l. for Small Aral. Regarding the depth to the groundwater table at the boundary, d_{GW} (see Fig. 2), numerous observation points in the catchments to the north, east and south of the Aral sea (e.g., Veselov et al., 2003) show that d_{GW} is around 5 m, and in many cases less than that, particularly in irrigated areas. However, in the high plateau to the west of Large Aral, observational data on groundwater levels are largely lacking, and we therefore define a greater range of possible d_{GW}-values (5 to 75 m).

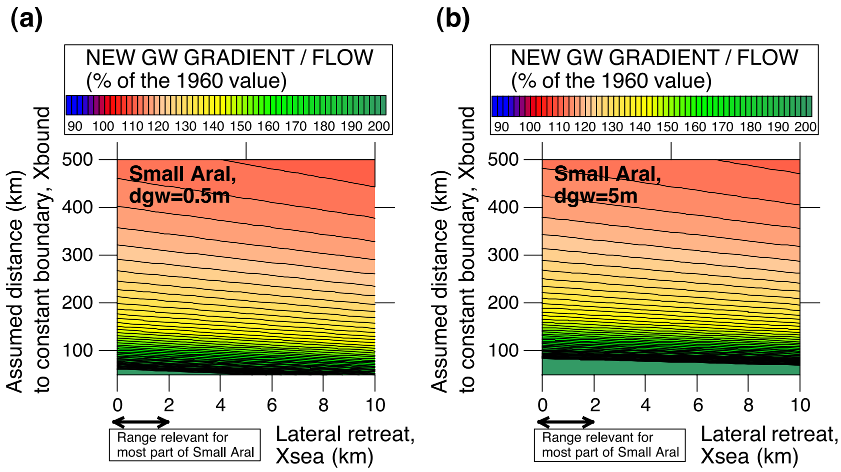

Fig. 9. Changes in groundwater gradients/flows for the *Small Aral*, assuming a depth to the groundwater surface at the boundary of (a) 0.5 m, and (b) 5 m.

Figs. 7–9 show Eq. (5) results for the new groundwater discharge into the Aral Sea in 2002, in percent of the corresponding pre-1960 value, as function of the lateral sea retreat X_{sea} and the assumed boundary distance X_{bound} (see Figs. 5 and 6). Fig. 7 shows possible regional changes in groundwater discharge over the SE shore of Large Aral; the displayed X_{sea}-range on the x-axis is relevant for the SE part of the region (see also Fig. 6), with an average retreat value of 90 km. Fig. 7 presents the result of about 3000 analytical predictions with different parameter combinations. The large, red regions in these figures imply essentially unchanged groundwater flow conditions in the SE part of the Aral Sea basin since the 1960s. This result is quite robust, since only a few extreme parameter combinations can produce increased groundwater flows. Fig. 7a particularly assumes a depth to the groundwater surface at the constant boundary, d_{GW}, of 0.5 m, and indicates that the groundwater discharge for the relevant average $X_{sea} = 90$ has not increased, or only marginally increased, in the SE region of the Aral Sea. The nearly parallel isolines in the vicinity of $X_{sea} = 90$ km further show that this prediction is not very sensitive to the assumed distance to the constant boundary, X_{bound} (y-axis). A more substantial increase in groundwater flow of 40% or more can only occur at locations with X_{sea}-values less than 60 km, which are not frequent on the SE shoreline, as shown by Fig. 6. In addition, this result requires an X_{bound}-value of less than 100 km, which is in the lowest range of possible values. With X_{bound} being in the middle range of possible values (300 km), or above, Fig. 7a shows that there is essentially no increase in groundwater discharge even at the few locations on the SE shore where X_{sea} is as short as 60 km. Fig. 7b further shows corresponding results for an assumed d_{GW} of 5 m. In this case, the results are slightly more sensitive to the X_{bound}-value, particularly in the low-end range of X_{bound}, less than about 100 km. For these low-end X_{bound} values and for smaller X_{sea}-values than the average of 90 km, Fig. 7b indicates a relative increase of the groundwater discharge to 150–200% of its 1960-value. However, for the major part of the parameter space shown in Fig. 7b, the general result of no increase, or marginal increase, of the groundwater discharge to the Aral Sea since 1960 holds true.

Fig. 8 shows the possible regional changes in groundwater discharge over the considerably steeper NW shore-line of Large Aral. As indicated on the x-axis, the relevant range of X_{sea}-values for the major part of this region is between 0 and 2 km; however, there are a few locations characterized by larger values, as can be seen in Fig. 6. The X_{bound}-range displayed on the y-axis in Fig. 8 is smaller than that of Fig. 7, because the catchment is smaller. For the 0 to 2 km X_{sea}-range, Fig. 8a indicates an increase of the regional groundwater flow to about 120–130% of its 1960-value, when assuming a d_{GW}-value of 5 m. Furthermore, the relatively uniform colour of the left part of Fig. 8a implies that the result is robust with regard to the assumed X_{bound}-value (on the y-axis). The right part of Fig. 8a shows that, for the few locations on the NW shore where X_{sea} is larger than 2 km, the increase in groundwater discharge is much less pronounced. Fig. 8b further shows that the resulting increase in groundwater discharge is generally much higher for an assumed d_{GW} of 50 m, up to 150% of the pre-1960 value for the 0 to 2 km X_{sea}-range; for an even larger d_{GW}-value of 75 m, the resulting groundwater discharge would exceed 200% of the 1960-value (not shown). All these results are relatively robust with regard to the assumed X_{bound}-value, and hence support a moderate to considerable increase in the groundwater discharge over the NW shoreline of the Aral Sea, as a direct consequence of the on-going sea level lowering.

Fig. 9 finally shows results of regional changes in groundwater discharge into Small Aral. As for the NW part of Large Aral, the shore is generally relatively steep, and the relevant range of X_{sea}-values for the major part of this region is between 0 and 2 km, with a few locations characterized by larger values (Fig. 6). In contrast to the results for Large Aral, the results are not very different for different X_{sea}-values (on the x-axis), as indicated by the flow isolines being nearly parallel to the x-axes in Fig. 9a and b. Furthermore, the similar colours and patterns over the whole space of Fig. 9a and b imply that the predictions are not sensitive to the d_{GW}-value either. However, the Small Aral results are sensitive to the assumed distance to the constant boundary X_{bound}, which was not the case for the Large Aral results. Fig. 9 shows that, without a more detailed assessment of the relevant values of X_{bound}, one must conclude that the present groundwater discharge into Small Aral may be anywhere between essentially unchanged since 1960 (which is the case for X_{bound}-values of 400–500 km), to approximately 200% of the 1960-value (for X_{bound}-values around 100 km).

5. Discussion and conclusions

The water balance and hydraulic gradient analyses yield consistent results in terms of the total groundwater discharge into the Aral Sea being at least as large as in 1960, with some relevant scenario results yielding increased groundwater discharge up to about 200% of the 1960-value. However, the regional groundwater discharge into the SE part of the Large Aral should not have increased since 1960. We reach this conclusion on pure hydraulic grounds, considering the possible hydraulic gradient effects of the on-going lowering of the Aral Sea level since 1960. Even though some parameters used for this result are uncertain, analysis of about 3000 different possible parameter combinations shows that the result is robust. Although this approach neglects additional evaporation from the groundwater table below the dried sea bottom, this process acts in the same direction as the considered hydraulic gradient effects for the SE part of the Large Aral, further supporting the conclusion of unchanged or even decreasing groundwater inflows to the SE part of Large Aral.

By contrast, our results also indicate that the groundwater discharge into the NW part of the Large Aral, characterized by steep shores and relatively small regions of dried sea bottom, have increased due to the on-going Aral Sea level lowering. The results, furthermore, show that the magnitude of this increase largely depends on the groundwater table depths beneath the plateau west of Large Aral; however, more detailed hydrogeological data and interpretations for this region are, to our knowledge, essentially missing in the scientific literature. For instance, a groundwater table depth of 5 m yields present groundwater discharge of 120–130% of the 1960-value, whereas a groundwater table depth of 75 m yields a groundwater discharge of 200% of the 1960-value.

For Small Aral, we show that the results are sensitive to the assumed value of X_{bound}, the distance to the constant boundary, which requires a more detailed evaluation of the regional hydrogeological data. However, through the analyses conducted here, we may conclude that the actual change of groundwater discharge into Small Aral since 1960 may be somewhere from essentially unchanged, if X_{bound} is relatively large (400–500 km), to an increase by approximately a factor of two, if X_{bound} is relatively small (around 100 km).

Regarding the resulting regional increase in groundwater flow in recent years, we note that even though the total Aral Sea water budget must be limited by total precipitation minus evaporation, which may be more or less unchanged in the 40-year perspective considered, other hydrologic subsystems (groundwater and streamwater) may experience considerable redistribution, such that groundwater may expand at the cost of river flow. Furthermore, our analysis shows that the groundwater discharge has remained unchanged or even decreased in some regions (mainly in the SE region of Large Aral), whereas it has increased in others (such as the NW region), which also implies a regional redistribution of groundwater flow.

The east and west parts of Large Aral presently (2003) are connected through a shallow and narrow strait, which may soon disappear due to the on-going sea level lowering, leaving two separate lakes: East Aral and West Aral. Our results imply a negative situation in terms of unchanged or even decreasing groundwater flows for the East Aral. However, considering the bathymetry of the West Aral, with steep slopes close to the present western shoreline, there is physical basis for believing that the groundwater discharge to the NW shore will be sustained, or even increase, after the two lakes have separated.

It must be noted that even for an unchanged groundwater discharge situation, the relative importance of groundwater discharge into the Aral Sea(s) has increased dramatically, from being about 12% of the total river discharge in 1960 to about 100% of total river discharge presently, due to the drastically reduced flow contributions from the Amu Darya and Syr Darya rivers in recent years. Hence, the groundwater flow component has become increasingly important for the overall Aral Sea water budget, which ultimately controls the fate of the present lake system. There are therefore strong reasons for taking great precautions when using groundwater resources in the region, both for avoiding further environmental stress on the Aral Sea system itself and for avoiding the present groundwater resources of the region becoming subject to salt water intrusion. Even though the sea surface lowering, in itself, may imply decreased risk for salt water intrusion into the coastal aquifers of the inhabited regions compared with the situation before 1960, the increasing salt content and water density of the Aral Sea does imply an increased potential for density-driven seawater intrusion into the aquifers. Hence, before further utilization of groundwater resources, this problem must be specifically addressed and quantified, since the risks are real and the effects for groundwater availability would be considerable.

Acknowledgements

Financial support for this work was provided by the Swedish Research Council (VR) and the EU INTAS Aral Sea Call 2000, project number 1014.

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