



## Variation of groundwater salinity in the partially irrigated Amudarya River delta, Uzbekistan

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### ABSTRACT

The Amudarya delta region contains surface and groundwater resources that discharge into the shrinking Large Aral Sea and ultimately control its future fate. These freshwater resources are prerequisites for sustaining the population of the region. However, salinization and pollution caused by agricultural irrigation is a key problem for these water systems. Here, we report results from a recent field measurement campaign conducted during April 2005 which included 24 monitoring wells located in an irrigated region of the Amudarya delta, thereby extending the historical data set of groundwater levels and salinity measurements. This data set is combined with corresponding data from a downstream, non-irrigated region that was formerly irrigated (together covering 16,100km<sup>2</sup> between the Uzbek cities of Nukus and Muynak). This comparison shows that in the downstream region, which is currently not irrigated, shallow groundwaters are far more saline (average 23g l<sup>-1</sup>) than the currently irrigated region (average 3g l<sup>-1</sup>). We estimate that the unconfined aquifer within the 13,500km<sup>2</sup> non-irrigated zone of study area contains 9billion tons of salt, or almost as much salt as the entire Aral Sea (containing 11billion tons of salt and covering an area of 20,000km<sup>2</sup> in year 2000). Within the non-irrigated zone, there are statistically significant large-scale spatial correlations between groundwater salinity and distance to the Amudarya River, irrigation canals and surface water bodies when distance is measured along the modelled regional groundwater flow direction. Generally, groundwater salinities are lower downstream of surface water bodies in the non-irrigated zone. Annual fluctuations in groundwater salinity are too large to be explained by input from surface water (Amudarya) or wind-blown salt from the dried Aral Sea sediments. Salt transport by groundwater is the only plausible remaining explanation for these changes.

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### 1. Introduction

The Aral Sea Crisis is one of the world's largest environment disasters, which has mainly been caused by an enormous expansion of agricultural irrigation within the Aral Sea Basin (ASB) during the 20th century. The sea's surface has decreased by 75% and its volume by 90% (Micklin, 2004) since the 1960s due to diversion of water of its tributaries for irrigation purposes. As a result, the sea is divided into two separate water bodies, the shallow Small Aral Sea in the north

and the southern Large Aral Sea. The shallow eastern basin and the deeper western part of the Large Aral Sea are currently connected by a narrow canal. This canal will dry up in the case of continuing sea level decrease.

Due to the considerably decreased surface water inflow, groundwater inflow has become a significant freshwater component of the water budget of the Larger Aral Sea (Jarsjö and Destouni, 2004). The discharge of the Syr Darya, which feeds the Small Aral Sea, is high enough to counterbalance the evaporative water loss of this lake. Additionally, discharge of water from the Small Aral Sea into the Large Aral Sea is restricted by an artificial dam. The groundwater discharge and the discharge of the Amudarya, which feed the Large Aral Sea,

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are not currently sufficient to prevent its ongoing salinization and shrinkage (e.g., Peneva et al., 2004; Friedrich and Oberhänsli, 2004; Benduhn and Renard, 2004; Gascoïn and Renard, 2005). Zavalov et al. (2003) found that the salinities<sup>1</sup> of the western basin of the Large Aral Sea in 2002 ranged between 90 and 104 g l<sup>-1</sup>, with the lower value representing conditions in the upper layer of the sea and the higher value representing conditions at the sea bottom. In 2005 the surface water salinity of the western basin reached above 109 g l<sup>-1</sup> (Zavalov et al., 2006). Due to the drastic change from the pre-1960 average salinity of 10 g l<sup>-1</sup> the Large Aral Sea has lost its former natural resource values, particularly its fish stocks which are not expected to recover in foreseeable future.

In contrast to the Aral Sea, artificial water reservoirs and small lakes within the adjacent Amudarya delta still possess realistic future potential for freshwater supply and fish production on the basis of an improved water resource management (Karimov et al., 2004). The United Nations Environmental Programmes Global International Waters Assessment (UNEP-GIWA) identified salinization and freshwater pollution as key problems hindering the development of the Aral Sea region (Severskiy, 2004). Today, the Amudarya River delta is severely affected by salinization, pesticide and nutrient pollution because it receives multiple irrigation waters from the catchment of the river. Additionally, the delta region receives influx of salt and pollutants from the dried sea floor by eolian deposition (Razakov and Kosnazarov, 1996). In order to understand the dominant processes that govern the spread of salt (and potentially also other pollutants), and to model these processes, detailed hydrogeological and geochemical data are needed. Furthermore, there is a need for the quantification of large-scale relationships between spatially varying land use-irrigation practices and downstream soil–water pollution and salinization development.

In (irrigated) arid areas with shallow groundwater tables, upward capillary water flow is the main cause for soil and groundwater salinization (e.g., Ceuppens and Wopereis, 1999; Northey et al., 2006). Understanding irrigation effects on large-scale salinity distribution is commonly limited by the availability of observational data, even though supporting analysis tools and models have been developed (see Utset and Borroto, 2001). Due to the clear environmental changes and existing monitoring sites and measurement data, the Amudarya delta region offers good conditions to investigate large-scale transport of salts and pollutants. Water quality data, including data on pesticide concentrations, are available for a long historical period at relatively high spatial and temporal resolution. Contaminant concentrations are often very high, which allows their detection over a large dilution range. Furthermore, as shown by e.g. Shibuo et al. (2006) and Alekseeva et al. (2009–this issue), the depth of the groundwater table is low. This means that analyses of surface topography and surface slopes can be used for quantification of hydraulic gradients, groundwater flows and near-coastal groundwater–sea water exchange (Shibuo et al., 2007; Jarsjö et al., 2008).

The major goals of our study are:

- Compilation of unpublished monitoring data of groundwater levels and groundwater salinity;
- Extending existing measurement series by our own measurements;
- Analysis of the spatial and temporal development of groundwater level and salinity in the Amudarya delta;
- Analysis of large-scale relations between land use-irrigation practices and downstream soil–groundwater–surface water salinization;
- Analysis of the causality of observed salinization trends of local groundwater and surface waters in the Amudarya delta and their consequences for the development of the Large Aral Sea.

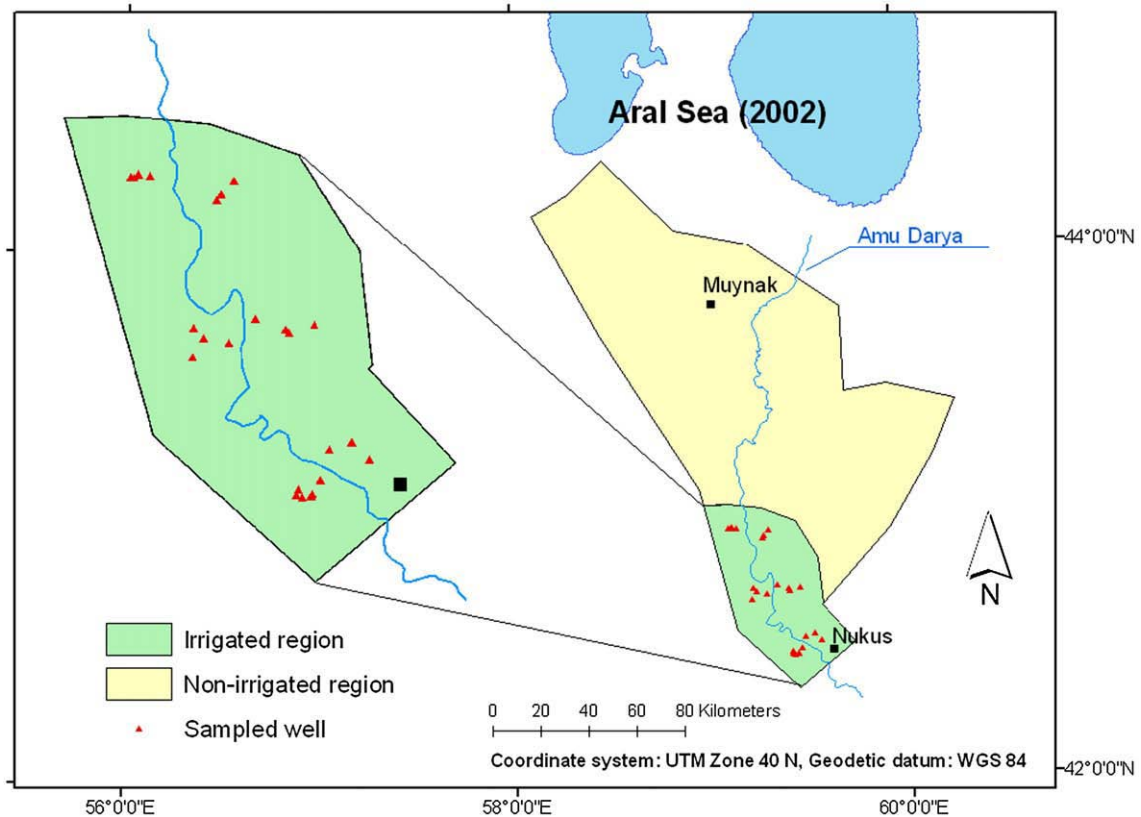
## 2. Field investigation site and methods

### 2.1. Study area and field measurements

Fig. 1 shows the study area, which covers approximately 16,100 km<sup>2</sup>. As part of the study we will investigate the top part (<5 m) of the unconfined aquifer, which is most likely to be affected by agricultural activities. The aquifer ranges in depth between 10 and 150 m (see e.g. summary of Shibuo et al., 2006). 90m Digital Elevation Data (Shuttle Radar Topographic Mission, National Aeronautics and Space Agency; <http://srtm.csi.cgiar.org/>, 2005-06-08) show that the elevation of the study area varies between – 18 and 255 m a.s.l., and most of the area is flat with an elevation of about 30 m a.s.l. A large part of the study area was formerly irrigated. Today, only the southern part is used for irrigated agriculture (Fig. 1). The surface waters of the study area contain a significant amount of irrigational return-waters from upstream areas, which in turn are again used for irrigation. The area comprises wetlands that are important reserves for the remaining flora and fauna (Verhoog, 2000; de Schutter and Dukhovny, 2003). Geologically, the area comprises dried-up sediments from the Amy Darya river on top of Quaternary deposits. The aquifers contain gravel, sand, sandstone and loamy sandy sediments. The soil salinity ranges between relatively low and high. When the salinity is moderate to high, the soils are called solonchaks and are commonly characterized by saline crusts (Singer et al., 2001).

The field campaign reported here is a continuation of the measurement series of the Karakalpak Hydromelioration Expedition (KHE). We used 24 groundwater monitoring wells (capped steel pipes with a diameter of 1 dm encased in concrete rings) that were also analysed in the monitoring program of the KHE and are located in the currently irrigated area (see Fig. 1). In order to obtain comparable results, the groundwater sampling procedures used were consistent with those used by the KHE. More than 500 wells are currently administered by the KHE. In previous hydraulic evaluations carried out by the KHE, the investigated 24 wells showed intact hydraulic connection with the surrounding aquifer. The depth to the groundwater table was measured using a floating weight on a graded string. Groundwater salinity was measured with a portable conductivity meter. The groundwater samples analyzed for conductivity were taken

<sup>1</sup> Volume-based units are used for consistency with our earlier work (e.g., Jarsjö and Destouni, 2004), noting that x g l<sup>-1</sup> corresponds to the mass fraction  $x/(1+x/1000)$  g × kg<sup>-1</sup>, yielding specifically 104 g l<sup>-1</sup> = 94 g × kg<sup>-1</sup> and 10.0 g l<sup>-1</sup> = 9.9 g × kg<sup>-1</sup>.



**Fig. 1.** The study area, covering 16,100 km<sup>2</sup> within the Amudarya delta to the south of the Large Aral Sea, and its division into an irrigated part (green color) a non-irrigated part (yellow color). Filled triangles indicate the location of measurement wells within the irrigated region; see Table 1 of the supplementary information for further details. See also Table 2 in supplementary information for details on groundwater wells within the non-irrigated region.

approximately 1m below the groundwater table. The geographical coordinates of the monitoring wells were determined by means of a GPS. We used groundwater level and salinity data from the month of April of the years 1996 to 2004. Furthermore, we analysed corresponding data for wells outside the currently irrigated region covering the years 1990 to 1999, as measured by the organisation "Prearialie Hydrogeologic Expedition" (2003) and listed in the supplementary information (Table 2).

## 2.2. Methods and software

Groundwater salinities in mass units per volume were determined on the basis of (electrical) conductivity measurements. The Standard SIS 028123 of the Swedish Standards Institute (Stockholm) was used for calibration, considering salinities up to 15 g/l. Variations in the cation and anion composition of the groundwater cause some uncertainties regarding the transformation of measured conductivities into solute mass per unit volume. Data from the lower Amudarya River region of Khamzina et al (2006) demonstrate a prevalence of Cl<sup>-</sup> and SO<sub>4</sub><sup>2-</sup> in the first metre of soil. The molar weight of SO<sub>4</sub><sup>2-</sup> exceeds that of Cl<sup>-</sup> by 2.7 times. Since the heavier SO<sub>4</sub><sup>2-</sup> ion has a molar conductivity that is about 2 times higher than that of Cl<sup>-</sup> (e.g. Matthews, 1992), the conductance per mass unit differs by about 25% between the two ions only. The errors of salinity determinations may be in

the order of 5 to 10% according to back-of-the envelope calculations, which we consider to be acceptable in the light of the very large salinity ranges. The reliability of inferred relative salinity differences is considerably better since any systematic errors due to uncertain basic salt composition will cancel.

Processing of spatially distributed data was performed using the software ArcGIS 9 (Environmental Systems Research Institute, Inc). ArcGIS 9 provides functions for coordinate system transformation and distance calculation, tools for vector to raster data and raster to vector data transformation, and database functions such as joining tables. Spatial data on ground surface and groundwater surface elevations were interpolated using the Natural Neighbour method (Sibson, 1981). Irregularities in the interpolated ground surface and groundwater surface were identified and subsequently smoothed. Furthermore, hydrological GIS tools (ArchHydro 1.1 Tools for ArcGIS 9) were used to calculate regional groundwater flow directions, groundwater flow paths, and distances along the groundwater flow paths; specifically distances from upgradient surface waters to downgradient groundwater observation wells.

The Aral Seas extent in 2002, the Amudarya, irrigation and drainage canals, and other (smaller) water bodies were represented by vector data, delineated by the Nukus GIS center, Nukus University (per contact Victor Statov). We tested whether or not regional mean groundwater properties

(salinities and levels) exhibited statistically significant differences between two considered regions, using Student's *t*-test of the Software Statistica (ver. 6; StatSoft). Significance tests of correlations between two variables were also performed using Statistica.

### 3. Groundwater hydraulics and salinity distribution

Fig. 2a shows the estimated regional groundwater flow directions in the study area representing average conditions of irrigated (1996–2005) and non-irrigated regions (1990–1999) during the month of April. Flow directions were derived from annual measurements of groundwater levels of overall 76 wells with 25 wells located in the irrigated area. Flow directions during spring do not show significant inter-annual variations in the considered periods (see Johansson, 2006 for details). Regional groundwater flow directions are divergent.

To the east of Amudarya groundwater flows towards the north-east, whereas it flows north-westwardly to the west of Amudarya.

Irrigated and non-irrigated areas have distinctly different groundwater tables (Fig. 2b). The average April depth of the groundwater table below the land surface was 2.2 m in the irrigated region (1996–2005) and 4.8 m in the non-irrigated region (1990–1999). Although the depths show some spatial variation in each region, the differences in the depths of groundwater tables between the regions are statistically significant. Since the time series of groundwater depth in the non-irrigated area is older than the time series of the irrigated area, the difference between the derived averages would represent actual mean differences in groundwater depth only if temporal trends are negligible. Fig. 2b indicates that the inter-annual variations of average groundwater levels seem to lack such trends.

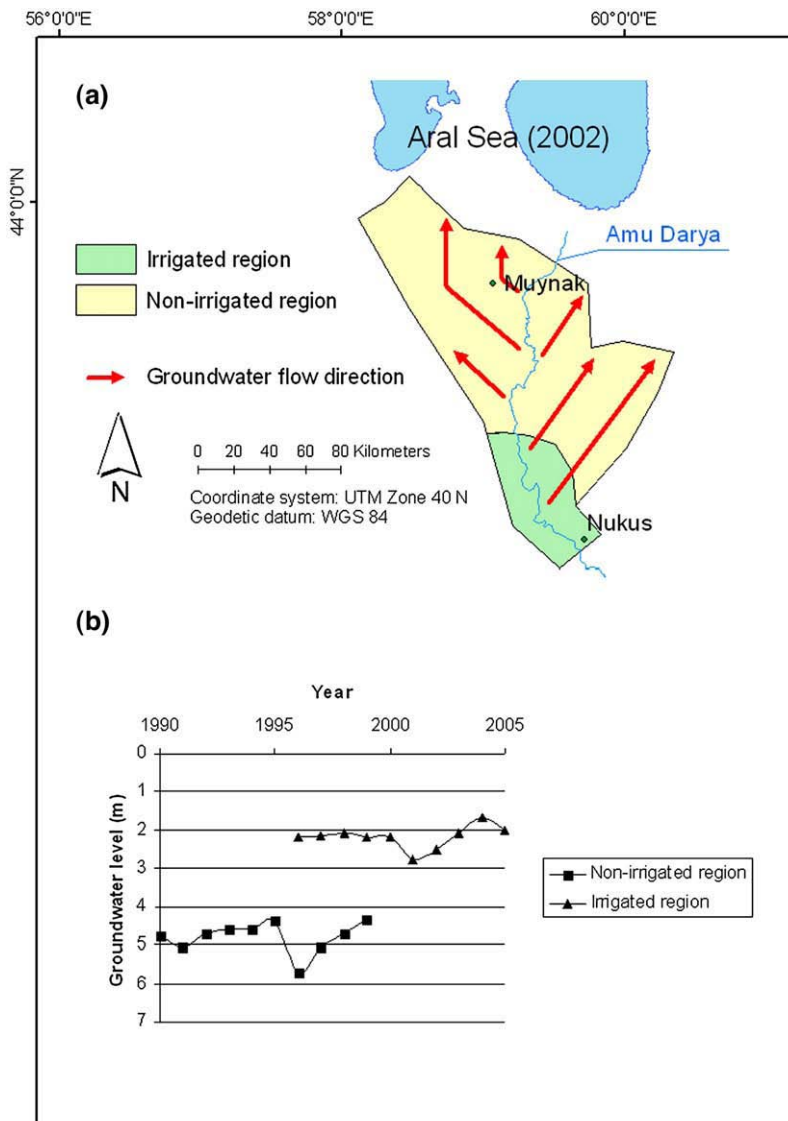


Fig. 2. (a) Groundwater flow directions in the study area, interpolated from measured groundwater levels in 76 wells, and (b) inter-annual groundwater level variability in both the non-irrigated and the irrigated parts of the study area, considering the conditions at the start of the growing season (month of April).

The inferred salinity distribution of groundwater in the irrigated area, based on measurements during the sampling campaign in 2005, is shown in Fig. 3. For the entire region, the mean groundwater salinity is  $2.7 \text{ g l}^{-1}$ , whereas it is as high as  $17.8 \text{ g l}^{-1}$  in its southern part. The lowest groundwater salinity was  $0.78 \text{ g l}^{-1}$ ; most of the wells showed much higher salinities (Table 1, supplementary materials). Water tastes salty above  $0.25 \text{ g l}^{-1}$ . The Uzbek national maximum limit for drinking water is  $1 \text{ g l}^{-1}$ , which means that most wells exceed this limit. The shallow groundwater of the study area is therefore not suitable as drinking water.

Observed inter-annual changes of groundwater water levels (for instance, Fig. 2b) indicate a highly dynamic groundwater system. In the following section, we extend the temporal and spatial analyses of groundwater levels and salinities by consideration of the data of previous measurement campaigns and monitoring. We focus on long-term

trends at the beginning of the growing season (April), when hydrologic conditions are of importance for the crop growth.

Fig. 4a shows the average salinities of monitored wells inside the given rectangles considering the period 1990–1999 in the non-irrigated region and 1996–2005 in the irrigated region. The plot demonstrates downstream groundwater salinity trends along the approximated groundwater flow directions (cp. Fig. 2a). In the non-irrigated area, the salinity decreases with an increasing distance to the Aral Seas. Salinity values above  $60 \text{ g l}^{-1}$  were obtained at the groundwater sampling sites that were the closest to the Seas. There are several possible explanations for this trend. (i) An increasing groundwater salinity towards the present sea margin may reflect the presence of brines below the sea bottom. (ii) Leaching of salts from dried sea sediments which cover the northern part of the study site can, at least, locally enhance the groundwater salinity. (iii) The former lake

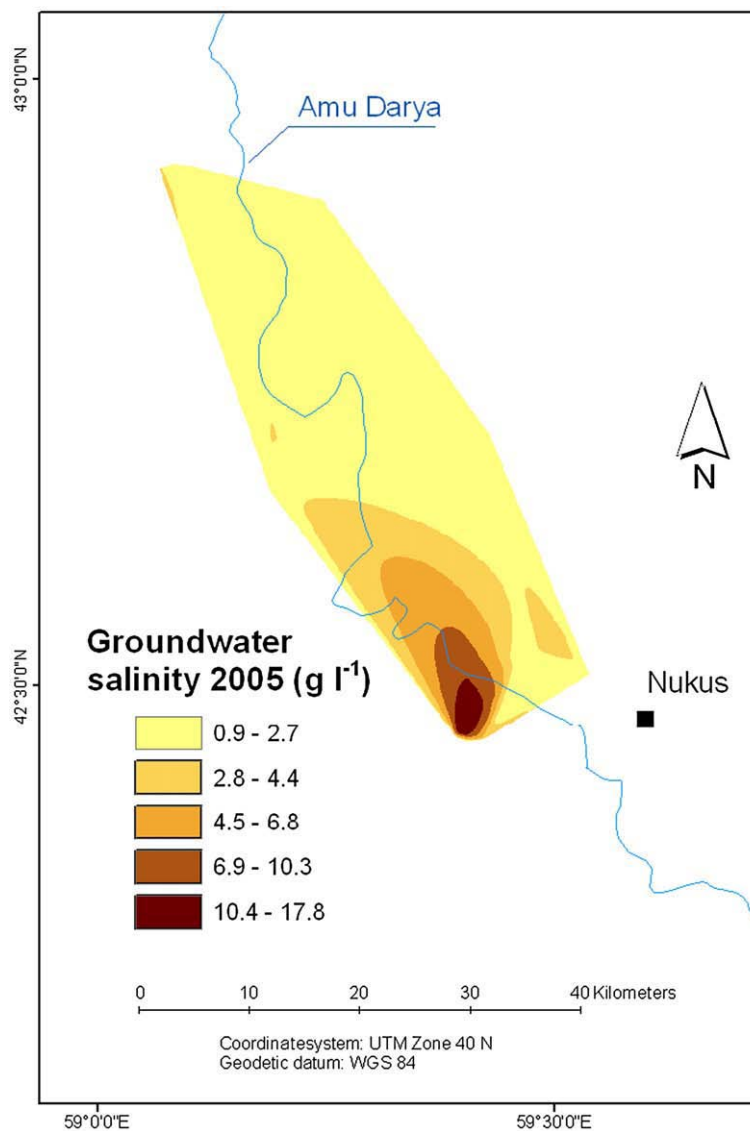
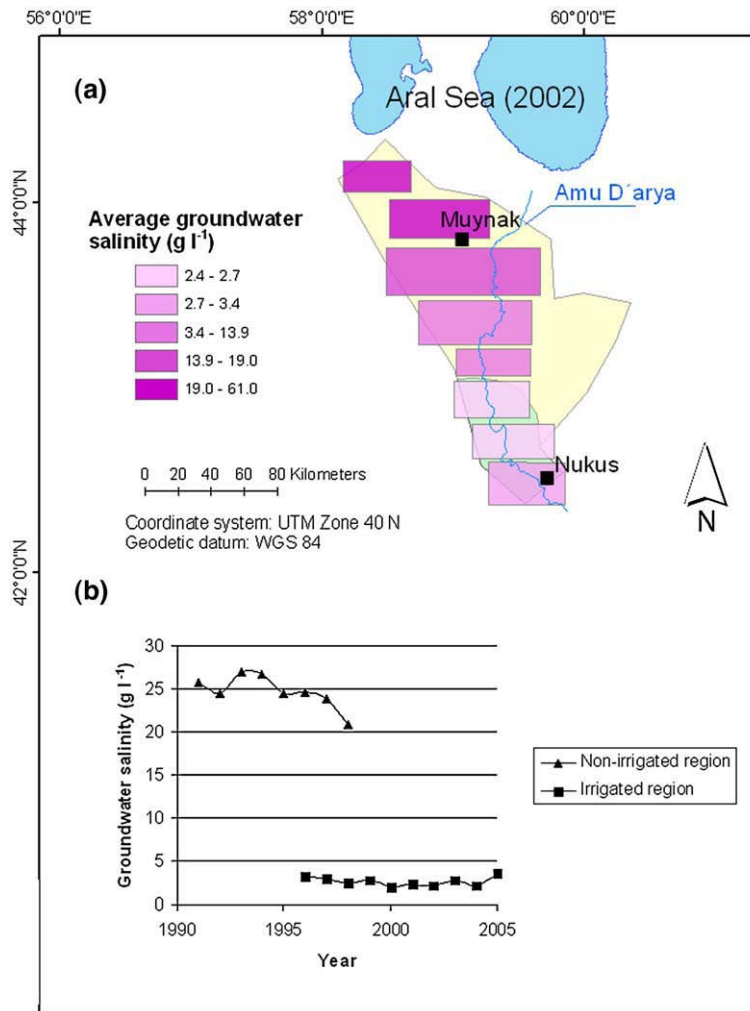


Fig. 3. Groundwater salinity above 5 m depth of the upper unconfined aquifer, in the irrigated part of the study area, at the start of the growing season (April 2005), obtained through interpolation of observations in measurement wells (see Fig. 1 and Table 1 of the supplementary information).

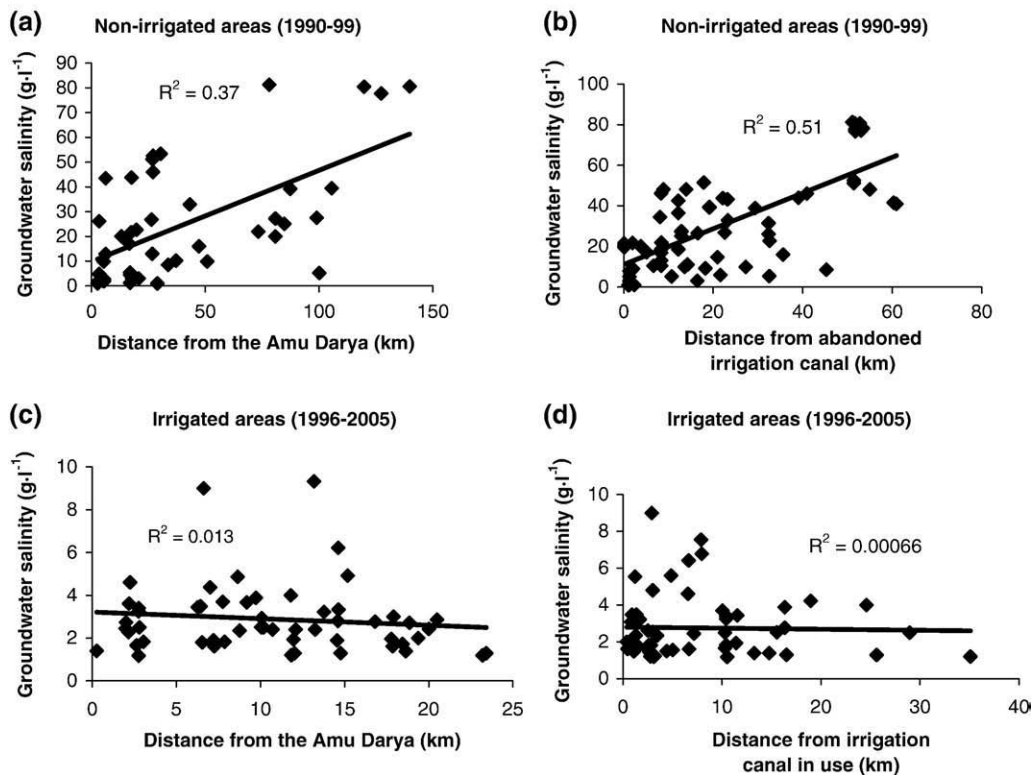


**Fig. 4.** (a) Groundwater salinity above 5 m depth of the upper unconfined aquifer, in different parts of the study area, at the start of the growing season (April). The colours of the squares represent the spatially and temporally averaged salinity of the measurement wells contained within the square, considering the period 1990–1999 in the non-irrigated region and 1996–2005 in the irrigated region. (b) temporal development of the groundwater salinity in the month of April, considering the whole (non-irrigated and irrigated) region.

bottom is exposed to wind erosion. Besides sea spray, it represents a source for eolian export of solid salt particles. Eolian deposition of sea salt onto the surface of the study area diminishes with increasing distance to the Aral Sea. Groundwater salinities show an opposite trend in the irrigated area (Figs. 3, 4a). This indicates that different and/or additional processes may act as a result of irrigation. For instance, evapo–concentration of salts in the irrigated fields can cause regionally increased salinities in upstream areas. Comparing the average groundwater salinities of the upstream irrigated regions and the downstream non-irrigated regions (that were formerly irrigated), it becomes clear that the latter region has much higher salinities (Fig. 4a). Fig. 4b specifically shows that the inter-annual variations of groundwater salinity within each region are much smaller than the salinity difference between the upstream irrigated region and the downstream non-irrigated region.

Groundwater salinities in monitoring wells differ considerably on a 10-km scale (Figs. 3, 4a). Fig. 5 shows local

groundwater salinity values measured between 1990 and 1999 for the non-irrigated areas and between 1996 and 2005 for the irrigated areas. These results illustrate the possible effects of local hydrologic conditions, such as the proximity to the Amudarya River and engineered water systems such as irrigation or drainage canals. Groundwater salinities are positively correlated with the distances to the Amudarya and to abandoned irrigation canals (Fig. 5a,b). Distance is measured along mean groundwater flow paths (red arrows in Fig. 2a) following the groundwater flow direction from the Amudarya (or the irrigation canal) to the groundwater observation well. Groundwater salinities are generally lower near the Amudarya and close to irrigation canals. Inter-annual salinity changes seem to weaken the correlation between salinity values and distances to the Amudarya or irrigation canals (entire data set:  $R^2 \approx 0.4$ ). The correlations distinctly improve at annual scale. In 1994, the correlation coefficient between salinity and distance to irrigation canals in use is 0.9, for instance.



**Fig. 5.** Observed groundwater salinity in measurement wells of the non-irrigated area versus their distance, measured along the groundwater flow direction, from (a) the Amudarya River and (b) abandoned irrigation canals; and in measurement wells of the irrigated area versus their distance, measured along the groundwater flow direction, from (c) the Amudarya River and (d) irrigation canals in use.

In the study area, the groundwater salinity generally exceeds the salt contents of the river water and that of freshwater used for irrigation. Therefore, infiltration of river water and seepage of freshwater in the irrigation canals should have a dilution effect on groundwater composition. In the non-irrigated area where there is no agricultural production, abandoned irrigation canals (considered in Fig. 5b) are still linked with the natural surface water system; some of these canals still receive an inflow of water from the Amudarya. Correlations between the groundwater salinities and the distance to drainage canals and to the terminal freshwater ponds of the wetlands could also be proved (Johansson, 2006). The interpolated salinities of the groundwater below the wetland reservoirs exceed that of the lower-salinity waters of the wetlands (Mamatov, 2002) by more than  $30 \text{ g l}^{-1}$ .

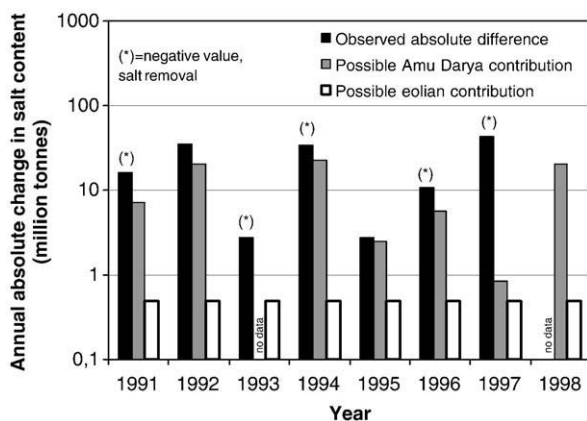
In contrast to the non-irrigated area, results for the irrigated area show that groundwater salinities (full data set in supplementary information, Table 1) are neither correlated with groundwater flow distances to the Amudarya nor with the distances to the irrigation canals (Fig. 5c,d). Inter-annual salinity variations in the measurement period (1996–2005) can possibly mask potentially existing salinity–distance correlations. However, considering single years only, no correlation between the groundwater salinities and the distances to the Amudarya, or the distances to irrigation canals in use, are detectable for the irrigated area. A possible explanation for the absence of salinity–distance correlations

in the irrigated area is that its lower salinity of shallow groundwater makes the salinity contrast between groundwater and surface water too small to be detectable. Three major factors can contribute to the lower salinity of the shallow groundwater in the currently irrigated area. One factor is that the irrigated area is located at a greater distance to the exposed former sea floor of the Aral Sea (as compared with the non-irrigated area; decreasing the exposure to wind-blown salts (see above discussion of Fig. 3). Besides the direct dilution effect by seepage of freshwater (e.g., O'Hara, 1997; Northey et al., 2006), a main factor is presumably the applied irrigation practice of flooding fields in spring, thereby dissolving soil salt and removing it in a dissolved form via surface water discharge into the Aral Sea or into one of the smaller artificial salt lakes in the region. The above irrigation practice can sustain shallow groundwater salinities at a relatively low level. If irrigation ceases (e.g. if land has to be abandoned due to water shortage), the salinity of local, shallow groundwater may increase, as observed in this study. However, without externally added irrigation water, soil water flows will decrease at the same time. In the upper part of the aquifer, salinities can get relatively high due to flow stagnation and evapo-concentration of salt, even though salt carried by the irrigation water will no longer be added. A factor that is likely to be important for the shallow groundwater salinity is the vertical transport of salts in the saturated zone, which will be discussed in the following section.

#### 4. Implications – possible total amount of salt and salt transport processes

We consider the upper 4m of the about 100m deep unconfined aquifer within the non-irrigated area (13,500km<sup>2</sup>; yellow in Figs. 1 and 2), and estimate that this zone contains approximately 360million tons of dissolved salt. The estimate is based on a mean aquifer porosity of 0.27 (Aimbetov, 1999) and the average of the derived groundwater salinities between 1991 and 1998 (Fig. 4b). The average shallow groundwater salinity of the irrigated area (2600km<sup>2</sup>) was about eight times lower than the average of the non-irrigated area during the period 1996 to 1998 (Fig. 4). The total amount of dissolved salt in the top 4m aquifer of the irrigated area is relatively small and accounts for less than 3% of the value derived for the non-irrigated area.

Assuming that the groundwater salinity of the upper 4m of the aquifer within the non-irrigated area is representative for the entire 100m deep aquifer of the non-irrigated area, the latter contains 9billion tons of dissolved salt, which is almost as much as the 11billion tons of salt dissolved in the Aral Seas (estimate of Glazovsky, 1995). The black bars shown in Fig. 6 give the total amount of salt that has to be added or removed to reproduce the inter-annual changes in groundwater salinity of the upper 4 m aquifer in the non-irrigated area (Fig. 4b). However, given that the inter-annual changes are relatively large, a key question posed is to which extent each of the plausible transport pathways (i.e., the eolian pathway, the surface water pathway, and the groundwater pathway) can contribute to the observed temporal changes in average salinity (cp. Fig. 4b). The changes observed in the non-irrigated area during the period 1991 to 1998 include two events where the derived mean shallow groundwater salinity increases between the consecutive spring seasons 1992/93 and 1995/96, whereas the groundwater salinity show decreasing trends between remaining consecutive spring seasons (Fig. 4b).



**Fig. 6.** Annual absolute change in groundwater salt content in the top 4 metres of the aquifer in the study area (estimated based on measurement data from observation wells), compared with possible addition of salt by eolian processes (Razakov and Kosnazarov, 1996) and by the Amudarya River (Mamatov, 2003). Since the salt mass is calculated as groundwater salinity times pore volume, the resulting salt mass estimate scales linearly with the assumed porosity value, which introduces an uncertainty in the estimation (black bars) of.

For comparison with the relatively large inter-annual salinity changes, we estimate a maximum salt addition from surface water, assuming that the complete dissolved salt load from the Amudarya River at the upstream Samanbay gauging station (this salt mass was derived from flow and salinity measurements at the gauging station by Mamatov, 2003) is evapo-concentrated and added to the groundwater in the non-irrigated part of the study area. We find that this maximum possible addition of salt to the groundwater in the study area from surface water (Amudarya; grey bars in Fig. 6) is not sufficient to explain the observed salinity variations in the non-irrigated area (black bars in Fig. 6) for the two events with substantial year to year salinity increase of the shallow groundwater that occurred during 1992 and 1995. An eolian influx of salt particles from the former Aral Sea-bed may also contribute to salinity increases of shallow groundwater. However, Fig. 6 shows that the observed inter-annual salinity changes exceed estimates for the possible annual atmospheric influx of salt particles (white bars; eolian contribution) by one order of magnitude. We calculated the shown value of possible annual eolian deposition over the non-irrigated area (0.5tons) on the basis of an estimate of the area-averaged eolian deposition as a function of distance from the Aral Sea by Razakov and Kosnazarov (1996).

Since the inter-annual salinity changes are too large to be explained by surface water transport or eolian transport, salt transport by groundwater is the only plausible remaining explanation. Such transport may occur through (i) (horizontal advective) salt movement along the mean groundwater flow direction, (ii) vertical groundwater movements and evapo-concentration of salt in shallow groundwater (e.g. driven by a possibly considerable evaporation from the groundwater surface during the warm season) or (iii) some combination of (i) and (ii). Although we show that considerable salt transport by groundwater must take place for explaining the observed large inter-annual salinity changes, the present data can not be used to draw further conclusions on the relative importance of (i) and (ii). Regarding soil salinity, Aimbetov (1999) and Ceuppens and Wopereis (1999) have identified vertical salt transport as important for explaining observations of temporal changes in soil salinities in the upper 10m of the soil.

#### 5. Conclusions

The study area is divided into an upstream irrigated zone and a downstream presently non-irrigated zone that was formerly irrigated to a large extent. The salinity of shallow groundwater is significantly higher in the non-irrigated zone than in the irrigated zone, which illustrates how the salinity of local, shallow groundwater may increase if irrigation ceases. In the non-irrigated zone, the shallow groundwater salinity is generally much higher than the surface water salinity reported for the same zone by e.g. Mamatov (2003). Near the Amudarya and abandoned irrigation canals the groundwater salinity is lower than the average value for the whole non-irrigated zone. Corresponding trends cannot be found in the irrigated zone. We observe distinct annual fluctuations in groundwater salinity that are too large to be explained by input from surface water (Amudarya) or wind-blown salt from the dried Aral Sea sediments. Salt transport by

groundwater is the only plausible remaining explanation for these changes. With extended groundwater monitoring (increased sampling density and vertical extent), the understanding of the dynamic groundwater and surface water systems can be further improved.

### Acknowledgements

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### Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at [doi:10.1016/j.jmarsys.2008.03.017](https://doi.org/10.1016/j.jmarsys.2008.03.017).

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