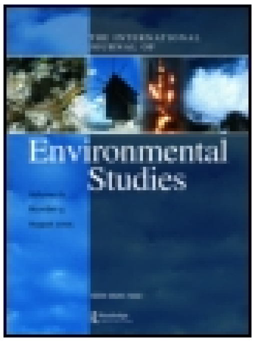

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Assessment and forecasting of the subsurface drain of the Aral Sea, Central Asia

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ABSTRACT
Mathematical simulation techniques have been used to study the subsurface water-lake system. The volume of the subsurface drain from the Syrdarya artesian basin (Kazakhstan) into the Aral Sea depression was computed subject to the geoinformation-mathematical model of its hydrogeological conditions. Since the surface and subsurface (underground) water are interconnected, their movement has been measured during the undisturbed period (1960), the epignostic (1961–2014) period, and for forecasting problems for 2044 under two water withdrawal options. The first forecast option assumes the same withdrawal volume of subsurface water level which existed at the end of 2014. The second forecast option envisages the model assignment (from the start of 2015) of the water withdrawal in the production volumes of the subsurface water approved by the National Reserves Committee of the Republic of Kazakhstan. The simulation results showed that the technogenic factors in the explored area have a significant impact on the movement of the subsurface and surface water. Reduction of the Syrdarya and Amudarya rivers flows, production of subsurface water with multiple water-intake and unowned self-flowing wellbores promoted the desiccation of the Aral Sea. The proposed mathematical simulation technique used to assess the subsurface drain proved its efficiency and can be used for surveying the similar subsurface water-lake systems.

KEYWORDS
Groundwater; mathematical model; GIS; Aral Sea

Introduction

Subsurface flow is one of the main lake water balance components. Its changes may impact the quantitative and qualitative composition of the lake water in a negative manner [1–3]. Mathematical simulation is one efficient technique to study the subsurface water-lake system.

Integrated surface and groundwater modelling are complex tools for interpreting the full water cycle balance [4]. The interchange of the water-bearing soil and lakes is simulated through various hydrogeological units [4–12]. The efficient use of water resources in the lake regions is assessed with subsurface drain models [13–15]. Numerical simulation allows

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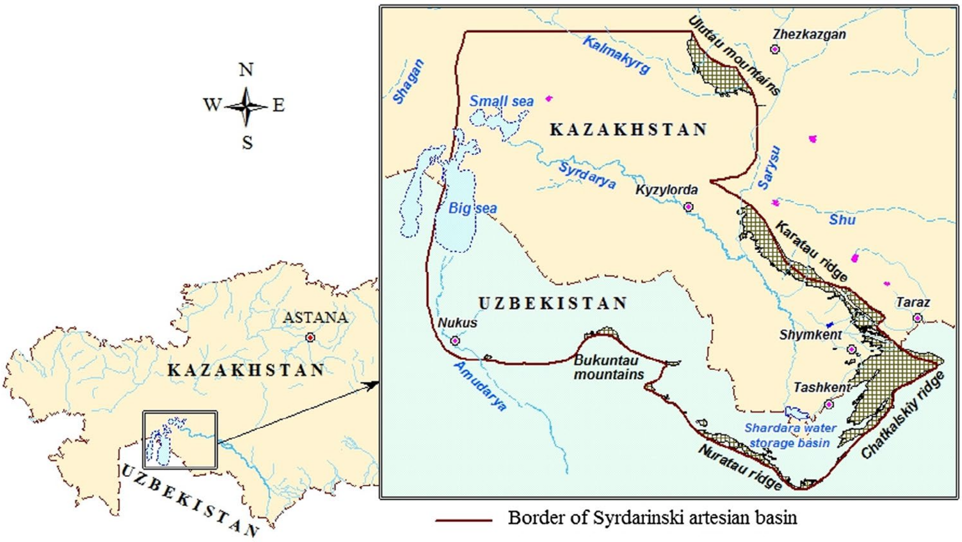

Figure 1. Research area: Aral Lake sub-basin with Syrdarinski artesian basin.

researchers to forecast the impact of climate variations on the water balance of bodies of water [16–19]. The mathematical subsurface drain models were established to identify causes and changes of a lake's salinity [20,21]. Human activities, such as agricultural work, significantly impact the subsurface water and present a potential threat to the lake's condition. The mathematical hydrogeological models were developed for these types of territories with anthropogenic changes [17,19,22–29]. Empirical or experimental surveying methods are complicated in many remote areas, because of difficulties in collecting detailed field data. Therefore, mathematical simulations are used both for collected field data and for prediction analysis [30–33].

The aim of this article is to improve the mathematical simulation techniques used to assess the subsurface drain to the Aral Sea depression, a no-flow salt lake in Central Asia. Over time, a number of scientists from various countries have dedicated their efforts to the problems of the Aral Sea region [34–43].

The Amurdarya and Syrdarya rivers are the main rivers in the Aral Sea (Figure 1). The Syrdarinski artesian basin represents a complex multiple-layer fluid-flow system with subsurface, underground water interchangeable system connected to the Aral Sea. The basin spreads from the mountain highlands in the east and south-east to the Aral Sea in the west and is located in the territory of two countries – Kazakhstan and Uzbekistan (Figure 1).

Studies of the devastating shrinkage of the Aral Sea and the subsurface water-salt drain directly in the depression were initiated by V.N. Lvov [44] and I.M. Chernenko [45], who published a number of articles from 1965 to 1972, as well as by N. S. Pashkovskiy, who built a model of the head water discharge across the low-permeable layers using the EHDA (electrohydrodynamic analogy) technique in 1969 [46]. This research was further continued by U.M. Akhmedsafin, J.S. Sydykov, S.M. Shapiro, N.N. Khodzhibayev, I.S. Zektser, V.I. Poryadin, T.N. Vinnikova, N.V. Kalmykova, and V.P. Zolotarev between 1975 and 1980 [47–49].

The basin territory was studied and measured with several mathematical models of hydrogeological conditions in the basin of the Aral Sea [50], the Eastern Aral Sea region [51,52], and the Kyzyljarmin Field of subsurface water [53,54].

These models were used to solve a certain range of hydrogeological problems and, in particular, they assessed the subsurface drain in the Aral Sea. According to the research data, the subsurface influx volume in the depression varied from 0.5 to 5.5 km^3/year. Veselov and Panichkin suggested using methods of geoinformational-mathematical simulation for the study of hydrogeological conditions of Eastern Aral Sea sub basin area [51].

Decision-making on the rational use of subsurface water resources, their protection against depletion and pollution, and assessment of the impact on the transboundary subsurface drain was assisted by the regional geoinformation-mathematical hydrogeological model of the Syrdarya artesian basin [52]. Related work was completed at the Hydrogeology and Geoecology Institute named after U.M. Akhmedsafin (in Almaty, Kazakhstan). In our current model we adjusted and refined the previous models, assessed the current subsurface drain of the Aral Sea, and predicted changes up to the year 2044.

Materials and methods

Input data

Figure 1 shows the border of the regional Syrdarya artesian basin model. The five main water-bearing geological layers singled out in the basin territory are the Neogene-Quaternary (N-Q), the Upper Eocene (P_2^3-sk), the Upper Turonian-Senonian (K_2t_2-sn), the Upper Albian-Cenomanian (K_1al_3-K_2s) and the Lower-Middle Albian-Jurassic (K_1al_{1-2}-J) deposits. The water-bearing geological layers are split by three regional deposits of impermeable material: the Paleogene (P), the Lower Turonian (K_2t_1), and the Lower-Middle Albian (K_1al_{1-2}). These are distributed throughout. There are also Chegan argillites in the north-western part of the described territory (P_{2-3}cg) (Figure 2).

Schematization of the hydrogeological conditions

MapInfo 10 [55] and ArcGIS 10.0 [56] were selected as tools for creating the geoinformation model, and the Groundwater Modeling System GMS 9 [57] was selected to make the mathematical model.

Schematization of the hydrogeological conditions includes justification of the fluid-flow chart, selection of the analysis method and tools, and drawing up of the initial filtration flow chart. The schematization was based on the hydrogeological sections, hydrogeological maps, actual data, data on the water intake efficiency, subsurface and surface water behaviours and other data, as well as distribution maps for the water-enclosing, water-resistant and low-permeable deposits of various age and plots of their outcrops, and on the daily measurements of surface water movement.

The schematization allowed the region's five water-bearing interconnected layers which flowed across four dividing low-permeable layers to be singled out.

The simulated region was approximated by the orthogonal uniform net in increments of 5000 m. The dimensionality plan of the grid is $M \times N = 232 \times 162$, while the sectional view of the grid is 22 units.

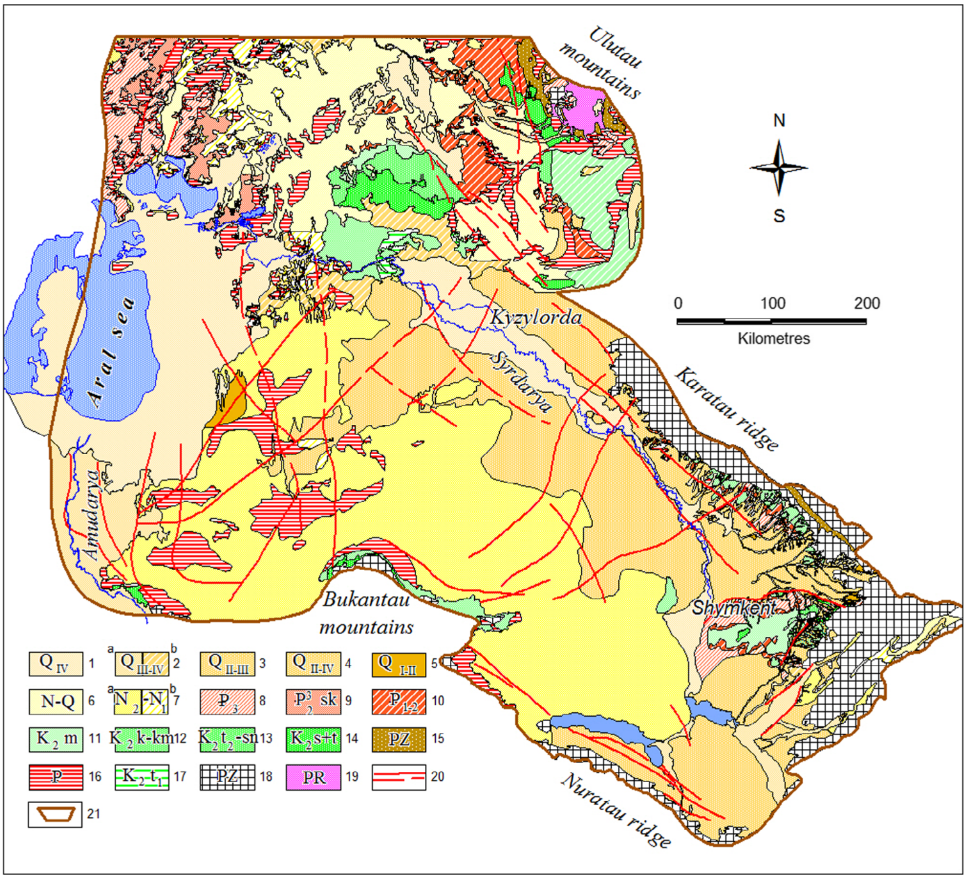

Figure 2. Schematic hydrogeological map of the Syrdarya artesian basin. Distribution of groundwater: (1) Aquifer of modern sediments, (2) Aquifer of Upper-Quaternary modern deposits (a) and sporadically flooded deposits (b), (3) Aquifer of Middle-Upper-Quaternary deposits, (4) Aquifer of Middle-Quaternary-modern deposits, (5) Aquifer of the Lower-Middle-Quaternary deposits, (6) Aquifer of Neogenic-Quaternary deposits, (7) Aquifer of Miocenic-Pliocenic deposits (a) and sporadically flooded deposits (b), (8) Sporadically flooded Oligocenic deposits, (9) Flooded Upper-Eocenic deposits of Saxaul suite, (10) Sporadically flooded Paleocenic-Eocenic deposits, (11) Maastrichtian aquifer deposits, (12) Aquifer of Conyac-Campagne deposits, (13) Aquifer of Upper-Turon-Senonian deposits, (14) Aquifer of Cenomanian-Turon deposits, (15) Groundwater confined to Paleozoic deposits. The distribution of aquifugeous rocks: (16) Aquifugeous non-separated Paleogenic deposits, (17) Aquifugeous Lower-Turon deposits. (18) Outputs of Paleozoic rocks to the surface. (19) Outputs of Proterozoic rocks to the surface. (20) Fault. (21) Model outline.

The water movement processes were presented with the use of the corresponding boundary conditions and simulated assignment of the positive and negative areal water recharge. The northern, north-eastern, western and southern boundaries of the model for the Neogene-Quaternary water-bearing geological layers, as well as the Syrdarya River and the Amudarya River were approximated by the boundary conditions of Category I. These assume assignment of the subsurface water head, water saturated bearing geological layers. The eastern, western, southern, northern and the north-eastern boundaries for the Neogene-Quaternary suite, as well as the areas lacking water-bearing suites and the areas

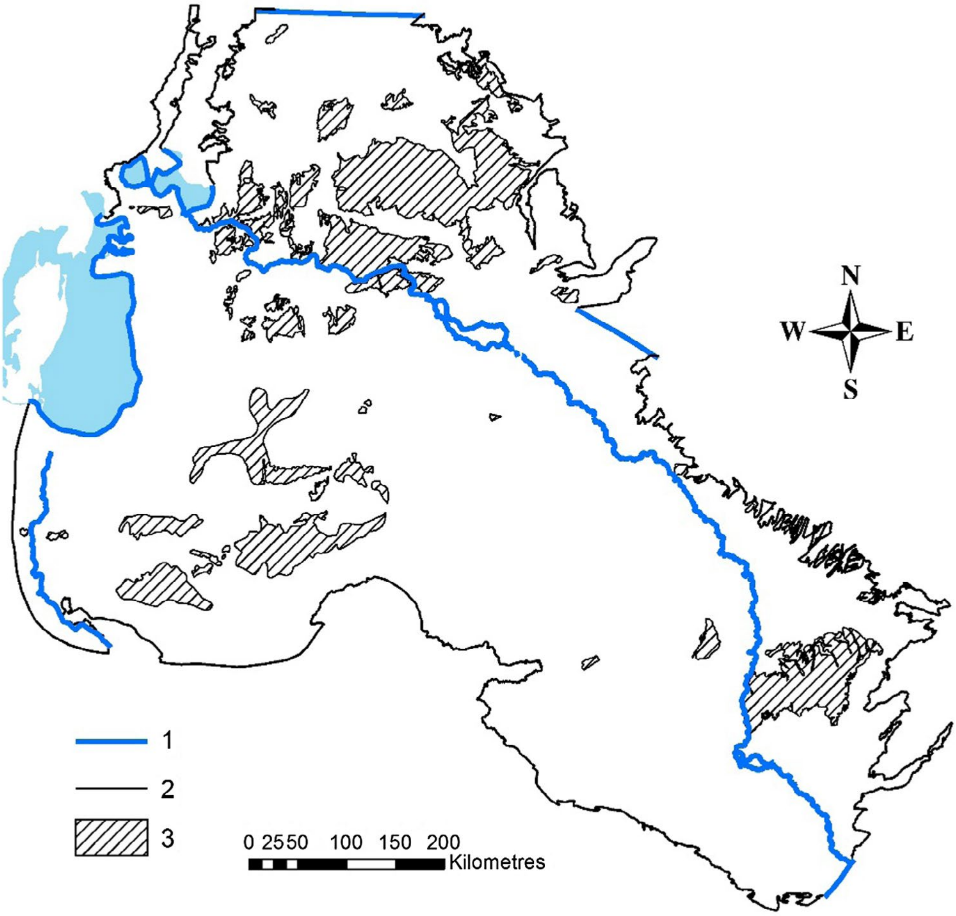

Figure 3. Filtration scheme of the Neogene-Quaternary water-bearing suite (1) Line assigning the boundary conditions of Category I, (2) Line assigning the boundary conditions of Category II, (3) Areas with the lacking Neogene-Quaternary water-bearing suite.

with tectonic faults were simulated as boundaries of Category II. These assume assignment of the subsurface water flow volume. The border over the Aral Sea contour was assigned as to its coastline position (Figure 3). The production of water intakes and infiltration of precipitation was schematized as a negative or positive areal recharge. Evaporation of subsurface water and the discharge in the lake depressions and in the Aral Sea across the bottom were assigned as the boundary conditions of Category III; reflecting the interconnectedness of the hydrogeological unit with the environment. The subsurface water intakes were schematized as the negative time-varying areal supply. Production of the self-flowing wellbores was schematized as the boundary condition of Category III.

Model calibration

The model calibration was developed by using the inverse stationary and nonstationary methods.

The inverse stationary solution included an update of the areal subsurface water supply volume; discharge by evaporation from the open groundwater surface; spring drain; plant transpiration; update of the model parameters describing communication processes of subsurface water with the surface water objects – rivers, lakes, and water storages; selection of the influx and drain over the outer borders of the simulated region. The subsurface water of the Neogene-Quaternary and the Cretaceous geological layers is mainly fed in the piedmont areas (river detrital cones and areas of the Cretaceous outcrops on the daily surface), in the sand massifs, as well as in the irrigated areas with atmospheric precipitation and irrigation water. The pattern and balance surveys ascertained that the percent of annual precipitation, which helps to form the subsurface drain in the sand massifs, ranges from 10 to 15%.

The amount of water discharge underground cannot exceed the volume of the efficient atmospheric precipitation. This was one of the basic requirements in the application of the inverse stationary problem methodology.

Subsurface water is affected by the water loss, including evapotranspiration and lateral spring flow. On the model, these boundary conditions are assigned to be Category III.

The inverse non-stationary solution included the reproduction of the changing hydrogeological conditions within the simulated area of the Syrdarya artesian basin from 1960 to 2014. The model was also used to select the volume parameter values, to update the boundary conditions, and to simulate drying of the Aral Sea – decrease of its water level, reduction of its water area, changes of the subsurface drain volume, as well as the shrinking of its coast line. The production of multiple self-flowing wellbores and the time-varying water withdrawal from the Neogene-Quaternary and the Cretaceous water-bearing suites by the water-intake holes were also considered. Changes in the evaporation volume from the groundwater level were reproduced subject to the depth of its occurrence.

The results of the inverse solution allow us to conclude that the model sufficiently replicated the existing hydrogeological conditions of the researched area.

Forecasts

The interconnectedness of the subsurface water with the surface water of the Aral Sea was assessed for both the undisturbed period (1960), and the epignostic (1961–2014) period. This data were used in order to forecast water changes and problems in the Aral Sea region for a period of 30 years, from 1 January 2015 to 31 December 2044.

The first forecast option assumed the same subsurface water withdrawal volume over the forecast period at the end of 2014 level. The second forecast option assumed the model assignment (from the start of 2015) of the water withdrawal volumes equal to the subsurface water reserves under the sum of A + B + C1 categories, which were approved by the National Reserves Committee of the Republic of Kazakhstan. Category A corresponds to the developed production reserves of subsurface water; category B – explored reserves; category C1 – the preliminarily assessed reserves. The production volumes of the current water intakes operating on the non-approved reserves were also considered.

Results and discussion

For the conditionally undisturbed period (prior to 1960), the volume of the subsurface water influx in the Aral Sea computed on the model was equal to 1.133 m^3/s. The drain

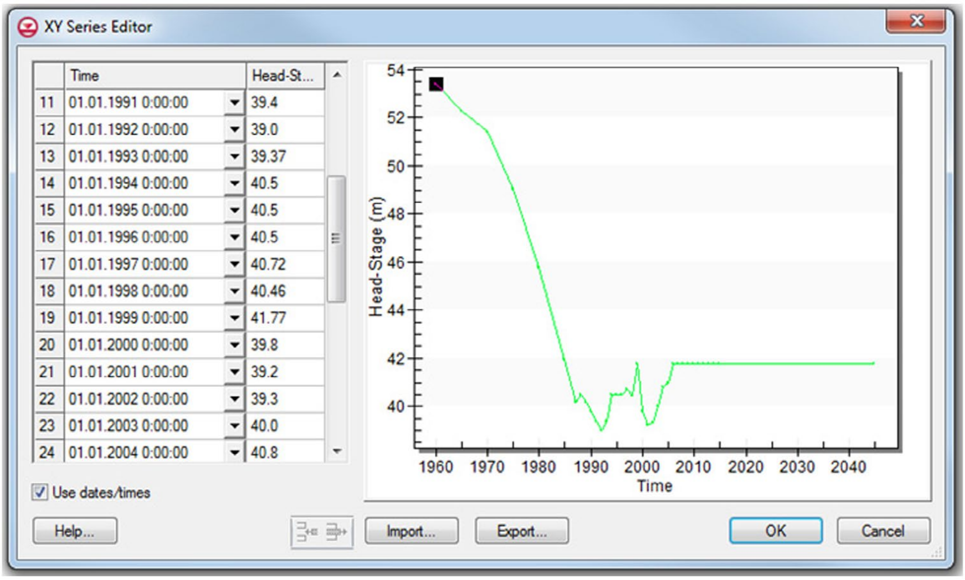

Figure 4. Variation chart of the water level in the Small Aral Sea.

from the Aral Sea occurred only to the Neogene-Quaternary water-bearing suite and was equal to 0.024 m^3/s.

At the end of the epignostic period (2014), the Aral Sea split into the Big Aral Sea and the Small Aral Sea. For the Small Aral Sea, the influx from the Neogene-Quaternary water-bearing geological layers was equal to 0.165 m^3/s and the one from the Upper Eocene water-bearing geological layers was 0.36 m^3/s. Drains from the Small Aral Sea seeped to the Neogene-Quaternary water-bearing geological layers and to the Upper Eocene water-bearing geological layers and were equal to 0.016 and 0.0003 m^3/s, respectively.

The cumulative influx from the water-bearing geological layers for the Big Aral Sea at the end of the epignostic period was equal to 1.525 m^3/s. No drain from the Big Aral Sea occurred or was measured.

The cumulative influx in the Aral Sea depression at the end of the epignostic period is equal to 2.05 m^3/s.

Figures 4 and 5 summarize the water levels variation charts assigned on the model for the Small Aral Sea and for the Big Aral Sea geological layers.

By the end of the forecast period (2044), the influx in the Small Aral Sea using *the first option* will occur only from the Neogene-Quaternary water-bearing geological layers and the Upper Eocene water-bearing geological layers, and it will be in the range of 0.48 m^3/s. The drain will be equal to 0.017 m^3/s. The cumulative influx from all the water-bearing geological layers for the Big Aral Sea will be 1279 m^3/s. The cumulative subsurface drain in the Aral Sea will be equal to 1.76 m^3/s.

At the end of the forecast period (2044), the influx in the Small Aral Sea from the Neogene-Quaternary water-bearing suite and the Upper Eocene water-bearing geological layers using *the second option* will likely be in the range of 0.291 m^3/s, and its drain will be 0.044 m^3/s. The cumulative influx from the water-bearing suites into the Big Aral Sea will be 1.27 m^3/s, and the Upper Cretaceous water-bearing layer, which is one of the most

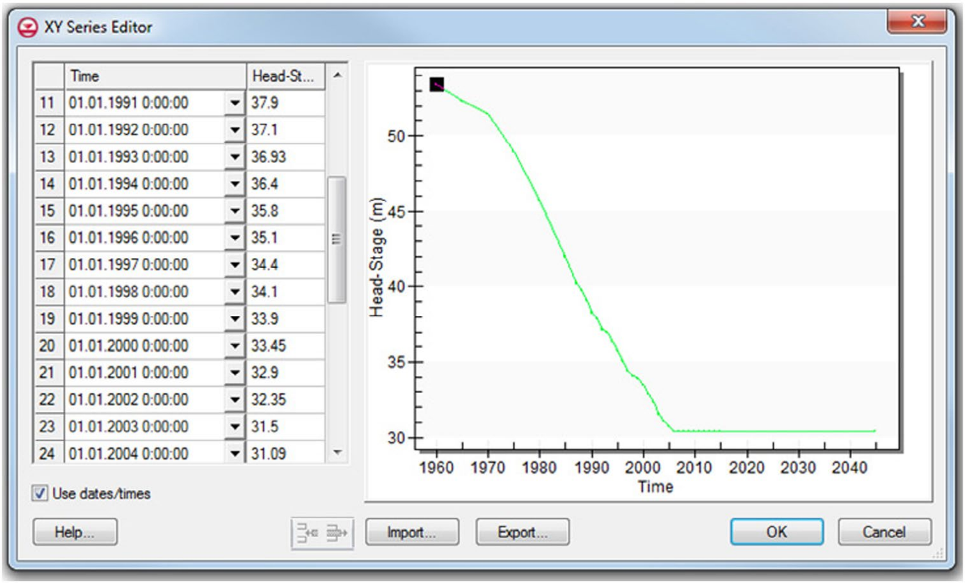

Figure 5. Variation chart of the water level in the Big Aral Sea.

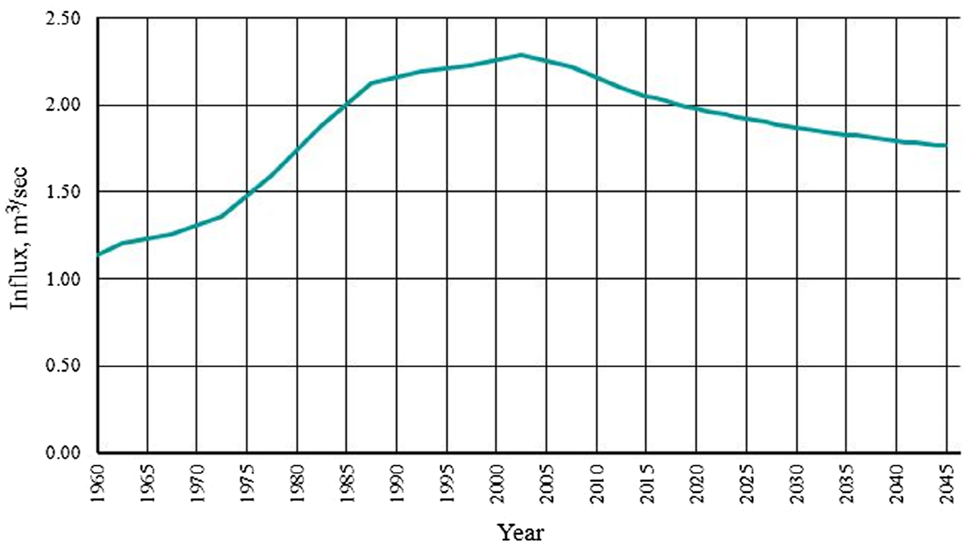

Figure 6. Variations of the subsurface water discharge in the Aral Sea for the first forecast option.

water-abundant influxes, will yield 0.91 m^3/s. No drain will occur. The cumulative subsurface drain in the Aral Sea will be equal to 1.52 m^3/s.

Figures 6 and 7 present the resulting data for the subsurface water discharge in the Aral Sea based on the mathematical simulation technique. The charts demonstrate that the cumulative discharge in the Aral Sea by the end of the prediction period increased to 2.05 m^3/s, which is associated with considerable decrease of the Sea level as the result of its drying.

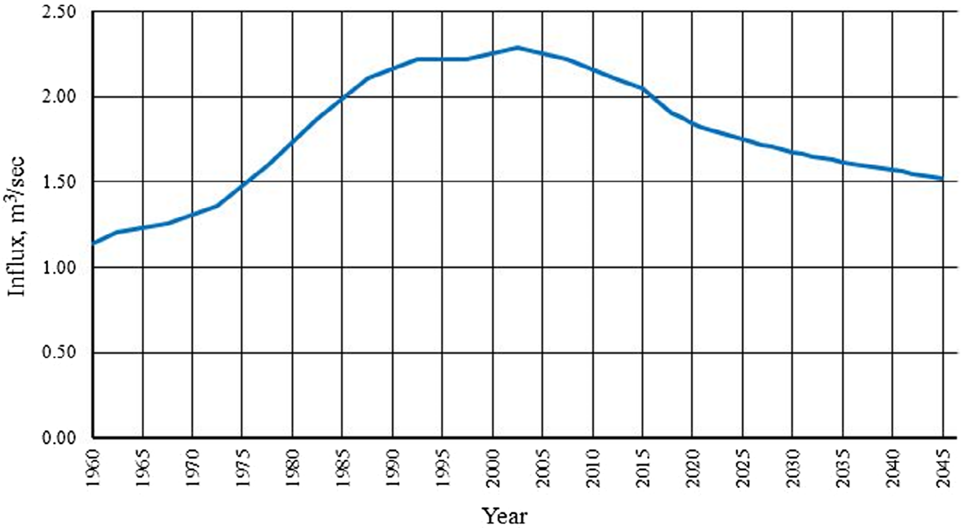

Figure 7. Variations of the subsurface water discharge in the Aral Sea for the second forecast option.

Conclusion

The simulation results allow us to conclude that, starting from 1960, the subsurface water in this territory has been significantly impacted by technogenic factors. The main impacts include a drastic reduction of the flow from the Syrdarya River into the Aral Sea and the nearly complete discontinuation of the Amudarya inflow into the Aral Sea. This has resulted in the desiccation of the Aral Sea. The intensive extraction of subsurface water from the multiple water-intake and unowned self-flowing wellbores is another negative impact. The cumulative water withdrawal in the analysed territory in 2014 is estimated to be 2500 ths. m^3/d or 29 m^3/s. These technogenic impacts resulted in considerable hydrogeological changes, which influenced the movement of the subsurface and the surface water, and led to the reduction in the level of subsurface water.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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