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Aral Sea; Irretrievable Loss or Irtysh Imports?

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Abstract The Aral Sea has shrunk and become a large salt pan, because the water from the two rivers that used to feed the lake (Amu Darya and Syr Darya) is almost entirely used for irrigation. In this paper some possibilities to return to the original (1960) situation are studied. After discussing some of the alternatives, it is proposed to construct a canal along a more southerly route than the original Sibaral canal, starting from the Zaisan Lake along the Irtysh river. This solution requires the construction of a major tunnel through the Khrebet Tarbagataj mountain range. Thereafter, it will flow through the Balkash Lake, saving several hundred kilometers of canal construction, and discharge its water in the lower reaches of the Syr Darya. From here it will flow into Aral Sea, slowly restoring it towards its original (1960) level. Several flanking water saving measures are considered. Most of the drive to restore the Aral Sea is for ecological reasons. There may also be a serious climatic threat to avoid, although this is a matter of debate. It is found that the discharge of the major Siberian rivers into the Arctic Ocean is on the increase, and this may affect the great world ocean conveyor belt. This would have dire consequences for the climate in Western and Northern Europe. This could be avoided by diverting part of the water towards the Aral Sea. A restoration of the Aral Sea will have beneficial effects on climate, human health, fishery and ecology in general.

Keywords Aral Sea · River water diversion · Water-accounting · Water exchange · Climate change · Great world ocean conveyor belt

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1 Introduction

A macro-project better known as the "Davydov Plan" has been proposed in 1949 to divert water from major Siberian rivers and use this water to irrigate the steppes of Uzbekistan and Turkmenistan (Davydov 1949). At that time the plan was dismissed as megalomaniac, and it was proclaimed that it would have dire implications for the climate. Since then the runoffs from the two rivers that feed into the Aral Sea, the Syr Darya and the Amu Darya have been used to irrigate the steppes. This has made Uzbekistan (and to a lesser degree Turkmenistan and Kazakhstan) one of the leading cotton producers in the world, at the cost, however, of causing the Aral Sea (which is an endorheic lake) to evaporate and transform into a dusty salt plain. Ironically, it has led indeed to a climate change for the worse, as the winter rains have become scarcer in the region.

The Aral Sea was once the fourth largest lake in the world, with a surface area of about 68,000 km^2 in 1960. Since then its size has been reduced by almost half with a concomitant rise in the pounded water's salinity. More than 20,000 km^2 of salt-coated former seafloor is now exposed, with some rusty hulls of fishing boats stuck in the crunchy salt crust as a memory to its glorious maritime past (Fig. 1). The first consequence is that the commercial fishery has almost been eliminated. Also, the land and water that remains is heavily polluted by pesticides, which has led to extreme health problems like cancers, kidney and liver problems in people living close by. The estimated economic damage is between $1.25–$2.5 billion a year just for human health, tourism and agriculture (Interlinking of Rivers 2008).

The Aral Sea desiccation is one of the world's major ecological disasters, and a serious attempt should be made to redress the current ecological and economic situation (Micklin and Aladin 2008). It should be noticed, however, that the decrease of the Aral Sea size can also take place without human intervention. The Aral Sea has undergone desiccation and salt deposition in prehistoric times, apparently in response to periods with lower precipitation (Boomer et al. 2000).

In this paper we will re-examine the Russian proposal to see if waters from the Ob River and its major tributary the Irtysh River could be diverted in times of

Fig. 1 Stranded Aral Sea boat. Photograph by courtesy of Michael Shamshidov, OrexCA.com

high water after the snow melt to the Syr Darya, which in turn would refill the Aral Sea. This should be done in conjunction with a better management of the drainage waters from the cotton fields, in order to minimize losses by evaporation. Macro-engineering projects like this have become more acceptable, and new technologies have brought their implementation closer. Acceptance will also be easier after the successful restoration of the (smaller) North Aral lake, where the local climate has measurably improved, and fishing has restarted.

The paper summarizes the main options of restoring the Aral Sea. The solution based on water transport from the Ob River basin to the Aral Sea is briefly analyzed and a new route for the inter-basin water supply canal is proposed. A simple water balance model is used to estimate the reasonable magnitude of the restoration process and its duration.

2 Options for Restoration of the Aral Sea

It has become accepted practice to move vast volumes of water by pumping or gravity from places where it is abundant to places where it is scarce, and many examples of existing or planned projects, like the South–North water transfer in China are presented in Vijayan and Schultz (2007), Liu and Zheng (2002). If the Aral Sea is to be restored, one can think of the following solutions:

1. Back to 1950. Restoring the original situation by stopping the cotton production, and let the waters of the Amu Darya and the Syr Darya flow again into the Aral Sea.
2. The water goes, the salts stay behind. Pumping water from the Black Sea (at ASL ~0 m) and/or the Caspian Sea (at ASL −26.5 m) to the Aral Sea (at ASL +53 m in restored state).
3. Competing water demands. Diverting waters from major Siberian rivers to the Aral Sea (Blagov 2002).

Each of these options has not only severe economical consequences, but geopolitical and ecological consequences as well. As in all macro-engineering projects, decisions must be based on weighing incomparable benefits and losses against each other (Schuiling et al. 2007). In case the decision goes in favor of the macro-project, care must be taken to limit the negative consequences as much as possible by taking appropriate mitigating measures.

In the following sections we will briefly describe each of these options, and will treat the last one in more technical detail.

2.1 Back to 1950

The goal of irrigating the dry steppes of Uzbekistan, Turkmenistan, Kazakhstan, Kirghizia and Tadjikistan has been achieved. Most of their irrigated fields are planted with cotton and rice, and together they produce more than 10% of the world's cotton. If irrigation is stopped, the economical losses for the countries involved, Uzbekistan and Turkmenistan in the first place, and the drop in the standard of living would be colossal and unacceptable. Revenues from fishing in a restored Aral Sea, and the expected improvement of the climate around the Aral Sea would provide some compensation for the loss of income. In its heyday, fishing from the Aral Sea landed about 50,000 ton of fish yearly. Fishing always played a major role in the region, as can be seen from the many geographical names in which the word balik or beluga appears (Turkish and Russian for "fish" or "sturgeon").

One can contemplate, however, a number of measures that could reduce the negative impact of irrigation on the water balance of the Aral Sea. It should be investigated if irrigation canals can be protected from evaporation, by covering them with a low-cost reflective water-retaining material, or by replacing open canals by closed pipelines wherever possible, and making the canal bottoms impermeable. In dry countries, wherever farmland is irrigated, irrigation must always be accompanied by drainage, as otherwise salts would accumulate in the soil, making it unfit for cultivation. Care should be taken for a maximum return of these drainage waters to the rivers by not letting them evaporate along the way. One can also promote the cultivation of cash crops that are less water demanding, or more suitable than cotton or rice for drip irrigation, while maintaining the same level of income. The negative consequences of monocultures are becoming apparent worldwide, so crop rotation would be a sensible policy, not only from the point of view of saving irrigation waters, but also to maintain a sustainable agriculture as well. Diversification of crops might include the planting of orchards, more grain and corn production, and maybe potatoes as well.

Each affected growing region should also start a system of periodically leaving arable fields fallow for a year, which will allow the soil to recover. The year that fields are left fallow can be used for repair and maintenance of the local irrigation and drainage systems, among others by making the floors of the canals impermeable, and thereby cut infiltration losses.

If an acceptable solution for the restoration of the Aral Sea can be found, the participating countries should set an agreed international limit to their planted cotton acreage, similar to oil production limits by OPEC. This way they can avoid interstate competition, leading to lower margins on their product, and it may even help them to secure a reasonable and stable price for their cotton, perhaps marketed by the cartel.

2.2 The Water Goes, the Salts Stay Behind

New challenging macro-project ideas have been brought forward for making up the water deficit of the Aral Sea by pumping seawater from the Black Sea into the Caspian Sea, and then pumping saltwater more than 80 m upwards into the (fully restored) Aral Sea (Cathcart 2008). All pumps were to be solar powered. In essence, this macro-project simply reverses what occurred naturally during the late Pleistocene (Svitoch 2008). To maintain a constant level of the Aral Sea, once restored, an annual volume of water of ~40 billion m^3 is required. For topographical reasons, Black Sea water cannot be channeled directly to the Aral Sea, unless one would construct very long photovoltaic-powered textile pipelines passing through Georgia and Iran among others, creating more trans-boundary problems.

Limiting the problem to pumping only Caspian Sea waters will not be acceptable, because this would lead to a significant lowering of the Caspian Sea level, although in the short-run it would alleviate the problems caused by the ongoing rapid rise of the Caspian Sea level. The problems one can expect in such a macro-engineering style solution are manifold, however.

The Black Sea is essentially a two-layered system, with a thin oxygenated layer of fairly low salinity, in the order of 17.5‰, i.e. about half the salinity of ocean water, on top of an almost stagnant anoxic body of deep water. The large outflow through the Bosporus is mainly from the surface layer, whereas a smaller undercurrent of denser saline Mediterranean waters represents the return flow. The anoxic waters start at a depth of about 50 to 100 m, and the anoxic boundary is sometimes even shallower, leading to massive fish kills occasionally. Roughly speaking, one can say that the salt composition represents a dilute marine water, which is also evident from the normal marine salinity/chloride ratio of just over 1.8.

The situation of the Caspian Sea is very different. Like the Aral Sea, the Caspian is also an endorheic lake. It has a salinity ranging from 10 to 13‰, but the ion ratios of its salts are very different from ocean water. Its water is refreshed every 300 years by the inflow of the Volga River, and this has been going on for several million years. It is clear, therefore, that its composition is essentially governed by the dissolved load of that river, and is not a relic of its marine past, many millions of years ago. The composition of the Volga River, as far as major components are concerned, is dominated by Na^+ and $SO_4{}^{2-}$ and it is low in chloride. When a water with a composition like that of the Volga evaporates, first a modest amount of calcite precipitates, followed by Na_2SO_4 on further concentration by evaporation, or at low temperatures by its hydrated equivalent, $Na_2SO_4{\cdot}10H_2O$.

The "brine tree" (Fig. 2) shows how saline waters develop when they evaporate, and which salts will precipitate (Schuiling et al. 1994, chapter 12). Evaporation of almost all natural waters will first lead to the formation of calcite. Depending on the ratio of Ca^{2+} to alkalinity two branches of brine evolution develop. If Ca^{2+} > alkalinity the next mineral to precipitate on further evaporation will be gypsum. Depending on the ratio of Ca^{2+} to $SO_4{}^{2-}$, the brines will develop into NaCl brines

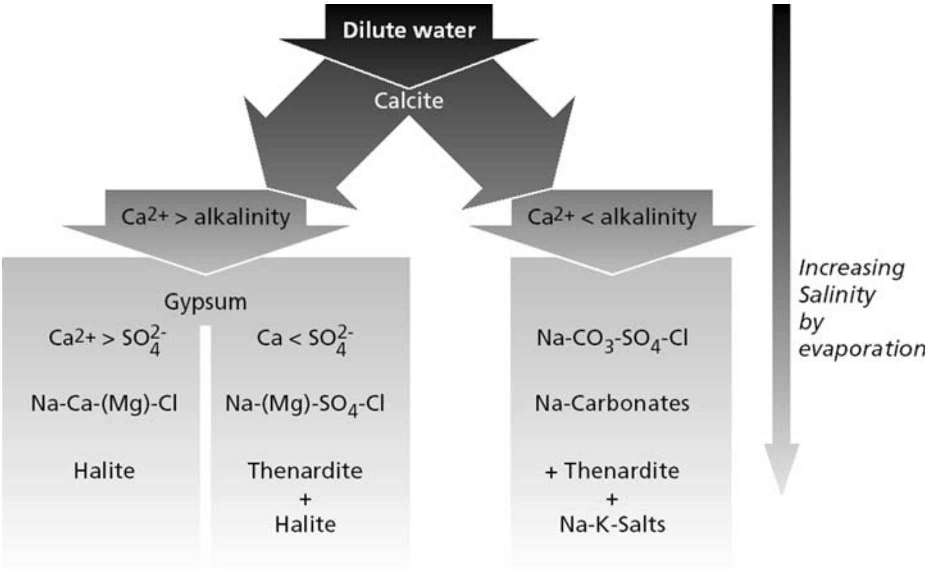

Fig. 2 The brine tree

(the normal marine sequence), or into Na_2SO_4 brines, like in the Caspian Sea. In case alkalinity > Ca^{2+}, the brines will become alkaline, and end up as soda lakes, with the formation of minerals like trona, natron or thermonatrite.

The Caspian Sea itself does not develop into a brine, because a small outflow over a shallow threshold into the almost closed Karabogaz keeps the salinity of the Caspian Sea more or less constant. Qualitatively one can say that the salt contained in the large volume of fairly fresh water flowing into the Caspian Sea equals the amount of salt in the much smaller outflow of a saline solution from the Caspian Sea into the Karabogaz. It is evident that the composition of the Caspian Sea differs drastically from that of a somewhat dilute marine water. Its salinity/chloride ratio is 2.39 compared to 1.8 for sea water, and after evaporation in the Karabogaz it precipitates mirabilite ($Na_2SO_4 \cdot 10H_2O$) in wintertime instead of halite (Fig. 2), which one would expect from evaporation of sea water (for a description of this, see Paustovsky 1969).

If we start to pump each year 40 billion m^3 of Caspian Sea water, or mixed Caspian Sea/Black Sea waters into the Aral Sea, evaporation will quickly transform the Aral Sea into a salt pan, because the evaporation and infiltration during 27.5 years equals the total volume of the (restored) Aral Sea. This means that the salinity of the Aral Sea will increase by the same salinity percentage as found in the incoming waters (10‰ for Caspian Sea water) for each period of 27.5 years. Within a century or so, the salinity will already have risen to such concentrations that all fish will die. So, instead of bringing a solution, in the middle long run this approach will make the situation worse than at the present.

Another disadvantage of this macro-engineering solution is the large amount of energy required to pump a volume of water, of the order of the annual discharge of the river Rhine, and lift it up by more than 80 m. Even so, this would be acceptable if that water is absolutely necessary to solve a huge environmental problem, but in this case it won't take long before the solution becomes itself the problem.

If, nevertheless, one would attempt to pump Black Sea water to the Aral Sea, the utmost care should be taken at the intake point of the Black Sea water, in order to avoid sucking up an admixture of deep, anoxic and H_2S rich waters, which would cause another type of environmental disaster.

2.3 Competing Water Demands

In view of the problems encountered with the first two macro-project options, let us see if the third realization option, diverting part of the water of one or more of the Siberian rivers, offers a useful macro-engineering solution. The long-discussed Siberian River Diversions project originated with N. Demchenko in 1871. The unrealized "Davydov Plan" sought to convey Siberia's excess freshwater to Central Asia (Davydov 1949) was estimated to 100 GUSD. Once realized, it might allow a 27–30 km^3/year input of freshwater to the Aral Sea (Davies et al. 1992; Duke 2006; Micklin 2007). This is in line with the ambitious plans for the southward diversion of the Siberian rivers, as formulated in the mid 1970's. The plan was shelved in 1986, but even in 1988 Salay (Salay 1988) alleged

> If the water management problems in Central Asia remain in the future, and if the Soviets wish to manage the critical situation of the Aral Sea, it is not unthinkable that the idea of a larger water transfer from the north, at least to

the Aral Sea, will be raised again. Perhaps in l0–20 years, and if then, perhaps in a reduced, less costly form.

In the post-USSR 21st Century, some Russian scientists seek to revive the Siberian River Diversions macro-projects (Pearce 2004) to import freshwater to Kazakhstan via a proposed "SibAral Canal Project", a 2,500 km-long, 200 m-wide, 16 m-deep concrete-lined canal conveying about 6–7% of the Ob River's yearly runoff to Central Asia, overcoming a 126 m-high topographic pass in the Turgai Depression. The planned macro-projects essentially boil down to diverting waters from the Ob and the Irtysh. The Ural River offers no, or at most a partial solution, because its average discharge is only 400 m^3/s, less than one third of what is required for a full recovery of the Aral Sea. Moreover, the Ural is polluted with municipal waste water from several major cities, and there may be some pollutants leftover from past aerial nuclear testing. If it would be necessary, however, to involve also water from the Ural River, an intake place should be selected upstream of the city of Uralsk, because its altitude is only 36 m ASL, i.e. lower than the level of a fully restored future Aral Sea.

Figure 3a shows one of the routes proposed in the past for the Ob–Aral Canal (Blagov 2002). In Fig. 3b, with tentative traces of canals to feed the Aral Sea, we have selected for the Ural an intake point at Orsk, which would avoid the induction of polluted municipal waste waters. One can also look at a possible positive side-effect of involving water from the Ural River. It might offer an elegant way to modulate the level of the Caspian Sea; if it rises, one can let more water of the Ural River into the Aral Sea Basin, and less should the Caspian Sea level drop.

The discharges of both the Ob and the Irtysh rivers (respectively $\sim$13,000 m^3/s and $\sim$3,000 m^3/s) would, in theory, be surplus to the Aral Sea's restoration to its 1960 form. There are other serious demands on these waters, however. Next to navigation or fishing, which do not affect the total water volume, we can distinguish three major claims on these rivers, namely:

- Hydropower generation
- Irrigation
- Human consumption

A number of hydropower stations have been installed along the Ob and the Irtysh rivers and any subtraction of water from a point higher up than the reservoirs means a diminished electric power production. A low-intake point, however, means that the required water must first be pumped up to a higher level to let it flow by gravity to the Aral Basin. It is evidently wasteful to first produce hydropower, and afterwards pump the water up to the same level again. This means that if construction costs for the canal or pipeline that will carry the river water are roughly similar, one should choose the intake point at the highest suitable elevation. We have selected, therefore, an intake point from the Zaisan Lake (alt. 420 m ASL) along the Irtysh (Fig. 3b), which would permit the water transport by gravity flow to Lake Balkash (alt. 341 m ASL). This would require the construction of an approximately 100 km long tunnel for water transport through the Khrebet Tarbagataj mountain chain.

Irrigation is a major claim on the waters in the middle reaches of these rivers, and the water spent for irrigation is essentially lost for any long-haul transport. Apart from measures to use the irrigation waters in the best and most economical way, by switching to modern, water-conserving methods of crop irrigation, and promote the cultivation of less water-demanding cash plantings, not much can be done about

Fig. 3 Siberia–Aral canal. **a** Route proposed previously; **b** route proposed in this work

Fig. 3 (continued)

this situation. The construction of greenhouses might help to reduce water demands to some degree, while at the same time extending the growing season and increase rentability.

Human consumption is less of a problem in terms of water volumes involved. Highest demand is for potable water quality for safe consumption, but the volumes are small compared to the demands for irrigation.

Even if waters of the Ob and the Irtysh rivers could be diverted and channeled to the Aral Sea, the construction costs of the mega-canal shown in Fig. 3a, capable of transporting in the order of 5–7% of their combined discharge are estimated between 12 and 20 billions US$ (Blagov 2002), or 40 billions US$ according to Pearce (2004). We do not dispose of similar calculations for the selected trace of the canal starting at Lake Zaisan (Fig. 3b), but we surmise that the costs will be significantly smaller. The tunnel costs will be large. For a somewhat smaller, but comparable tunnel project of 75 km for water transport, the costs were estimated to be in the order of 1.5 to 2 billion US$ (Ezekiel Water Project 2008), so the costs of a Khrebet Tarbagataj tunnel, which would be the largest engineering effort along the proposed Irtysh–Aral canal, probably will not exceed 3 to 4 billion US$, if constructed by modern TBM (Tunnel Boring Machine). It should be realized, however, that not every lithology can be drilled by TBM, so our cost estimate is provisional. Geological and engineering studies are required to determine whether our proposal is realistic No power will be needed for water transport, as the selected route allows the fresh water to be carried by gravity flow. Close to six hundred kilometers of the trace pass through Lake Balkhash, and the final point of discharge is not in the Aral Sea itself,

Table 1 Dissolved load (major ions) of the waters under consideration

	Na + K	Ca	Mg	SO_4	Cl	HCO_3	Total (mg/L)
Volga Astrakhan	310	160	70	700	200	430	1,870
Ob	5.2	21.2	2.6	11.1	0.8	75.1	116
Irtysh	8.6	23.2	4.4	8.6	7.5	4.1	61
Caspian	3,260	330	740	3,040	5,350	100	12,820

Caspian Sea data after Blinov (1962)

but at a point upstream of Kizil Ordu along the Syr Darya. These two measures will save 700 to 800 km of canal construction. Moreover, letting the water not flow directly into the Aral Sea, but into a point upstream along the Syr Darya will make it possible to restore as much as possible the valuable ecology of the Syr Darya's delta wetlands.

An advantage of this solution is that, contrary to the situation when saline solutions of Black Sea or Caspian Sea are used, the low salinities of the Ob River and the Irtysh River (see Table 1) mean that it will take many years before the salinity of the restored Aral Sea reaches values approaching those of the Caspian Sea.

2.4 Water Accounting

Any freshwater redistribution scheme agreed amongst the existing Central Siberian republics will require the set-up of a trans-boundary water allotment and monitoring board. By treaty the shares of water allotted to each of the participating countries must be determined and delineated clearly in an international treaty. Freshwater is not a free commodity, but each of the users has to pay a price. This price should be kept low in order not to harm the fragile developing economies of the region, but at the same time it should encourage the users to utilize all available waters wisely and without wastage. For example, the amount charged to each country for their water intake should be reduced by the amount of their drainage waters that they release back into the eco-system, unless these waters exceed a certain limit of pollution. This will make it financially more attractive for the participants to repair and maintain their systems and to minimize water losses by infiltration, evaporation or pollution by excessive use of pesticides or fertilizers. Every directly involved riparian country should be a full member of the governing water board, but it would be advisable to invite China and Afghanistan to become permanent observers and/or advisors.

3 The Restoration Process: How Long and How Much?

The simple time-dependent model we propose below is mainly based on (but not reduced to) the model by Létolle et al. (2005). The model is based on deterministic assumptions. It provides reliable mean values because its core consists of basic principle (mass conservation for water and salt, respectively). A simple form of the time-dependent water volume balance equation for the Aral Sea is:

$$\frac{\mathrm{d}V}{\mathrm{d}t} = Q_{\mathrm{river}} + Q_{\mathrm{prec}} + Q_{\mathrm{g-w}} + Q_{\mathrm{add}} - Q_{\mathrm{inf}} - Q_{\mathrm{evap}} \tag{1}$$

where V is the volume of water while the five terms in the r.h.s. member of Eq. 1 refers to the incoming volumic flow rates due to rivers, precipitation, groundwater and from other sources, respectively, and to the lost volumic flow rates due to infiltration and evaporation, respectively. The main novelty is that the contribution of additional water input flux Q_{add} is taken explicitly into account. In writing Eq. 1 we assumed all water flows have the same mass density. Thus, the mass balance equation turned into a volume balance equation. Presently, the term Q_{evap} dominates the r.h.s. member of Eq. 1.

The time-dependent salinity balance equation for the Aral Sea is:

$$\frac{\mathrm{d}(sV)}{\mathrm{d}t} = s_{\mathrm{river}} Q_{\mathrm{river}} + s_{\mathrm{g-w}} Q_{\mathrm{g-w}} + s_{\mathrm{add}} Q_{\mathrm{add}} \tag{2}$$

where s, s_{river}, $s_{\mathrm{g-w}}$ and s_{add} is the average salinity (in kg salt per cubic meter of water) of the Aral Sea, of the water incoming from Amu Darya and Syr Darya rivers, of the ground-water and from additional sources, respectively. The salinity content associated to precipitation and evaporation in the r.h.s. member of Eq. 1 is zero and these terms do not contribute to Eq. 2.

Describing quantitatively the Aral Sea evolution process requires solving the time dependent Eqs. 1 and 2. The following hypotheses are adopted.

The precipitation volumic rate is proportional to the Aral Sea surface area, i.e.:

$$Q_{\mathrm{prec}} = r_{\mathrm{prec}} S(V) \tag{3}$$

where r_{prec} is the precipitation rate (in m/year). Previous studies (Létolle et al. 2005) assume the infiltration volumic rate is proportional to the Aral Sea volume, i.e.:

$$Q_{\mathrm{inf}} = p_{\mathrm{inf}} V \tag{4}$$

where p_{inf} is the infiltration factor (in year^{-1}). The evaporation volumic rate is given by:

$$Q_{\mathrm{evap}} = r_{\mathrm{evap}} S(V) \tag{5}$$

For larger values of the free water level surface, the volumic water flow input by rivers Q_{river} comes from Amu Darya and Syr Darya river (each river adds about 10 km^3/year). When the free water level decreases below a given value h^*, most of the input from the Syr Darya River remains in the Small Sea (which evolves as a separate water body) and only a small part will go to the eastern basin, much larger and less deep than the western basin (Létolle et al. 2005). Consequently, the volumic rate income by rivers is described by:

$$Q_{\mathrm{river}} = \begin{cases} Q_{\mathrm{river},1} \text{ for } h > h^* \\ Q_{\mathrm{river},2} \text{ for } h \le h^* \end{cases} \tag{6}$$

For free water surface levels below h^*, the Eqs. 1 and 2 refer to the Eastern and Western basins of Aral Sea.

A discrete solving procedure is adopted here with the time measured in years. Then, the ordinary differential equations (1) and (2) are transformed into the following finite-difference equations, respectively:

$$V(n+1) - V(n) = Q_{\text{river}}(n) + Q_{\text{g-w}}(n) + Q_{\text{add}}(n) + Q_{\text{prec}}\left[n, S(V(n))\right] - Q_{\text{inf}}\left[n, V(n)\right] - Q_{\text{evap}}\left[n, S(V(n))\right] \quad (7)$$

$$V(n+1)\,s(n+1) - V(n)\,s(n) = Q_{\text{river}}(n)\,s_{\text{river}}(n) + Q_{\text{g-w}}(n)\,s_{\text{g-w}}(n) + Q_{\text{add}}(n)\,s_{\text{add}}(n) \quad (8)$$

Here n refers to the number of years from the beginning of the refilling process.

The main difficulty in using the model Eqs. 7 and 8 (or, in other words, Eqs. 1 and 2) consists in providing accurate input values for the numerous parameters. Various assumptions were adopted during implementation and the reference for the input parameters is always presented.

Equations 7 and 8 may be solved numerically for V and s by using Fig. 4 showing the dependence of the total Aral Sea free water surface area S and the total Aral Sea water volume V on the free water surface level h. Data used to produce Fig. 4 is used to compute by interpolation, for given value of S, or V, or h, the associated values

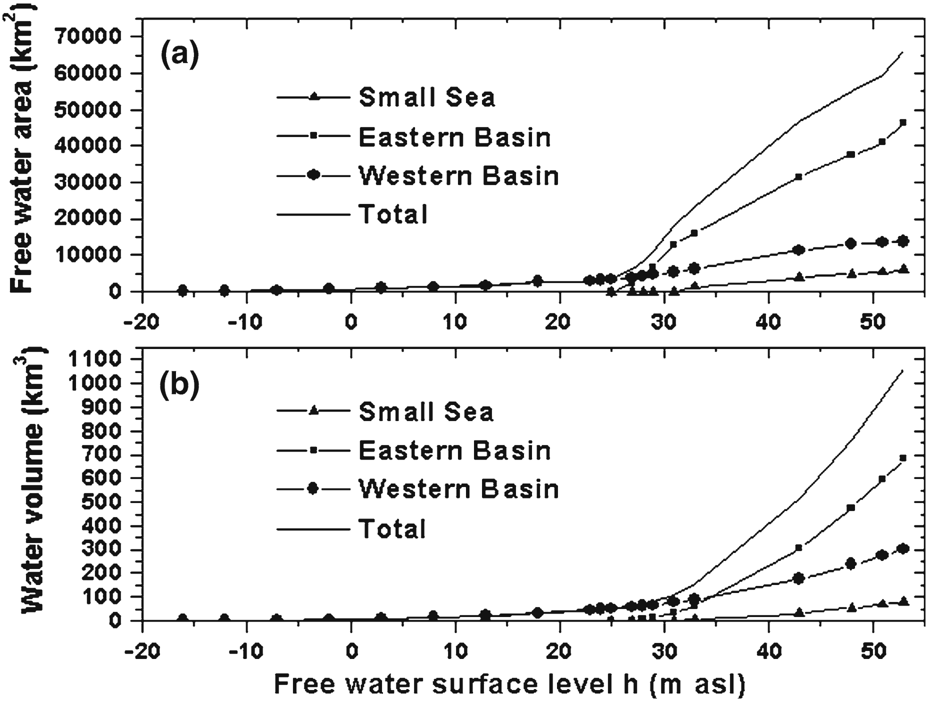

Fig. 4 **a** The free water surface area and **b** the water volume in the North Basin (Small Sea) and in the Western and Eastern basin of the Aral Sea, respectively, as a function of the free water surface level (Létolle et al. 2005)

of the other two quantities. Knowing all information associated to the year n, Eq. 7 allows computing $V(n+1)$ while Eq. 8 allows computing $s(n+1)$.

In computation we adopt constant (in time) values for the flow rates Q_{river}, $Q_{\text{g-w}}$ and Q_{add}. Note that the evaporation rate r_{evap} decreases by increasing the water salinity (Létolle et al. 2005) while the precipitation rate r_{prec} is slightly dependent on the free water surface area S. However, in our rough calculations we use constant (in time) values for the parameters r_{prec}, r_{evap} and p_{inf}, as well as for the salinity contents s_{river}, $s_{\text{g-w}}$ and s_{add}.

3.1 Steady-State Aral Sea

The steady-state Eq. 1 reduces to

$$Q_{\text{river}} + Q_{\text{prec}} + Q_{\text{g-w}} + Q_{\text{add}} - Q_{\text{inf}} = Q_{\text{evap}} = r_{\text{evap}} S(V) \tag{9}$$

where r_{evap} is the evaporation rate (in m/s) and $S(V)$ is the free water surface area. Here Eq. 5 was also used. The evaporation rate r_{evap} in Aral Sea is evaluated now at 1.3 m/year (this has to be compared with the rate 1 m/year accepted in previous studies; for discussions see Letolle et al. 2005, p 54).

First, we evaluate the evaporated water flow rate for a given water level height h in a steady state Aral Sea. To this purpose we use Table 1 and Fig. 2 of Létolle et al. (2005). Figure 4 shows the free water surface area and the water volume V in the North basin (Small Sea) and in the Western and Eastern basins of the Aral Sea as a function of the free water surface level (Létolle et al. 2005).

For given value of Q_{evap}, Eq. 9 provides the associated free water surface area S, which in turn, allows to estimate by interpolation in Fig. 4 the free water surface level h. The procedure may be used for values of h smaller than 33 m asl. In case h exceeds 47 m asl, the associated value of the flow rate Q_{evap} may be obtained by direct interpolation from Fig. 2 of Létolle et al. (2005). For h values between 33 m and 47 m asl the following procedure has been adopted. Knowing the values of Q_{evap} associated to $h = 33$ m and $h = 47$ m, respectively, linear interpolation has been used to associate Q_{evap} values to h values in this range. Results are given in Table 2 which

Table 2 Water flow rate Q_{evap} evaporated from a steady-state Aral Sea, for a given water level height h and evaporation rate r_{evap}

Free water surface level h (m ASL)	Evaporated flow rate Q_{evap} (km^3/year)	
	$r_{\text{evap}} = 1$ m/year	$r_{\text{evap}} = 1.3$ m/year
1	0.8	1
12	1.5	2
16	2.3	3
25	3.8	5
27	7.7	10
30	15.4	20
33	22.3	29
36	30	39
39	37	48
43	47	61
47	57*	75*
50	61*	80*
53	65*	85*
58	72*	90*

Values marked with (*) are taken from Fig. 2 of Létolle et al. (2005). Other values are computed by using the procedure described in the text shows the value of Q_{evap} estimated by using Eq. 9 for several values of h and two values of r_{evap}.

3.2 The Natural Stabilization Process

The Aral Sea's surface area shrank by approximately 60% and its volume by 80%. In 1960, the Aral Sea had an area of approximately 68,000 km^2 and a volume of 1,100 km^3; by 1998, it had dropped to 28,687 km^2. Over the same time period its salinity increased from about 10 g/L to about 45 g/L. As of 2004, the Aral Sea's surface area was only 17,160 km^2, 25% of its original size, and still contracting (Micklin and Aladin 2008).

Presently, the total output from Syr Darya River is about 10 km^3/year but only about 2–3 km^3/year remains to pour into the southern basin of the Aral Sea (Létolle et al. 2005, p 54). Note that some scenarios for the period 2010–2099 estimated the inflow from Syr Darya River to range from 2.1 to 7.1 km^3/year, depending on scenario (Savoskul et al. 2003, Tables 8.4 and 8.5, p. 53–54).

First, the natural stabilization of the water level in Aral Sea is roughly described. The following input values in Eq. 1 are adopted: $r_{\mathrm{prec}} \approx 0.1$ m/year, $p_{\mathrm{inf}} \approx 0.05$ year^{-1}, $r_{\mathrm{evap}} = 1.3$ m/year. These values are close to present day values. An inflow of about 4 km^3/year into the bottom of the Aral Sea has been taken into account (Bendhun and Renard 2004). This groundwater originates in the Pamirs and Tian Shan mountains and seeks its way through geological layers to a fracture zone at the bottom of the Aral Sea. Thus, a constant value $Q_{\mathrm{g-w}} = 4$ km^3/year will be adopted in the following. No water is imported from other hydrological basins yet ($Q_{\mathrm{add}} = 0$).

Three scenarios concerning the water inflow rate by rivers are considered. The first scenario ($Q_{\mathrm{river,2}} = 13$ km^3/year) is close to present day situation. The last scenario ($Q_{\mathrm{river,2}} = 4$ km^3/year) corresponds to both Amu Darya and Syr Darya rivers contributing 2 km^3/year. This case might be appropriate if the Aral Sea level drops very much and part of the river water is lost to the desert area. The second scenario ($Q_{\mathrm{river,2}} = 7$ km^3/year) is a middle value between the first two cases.

The Syr Darya River in its upper reaches has a salt content between 0.3 and 0.5 g/L, but in the lower reaches, where there is a fairy saline return flow from the post-use irrigation waters, its salt content is between 1.3 and 1.7 g/L (at the Kizil Ordu station). For the Amu Darya the salt content in the lower/middle reaches was around 1.05 to 1.15 g/L in the period 1980 to 1990, but it may have come down slightly to around 1 g/L. In calculations we shall adopt an average value for the river salinity $s_{\mathrm{river}} = 1.1$ g/L as a compromise between the larger salinity of Syr Darya River and the larger amount of water from Amu Darya River. The salinity of groundwater is neglected ($s_{\mathrm{g-w}} = 0$).

The characteristics of Aral Sea in the year 2005 are adopted as initial values: salinity $s_0 = 48$ g/L and free water surface level $h_0 = 33$ m.

The water level stabilizes to 28.9 m (in 17 years), 27.2 m (in 20 years) and 25.7 m (in 20 years) for the three scenarios, respectively (Fig. 5a). In the last case, the Eastern basin is almost completely dried. In fact, the water level reaches 95% of the steady state level much faster (i.e. 8, 9 and 10 years, respectively, for the three scenarios). The water surface reduces to a few thousand km^2 (Fig. 5b) while the salinity increases about two times for first scenario to up to three times in the last scenario (when salt precipitation may occur; this phenomenon is not considered here) (Fig. 5c). These

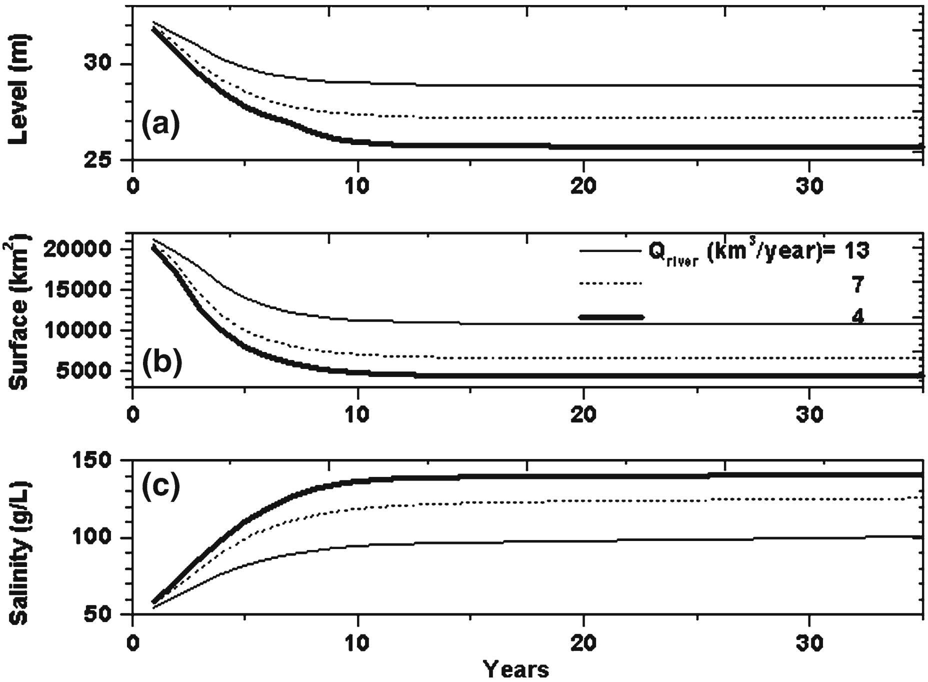

Fig. 5 Natural time variation of various Aral Sea parameters in the next 35 years. **a** Free water surface level; **b** water surface area; **c** salinity. Three different values of the river inflow rate Q_{river} were considered

results are in agreement with satellite observation: In October 2008 the Eastern basin was almost dried (Fig. 6).

3.3 Macro-Engineered Restoration Process

In this section a naturally stabilized Aral Sea is considered. Previous results show that the water body consists of the Western and Eastern basins only. The stabilized level and salinity content is $h_0 = 27.2$ m asl and $s_0 = 125$ g/L, respectively. These values are reached in about 20 years if the river inflow is $Q_{\text{river},2} = 7$ km^3/year. We shall accept $Q_{\text{river},1} = 17$ km^3/year. The two values act as initial inputs for all next simulations. In all cases the results were derived by simulation with runs for a period of 75 years after the level stabilization happened. The end of this simulation time interval corresponds roughly to 2099, which is the end of the prognosis in (Savoskul et al. 2003).

Note that the highest possible level of the Aral Sea is $h_{\max} = 58$ m asl, based on the highest altitude reached by the Amu Darya sediments south of former lake Aibugir, south-west of Kungrad City (Létolle et al. 2005). This corresponds to the largest possible surface of Aral Sea. Before 1960 the Aral Sea level oscillated around 53 m ASL, damped by evaporation (see Fig. 7).

The best strategy would be to refill the Aral Sea to its original (circa 1960) size, but to do it fairly slowly. If one would go for a rapid refilling, one would need a much larger imported water volume from the Ob River Basin, and have to construct

Fig. 6 Satellite view of Aral Sea. *Left*: July–September 1989; *right*: October 5, 2008. The Western, Eastern (almost dried) and Northern basins are clearly visible in the *right* (Permission: PD-USGOV-NASA)

a costly over-sized canal, which would soon after lose its over-capacity function, once the Aral Sea stabilization is achieved. It is also possible that a compromise would be reached by not completely refilling the Aral Sea to its former level. This, of course, would reduce the evaporation, and reduce the inter-basin imported water demand for the Aral Sea.

Five Aral Sea macro-project filling scenarios will be studied here. The first scenario is $Q_{\mathrm{add}} = 30$ km^3/year and corresponds to the previously proposed water income from Ob River of 27–30 km^3/year. This will not upset the water balance in the Ob and Irtysh river basins too much (i.e. about 6–7%) but in the beginning it would require more time to refill. However, in years of exceptionally high discharge during the snow melt in May/June the inflow can be increased to speed up the process of refilling. In the second scenario, the inflow "expected" from the Ob and Irtysh rivers would amount to $Q_{\mathrm{add}} = 40$ km^3/year at steady-state conditions. The third, fourth and fifth macro-engineering scenarios correspond to $Q_{\mathrm{add}} = 50$ km^3/year, 60 km^3/year and 90 km^3/year, respectively. They are associated to too-large macro-projects to be used in practice but may be useful as an illustrative perspective for the accounting results. The salinity of Ob River (Table 1) is $s_{\mathrm{add}} = 0.116$ g/L (in fact the salinity of Irtysh River is only 0.061 g/L).

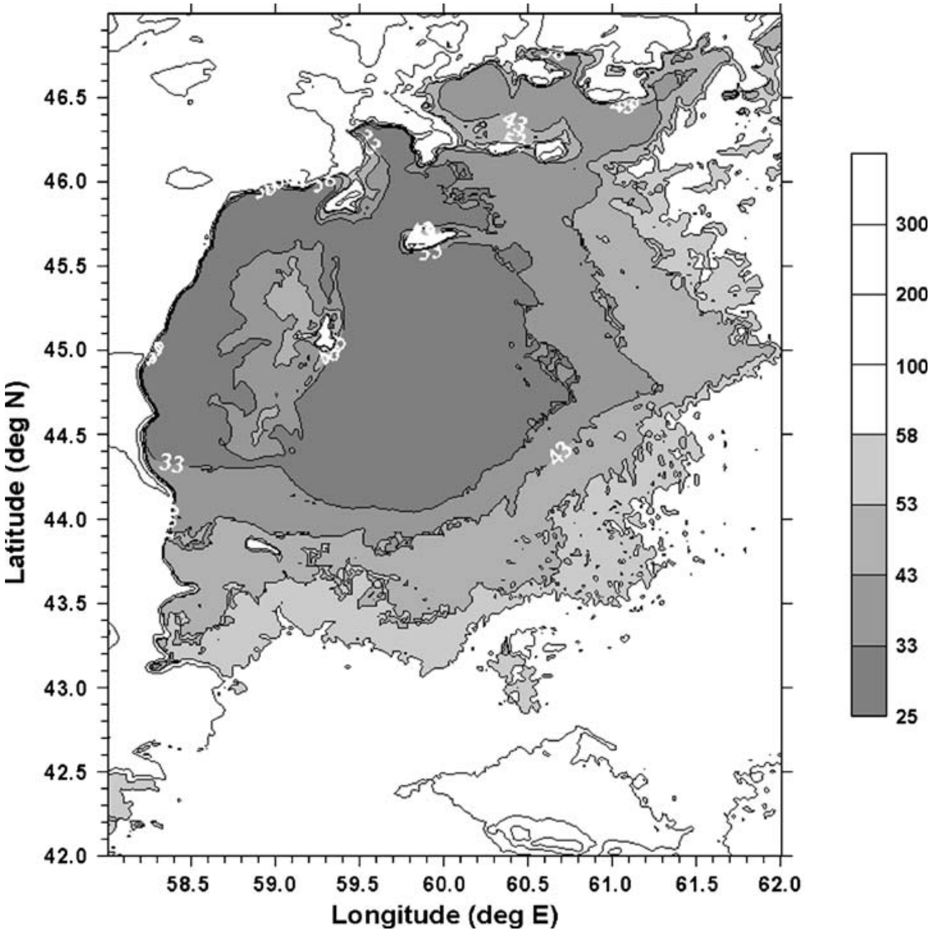

Fig. 7 Bathymetry of Aral Sea. The 1960 year level of the free water surface was 53 m asl

The influence of importing water from the Ob River Basin is shown in Table 3. The water level h in the Aral Sea increases and the salinity s decreases by increasing the inflow rate Q_{add}, as expected. Note that when h exceeds 33 m, the North basin of the Aral Sea becomes reconnected to the Western basin. The level reaches 99% of

Table 3 Influence of importing the water flow Q_{add} from Ob basin on Aral Sea free water surface level (h), surface (S) and salinity (s) after 75 years of refill

Q_{add} (km^3/year)	$r_{\mathrm{evap}} = 1.3$ m/year			$r_{\mathrm{evap}} = 1$ m/year		
	h (m asl)	S (km^2)	s (g/L)	h (m asl)	S (km^2)	s (g/L)
30	36.3	31,100	34	38.7	36,700	26
40	38.5	36,200	27	41.3	42,700	21
50	40.7	41,300	22	43.8	48,100	17
60	42.9	46,300	19	46.2	52,300	14
90	49.3	57,200	12	52.7	65,100	10

the stabilized value in Table 3 in about 30 to 40 years. The results prove to be strongly dependent on the evaporation rate r_{evap}. In case the evaporation rate continues to keep its present-day large value $r_{\text{evap}} = 1.3$ m/year, there is no reasonable macro-engineering solution to refill the Aral Sea to its ante-1960 volume (see Fig. 5). Even if the evaporation rate drops to its old value of $r_{\text{evap}} = 1$ m/year, only part of the old 1960 Aral Sea may be re-filled by "reasonable" large macro-projects.

4 Other Considerations

There are probably insufficient economical arguments to justify the major diversion of Siberian rivers to restore the Aral Sea, so it must be defended in part from a moral obligation by the world not to let persist such a long-term major ecological global eco-disaster. A reduction of the health problems caused by the saline and toxic dust storms originating in the dried up parts of the Aral Sea constitutes another ground for restoration.

Its execution may become beneficial for a very different reason. It is observed that the discharge of the Siberian rivers is recently on the increase, possibly as a consequence of post-Ice Age global warming. It is claimed that the additional inflow of large volumes of freshwater into the Arctic Sea may threaten the persistence of the great world ocean conveyor belt (Peterson et al. 2002). If the world conveyor belt would be affected, it could cause a drastic deterioration of the climate regimes in northwestern Europe. In that case the decision would no longer only depend on the rehabilitation of an ecological disaster region, but on the dire necessity to avoid a climatic catastrophe affecting hundreds of millions of people. The authors cannot judge the seriousness of this threat, as this is outside their field of competence.

A minor argument for the restoration of Aral Sea might be the fact that the drying up of the 1960 timeframe Aral Sea and the transfer of its water to the ocean has led to an additional global sea level rise of 3 mm, equivalent to almost 2 years of sea level rise as experienced during the 20th century. A restoration of the Aral Sea, associated with an expected increase of rainfall in the region, would, therefore, compensate 2 years of sea level rise.

5 Impact on Ecology

This paper focuses mainly on technical aspects. Ecological, cultural and social consequences of the macro-project (both positive and negative) have not been fully considered. To give a perspective, a few considerations are presented next.

Our proposal aims to achieve the best possible restoration of the situation before 1960, with lush wetlands in the Syr Darya delta, rich and diverse fishing in the Aral Lake itself, and absence of salty and toxic dust storms affecting public health. It is probably not possible to completely avoid the introduction of species foreign to the Aral Lake. On the other hand, if it turns out that valuable species have disappeared (like certain fish stock) due to the deterioration of the ecology of the Aral Basin, one should not hesitate to reintroduce such species.

Soils around the Aral Sea will have suffered from salinization, and an irrigation/drainage treatment should be set in motion to redress this. Based on experience in the Netherlands at the end of World War II, when large areas were inundated by sea water, addition of gypsum to saline soils may be useful, because thereby Na-clays are transformed into Ca-clays, with better agricultural properties.

Long-term refilling of the Aral Sea may have some important consequences for the nearby human population. First, a water-filled Aral Sea may change the climate, making it more favorable for human resettlement. Actually, it may to some extent restore the more benign climate as it was prior to the Aral Sea's technogenically-induced disappearance. Second, salty water from a regenerated Aral Sea may be used for seawater agriculture on suitable immediately adjacent farmable land.

Before the restoration is undertaken, it is recommended to

1. remove all rusting shipwrecks from the exposed seabed, except may be one or two to remain as a memorial, a landmark of warning against one-sided man-made impacts on a vulnerable ecology.;
2. fully map the restoration work site for future hydrographic and navigational charts
3. fully assess bathymetrically the new saline lake's bottom, just as if it were a commercial "real-estate" development lake.

6 Conclusions

The main options of restoring the Aral Sea are: (1) halting the cotton production, and let the waters of the Amu Darya and the Syr Darya rivers flow again into the Aral Sea; (2) pumping seawaters from the Black Sea and/or the Caspian Sea to the Aral Sea and (3) diverting waters from major Siberian rivers to the Aral Sea. The first two options are critically examined and arguments for the solution based on water transport from the Ob Basin to the Aral Sea are provided. It is concluded that water supply from major Siberian rivers offers a viable and sustainable solution. Even if this third solution is adopted, only part of the old 1960 Aral Sea may be re-filled by "reasonable" large macro-projects.

A new route for the required channel is proposed, which includes a long tunnel from Lake Zaisan to the Balkhash Lake. This track will depend essentially on gravity flow, it will be shorter and is likely to be considerably less expensive than earlier proposals. If successful, the Aral Sea restoration may serve as an example for other macro-engineering water redistribution schemes.

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