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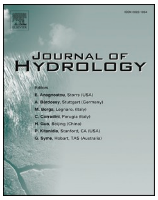

Research papers

Modeling the effects of improved irrigation methods in a groundwater system: A case study from the Amu Darya Delta, Uzbekistan

Xiaohui Pan [a,b,c,d,e,f], Weishi Wang [h,*], Tie Liu [a,b,c,e,f,g,j,*], Anming Bao [a,b,c,g,j], Xi Chen [c,e,f,g], Shamshodbek Akmalov [g,i], Philippe De Maeyer [c,d,e,f], Tim Van de Voorde [c,d,e,f]

[a] *State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China*
[b] *Key Laboratory of GIS & RS Application Xinjiang Uygur Autonomous Region, China*
[c] *University of Chinese Academy of Sciences, Beijing 100049, China*
[d] *Department of Geography, Ghent University, Ghent 9000, Belgium*
[e] *Sino-Belgian Joint Laboratory of Geo-information, Urumqi 830011, China*
[f] *Sino-Belgian Joint Laboratory of Geo-information, Ghent 9000, Belgium*
[g] *CAS Research Centre for Ecology and Environment of Central Asia, Urumqi 830011, China*
[h] *School of Environmental Science and Engineering, Hubei Polytechnic University, Huangshi, Hubei 430050, China*
[i] *Tashkent Institute of Irrigation and Agricultural Mechanization Engineers, Tashkent 999033, Uzbekistan*
[j] *China-Pakistan Joint Research Centre on Earth Sciences, CAS-HEC, Islamabad 45320, Pakistan*

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ABSTRACT

Suitable groundwater levels have a significant influence on vegetation growth, regional salinization, and ecological sustainability. Because of long-term low-efficiency irrigation methods and water canals, the stream flows vanish before reaching the South Aral Sea, leading to a rapid shrinkage of lake coverage since 1960. Meanwhile, the groundwater table in agricultural zones has continued to grow and recharge the Aral Sea, leading to increased salinization. Using a joint application of observation, remote sensing, and reanalysis data, a groundwater model was established to represent the historical aquifer condition and the efficiency of four possible management scenarios: drip irrigation under plastic mulch (Drip scenario), surface water-groundwater conjunctive irrigation (Conjunction scenario), drainage system methods (Drainage scenario), and mixing of the aforementioned methods (Mixed scenario). The simulation results demonstrate distinct spatial distribution of groundwater tables: the decline in the groundwater level was discovered in all proposed methods, but the decline was more drastic in the Conjunction and Mixed scenarios, and least in the Drainage scenario. The decrease in the groundwater table can be attributed to the decrease in the recharge rate (Drip and Conjunction scenarios) and the increase in the pumping rate (Conjunction scenario). Of all the scenarios, the Drainage scenario shows the smallest global decline in the water table, with an average decline of 0.15 m, but a maximum regional decline of 3.93 m (on the sides of the drainage). Evaluated by analyzing the water balance at a regional scale, evapotranspiration (ET) is still the major consumer of groundwater resources, at approximately 52%. Groundwater extraction and leakage into drainage accounted for approximately 6.9% and 23.5%, respectively. However, improved irrigation measures could reduce surface runoff and convert excessive groundwater into drainage systems. The improved irrigation methods could increase the total surface water runoff to 19.16 km^3/yr, which is 29% higher than the maximum annual runoff (14.82 km^3) and 406% higher than the mean annual runoff (3.79 km^3) of the Amu Darya River over the past two decades. This study indicates that proper groundwater management measurements in irrigation areas could greatly help address water scarcity problems and promote sustainability in these ecosystems.

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* Corresponding authors at: The School of Environmental Science and Engineering, Hubei Polytechnic University, Huangshi, Hubei 430050, China; State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China.

E-mail addresses: weishi.wang.groundwater@gmail.com (W. Wang), liutie@ms.xjb.ac.cn (T. Liu).

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1. Introduction

Global water use has increased by approximately 300% since the 1950 s, and irrigation is the most vital water-use sector, accounting for approximately 90% of consumption (Döll, 2009; Döll et al., 2012). Groundwater is the largest freshwater resource on the planet and is essential for agriculture and global food security (Aeschbach-Hertig and Gleeson, 2012). However, to meet society's demands, intensive extraction of groundwater can generate a wide range of processes, including river runoff depletion, earthquakes, and land subsidence (Galloway and Burbey, 2011; González et al., 2012; Stahl, 2019).

In semi-arid to arid regions, water shortages and soil salinization are serious and chronic problems for irrigated cropland (Chen et al., 2010), yet aquifers usually serve as the main drought-resistant buffer zones for both resident demand and crop growth (Siebert et al., 2010). Under the semi-arid climate of the Aral Sea Basin, the rapid expansion of irrigation diminished the runoff of two tributaries, the Amu Darya River and Syr Darya River, resulting in the overwhelmingly abrupt desiccation and salinization of the Aral Sea (Micklin, 2016). Meanwhile, high losses during irrigation caused shallow groundwater tables in the lower Amu Darya reaches, and groundwater table depth rose from to 15–20 m in the 1980 s to 1–1.5 m in the early 20th century (Borisov et al., 2002; Khalid Awan et al., 2015). Moreover, the centre of the irrigation area is approximately 120 km away from the South Aral Sea, which increased the gradient between the lake water level and groundwater level in the irrigation area, as shown in a previous investigation (Pan et al., 2022). This makes groundwater a vital recharge source for the South Aral Sea.

The agricultural sector is an important component of the economy in Central Asia and employs one-third to one-half of the population and generates between 15% and 25% of the GDP (Lobanova et al., 2021). However, the Amu Darya Basin's ecological environment has suffered from inefficient irrigation and overexploitation. During the growing season, irrigation water demand takes precedence, even during minimal river flow, which puts great pressure on the base flow to sustain the downstream ecosystem (Leng et al., 2021). At the end of the 20th century, groundwater used for irrigation accounted for 6.4% of the total irrigation water usage in Uzbekistan (Antonov, 2000). Mavlonov et al. (2003) determined that groundwater recharge in Uzbekistan is approximately 27 km^3/yr, and the extraction of groundwater was estimated to be approximately 7.5 km^3/yr, which has caused severe decreases in the surface water flow (Kazbekov et al., 2007; Rakhmatullaev et al., 2011, 2010). Therefore, improving irrigation efficiency, reducing evaporation, and applying sustainable groundwater use strategies are key to ensuring economic development and improving the local ecological environment.

In arid regions, practices to mitigate water shortages have been widely applied. Drip irrigation under plastic mulch, agricultural drainage systems, and conjunctive irrigation by surface water-groundwater have been proven to be effective water-saving and groundwater level regulation measures in different investigations. Drip irrigation under mulch methods can effectively reduce soil evaporation and deep percolation, which is already widely promoted in arid regions (Li et al., 2016; Liu et al., 2012; Selim et al., 2013). Drainage water management is the best measure to control groundwater tables during crop growth seasons to increase crop yields (P. Li et al., 2018; S. Li et al., 2018; Li et al., 2020). However, in the Aral Sea Basin, which has intensive agricultural activities, drip irrigation is not applied at a large scale, and the previous drainage network has experienced complete destruction due to a lack of facility maintenance after the disintegration of the former Soviet Union (Dukhovny et al., 2007). A modeling exploration can provide insight into how the aforementioned improved irrigation methods could influence surface water and groundwater interactions.

This study uses the Nukus region downstream of the Amu Darya agricultural land as the research object and explores how sustainable irrigation strategies could influence local hydrological conditions. First, a groundwater flow model is set up and calibrated based on local groundwater observations, and the different combinations of irrigation strategies are conceptualized into the model for further investigation. The objectives of this study were to i) estimate groundwater level variations under improved irrigation method scenarios, ii) quantify the exchange flux between the surface water and groundwater under improved irrigation method scenarios, and iii) investigate the groundwater flux into the South Aral Sea. The results of this study are expected to help improve water management practices. Additionally, this type of case study may enhance our understanding of the potential environmental and ecological impacts of agricultural activities.

2. Materials and methodology

2.1. Study area

The Nukus region is located in the lower reaches of the Amu Darya River within the transition zone of the Karakum and Kyzylkum deserts and is connected to Turkmenistan in the south and the South Aral Sea in the north (Fig. 1). This region is a typical semi-arid to arid region, in which the annual precipitation is less than 200 mm, while the actual evapotranspiration (ET) of cultivated land can reach 700–1100 mm per year (Liu et al., 2020). This region is one of the largest agricultural irrigation areas in Central Asia, covering an area of 14,247 km^2, and its major crops include cotton, wheat, and rice. Irrigation water has been mainly obtained from the Amu Darya River, causing a substantial water shortage in the lower reaches of this river. Currently, the Amu Darya River vanishes hundred kilometers before it reaches the South Aral Sea. The Ministry of Agriculture and Water Resources in Uzbekistan has divided the country into several Irrigation System Management Organizations, four of which are located within the investigation area in this study: Suenli, Kattagar-Bozatau, Kizketken-Kegeyli, and Kuanishjarma (Fig. 1). The land cover within the area is mostly cultivated and bare land, and the surface elevation ranges from 41 to 145 m a.s.l. (meters above sea level). The shallow aquifer is primarily an unconfined aquifer formed by alluvial and lacustrine sediments, composed of loam and sand eroded from the younger Aral Sea during the eopleistocene (Schettler et al., 2013).

2.2. Data collection

Multisource data were applied to model construction and used to quantify the groundwater flux into the South Aral Sea and include remote sensing data, ground-based observations, and reanalysis data (Table 1). The regional mean groundwater level data and ten monitoring wells were reported on by the Centre of Hydrometeorological Service of Uzbekistan. The regional mean groundwater levels were used as the specified head boundaries in the model, while the in-situ measurements were used as calibration targets. Monthly groundwater level measurements were continuously recorded from January 2005 to December 2017 in the ten observation wells and were relatively well distributed across the region. The actual water delivery of each irrigation district was obtained from the Centre of Hydrometeorological Service of Uzbekistan, which was used to quantify the recharge rate of each crop type based on crop coverage and crop water demand. ET was estimated using the FAO Penman-Monteith method based on meteorological station data obtained from the National Oceanic and Atmospheric Administration (https://gis.ncdc.noaa.gov/maps/ncei/cdo/) (Khaydar et al., 2021). Land use classification was extracted from Sentinel-2 Multispectral Instrument imagery (https://earthexplorer.usgs.gov).

2.3. Groundwater flow modeling

2.3.1. Model used

To investigate different irrigation combinations, a 3-D groundwater flow model was set up based on the MODFLOW-NWT (Harbaugh, 2005;

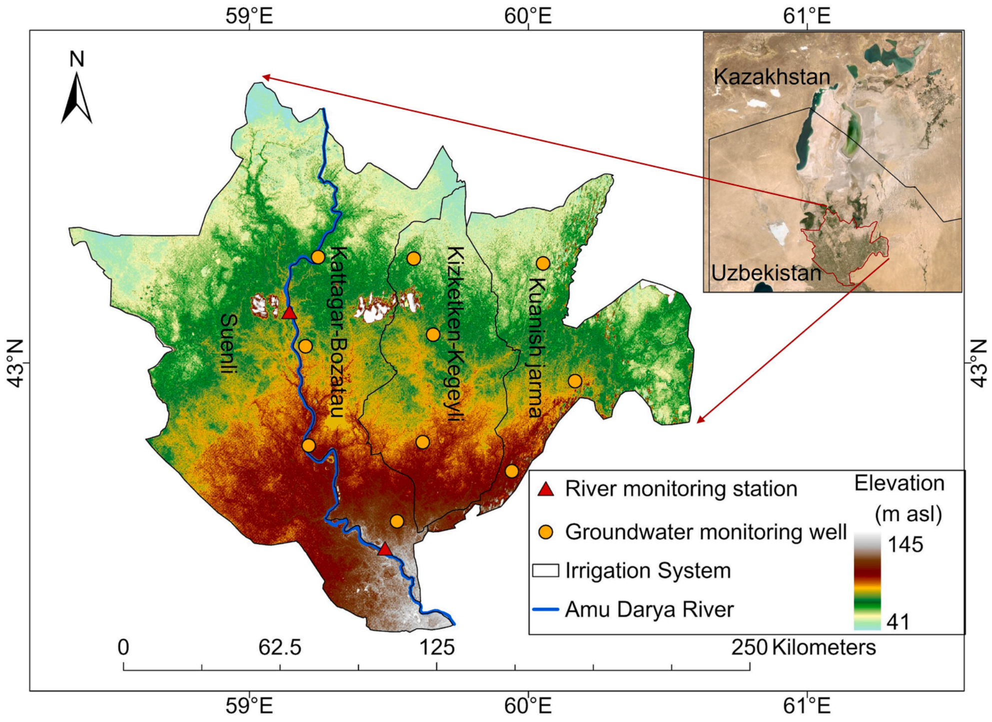

Fig. 1. Location of the Nukus irrigation area, the topography of the MODFLOW model domain. The names Suenli, Kattagar-Bozatau, Kizketken-Kegeyli, and Kuanish-jarma are Irrigation System Management Organizations as divided by the national Ministry of Agriculture and Water Resources. The Digital Elevation Model comes from the Shuttle Radar Topography Mission (http://srtm.csi.cgiar.org/). The base map in the upper right corner originates from ESRI (https://www.arcgis.com/home/item.html?id=413fd05bbd7342f5991d5ec96f4f8b18).

Table 1
Data sources with frequency and resolution used for the MODFLOW model.

Data type	Frequency/ resolution	Source
Terrain	90 m × 90 m	CGIAR-CSI SRTM 90 m Database (Jarvis et al., 2008)
groundwater level	Monthly/station	Centre of Hydrometeorological Service of Uzbekistan
groundwater level	Monthly/ administrative area	Centre of Hydrometeorological Service of Uzbekistan
River stage	Monthly/station	Centre of Hydrometeorological Service of Uzbekistan
Irrigation water	Monthly/crop type	Centre of Hydrometeorological Service of Uzbekistan
Precipitation	Monthly/0.25° ×0.25°	GPM_3CMB (https://disc.gsfc.nasa.gov/datasets/GPM_3CMB_06)
Evapotranspiration	Monthly/30 m × 30 m	Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences
Land use classification	Statistical data	Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences

Niswonger et al., 2011), with the upstream weighting (UPW), time-variant specified head (CHD), evapotranspiration (EVT), recharge (RCH), river (RIV), drain (DRN), and well (WEL) packages.

2.3.2. Conceptualization and discretization

The aquifer domain of the Nukus region was discretized into 400 × 400 cells, and each cell was 686 m on the x-axis and 603 m on the y-axis (Fig. 2). The simulation period from January 2005 to December 2017 was divided into 155 stress periods, each with a length of one month. The bottom elevation of the model reached 0 m a.s.l. and was bordered by a poorly water-conducting horizon (mainly clay and sandstone), which can be traced back to the Paleocene-Upper Cretaceous (Schettler et al., 2013). Accordingly, the bottom boundary was set to represent no-flux. Vertically, the model was categorized into two layers. The first layer ranged from the surface to 40 m a.s.l. and consisted of sand and loam, while the second layer was mainly sand and ranged from 40 m a.s.l. to 0 m a.s.l. Crop coefficients are properties of plants used in predicting ET, which represent the crop type and the development stage. In MODFLOW simulation, crop coefficients are used to calculate actual ET. The crop coefficients used in the study are listed in Table 2 (Liu et al., 2020). The hydrogeological parameters were based on previous research and empirical values (Table 2). The initial groundwater heads we obtained from a steady-state simulation conducted in 2005.

2.3.3. Improved irrigation method scenarios set up

After the disintegration of the Soviet Union, the existing agricultural facilities malfunctioned owing to insufficient investment and poor maintenance. Currently, in the Nukus irrigation area, flood irrigation is the primary method used for watering crops, with the majority of the water supply sourced from surface water. To understand the simulated hydrological response to agricultural activities, this study investigated four improved irrigation scenarios, with 14 cases in total (Table 4). To improve the irrigation efficiency, the local ecological environment was the main target of this study. To develop feasible strategies for local irrigation management based on recent agricultural practices, the modeled scenarios included the current irrigation efficiency (HST, our baseline) and the hypothesis scenarios listed in Table 4. The pumping wells designed in the hypothesis model are randomly distributed in the irrigation area. In addition, the water stage of the Amu Darya River in the model was changed along with the volume of the surface water saved in each scenario.

2.3.4. Model calibration

This study conducted a transient calibration based on ten in-situ observation wells, which were well distributed within the model domain. To provide a reasonable representation of the local hydrogeological conditions, the hydraulic conductivity was automatically calibrated using PEST (Doherty and Hunt, 2010). The parameter range was restricted by empirical values based on aquifer characteristics (Table 3).

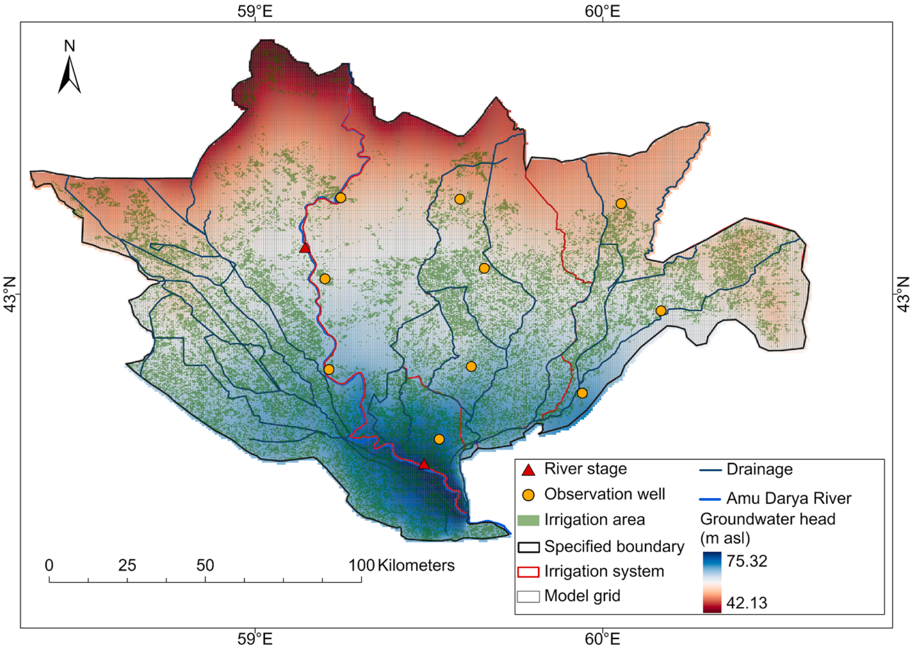

Fig. 2. The discretized domain of the MODFLOW model. The Polygons surrounded by red boundaries are the different irrigation divisions. The serial number of wells is given in order from west to east and north to south. The groundwater head is based on the simulation results of February 2005. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Crop coefficients of cotton, wheat, rice and bare land during the growing season (Liu et al., 2020).

Crops	April	May	June	July	August	September	October
Cotton	0.35	0.4	0.87	1.2	1.2	0.99	0.71
Wheat	1.15	0.97	0.4	–	–	–	–
Rice	–	1.05	1.13	1.2	1.2	0.95	–
Bare land	0.2	0.2	0.2	0.2	0.2	0.2	0.2

Table 3
Summary of the main hydrogeological parameters adopted in this investigation.

Parameter	Value	Source
Horizontal hydraulic conductivity	10–5–10–3 (m/s)	(Fetter, 2018)
Specific yield	Layer 1: 0.2 Layer 2: 0.27	(Domenico and Schwartz, 1998)
Specific storage	10–5	
Recharge rate	0.2	(Rakhmatullaev et al., 2012)
ET extinction depth	230 cm	(Shah et al., 2007)

2.4. Estimation of groundwater flux from the irrigation area into the South Aral Sea

To evaluate the impact of improved irrigation measures on the South Aral Sea, Darcy's law (Darcy, 1857) was adopted to assess the exchange flux between the lake and groundwater, which can be written as follows:

$$Q = -K \times A \times \frac{dh}{dl}$$

where Q represents the groundwater flow rate, K represents the hydraulic conductivity, A represents the column cross-sectional area, and $\frac{dh}{dl}$ is the hydraulic gradient. In this study, dh is the difference between the regional average groundwater head in the irrigation area and the water level of the South Aral Sea (monthly scale), dl is the distance from the centre of the irrigation area to the centre of the lake.

3. Results

3.1. Model performance

The MODFLOW calibration results between the simulated and observed data at the ten observation points are presented in Fig. 3. The calibration results show that the MODFLOW model performed acceptably; points with larger root mean square error (RMSE) were mainly distributed in a relatively distant area from the south boundary, for example, OB1(2.81 m), OB2 (2.22 m), and OB5 (1.82 m), while the southern points had much better accuracy, for example, OB4 (0.23 m), OB6 (0.14 m), OB7 (0.77 m), OB8 (0.07 m), and OB10 (0.24 m). This mismatch may be caused by several factors. According to previous research (Pan et al., 2020), groundwater level dynamics are highly correlated with irrigation water used. Furthermore, hydrogeological conditions have more pronounced spatial heterogeneity in croplands and are greatly affected by human activities. This highlights a limitation of the numerical model in simulating groundwater-related components in the irrigation area. With automatic calibration, the horizontal hydraulic conductivity was 2.3×10^{-4} m/s for layer 1 and 7.4×10^{-4} m/s for layer 2, and the vertical anisotropy ratio was 0.2.

3.2. Mulched drip irrigation scenario

To evaluate the influence of drip irrigation on the groundwater level, we set up four drip irrigation coverage levels based on the current irrigation area; these levels were 25%, 50%, 75%, and 100%. For each hypothetical case, we extracted the corresponding coverage proportion of each crop and assigned the recharge rate and ET rate of the drip irrigation scenario, leaving the remaining irrigated area to maintain the flood irrigation condition. According to the local field practices carried out by the Xinjiang Institute of Ecology and Geography, drip irrigation water consumption accounts for approximately 50% of the flood irrigation. Based on a local investigation by Liu et al (2020), the coefficients for crops and bare land in the Nukus irrigation area are listed in Table 2. In addition, under mulch drip irrigation, crop transpiration accounted for 98.6% of the total ET during the growing season (Li et al., 2016). Accordingly, we assigned 50% of the current recharge rate during the

Table 4
Specific settings used for simulating the improved irrigation method scenarios and their abbreviations.

Improved irrigation method scenarios	Specific settings of cases	Abbreviation
Drip irrigation under plastic mulch	With 25% drip irrigation coverage and 75% flood irrigation coverage	Drip-25
	With 50% drip irrigation coverage and 50% flood irrigation coverage	Drip-50
	With 75% drip irrigation coverage and 25% flood irrigation coverage	Drip-75
	With 100% drip irrigation coverage	Drip-100
Surface water-groundwater conjunctive irrigation	With 25% drip irrigation coverage, 75% flood irrigation coverage and 2007 pump wells, the water use ratio of surface water-groundwater is 1:1	Conjunction-25
	With 50% drip irrigation coverage, 50% flood irrigation coverage and 1720 pump wells, the water use ratio of surface water-groundwater is 1:1	Conjunction-50
	With 75% drip irrigation coverage, 25% flood irrigation coverage and 1434 pump wells, the water use ratio of surface water-groundwater is 1:1	Conjunction-75
	With 100% drip irrigation coverage and 1147 pump wells, the water use ratio of surface water-groundwater is 1:1	Conjunction-100
Drainage	With 2 m depth drainage with flood irrigation	Drainage-2
	With 2.5 m depth drainage with flood irrigation	Drainage-2.5
	With 3 m depth drainage with flood irrigation	Drainage-3
Mixed	With 25% drip irrigation coverage, 75% flood irrigation coverage, 2007 pump wells and 2 m depth drainage, the water use ratio of surface water-groundwater is 1:1,	Mixed-low
	With 50% drip irrigation coverage, 50% flood irrigation coverage, 1720 pump wells and 2.5 m depth drainage, the water use ratio of surface water-groundwater is 1:1	Mixed-medium
	With 100% drip irrigation coverage, 1147 pump wells and 3 m depth drainage, the water use ratio of surface water-groundwater is 1:1	Mixed-high

growing season and ignored the evaporation of bare land in the drip irrigation area.

Drip irrigation reduces irrigation water consumption while reducing the demand for water from the Amu Darya River. The heat map demonstrates that the groundwater fell in drip irrigation areas, but slightly increased around the north part of the Amu Darya River (0.01 m to 0.02 m) (Fig. 4). Along with the increase in drip irrigation coverage, areas with declining groundwater also increased. Moreover, the average depth of groundwater declined in each case by −0.09 m (Drip-25), −0.20 m (Drip-50), −0.22 m (Drip-75) and −0.29 m (Drip-100).

3.3. Surface water-groundwater conjunctive irrigation scenario

To utilize groundwater for irrigation purposes, the salinity tolerance of crops should be considered a primary concern. The average salinity of shallow groundwater in the Nukus-irrigated region is 3 g/l (Johansson et al., 2009), which is within the feasible salinity (3–4 g/l) for brackish water irrigation (Wang, 2016). However, given the water demand of the Nukus region and the annual groundwater available in Uzbekistan, which are $0.8 \times 10^{8} km^{3}/yr$ and $2.16 \times 10^{8} km^{3}/yr$ (Deng and Long, 2011), respectively, it is not feasible to put all the irrigation load on the aquifer. Therefore, a joint condition combining groundwater extraction and drip irrigation was assumed to maintain the water use ratio of surface water-groundwater at 1:1. Considering that each level of drip irrigation coverage will cause different groundwater requirements for the crops, 2007 (Conjunction-25), 1720 (Conjunction-50), 1434 (Conjunction-75), and 1147 (Conjunction-100) wells were set in the model, with a pumping rate of 1000 m^3/d per well.

The results indicate that pumping groundwater for irrigation will lead to further decline in the groundwater table, with average declines of −0.53 m (Conjunction-25), −0.3 m (Conjunction-50), −0.38 m (Conjunction-75) and −0.39 m (Conjunction-100). The spatial distribution of the groundwater table decline is shown in Fig. 5, which shows that the most profound groundwater decline is located in the non-irrigation area, with maximum depths of decline of −3.62 m (Conjunction-25), −2.68 m (Conjunction-50), −2.49 m (Conjunction-75), and −1.95 m (Conjunction-100). A regional increase in groundwater could be seen in Conjunction-50 and Conjunction-75, with maximum increase of 0.5 m and 0.4 m.

3.4. Drainage system scenario

After the disintegration of the Soviet Union, the existing drainage malfunctioned owing to insufficient investment and poor maintenance. Considering the computational burden of the model, the drainage canal design in the MODFLOW model is based on the existing main canals in the irrigated area. In this investigation, we assumed that the drainage system returned to normal when the drainage depths were 2, 2.5, and 3 m.

As shown in Fig. 6, declining groundwater level is notably distributed on both sides of the drainage. The depth of groundwater decline increased as the drainage depth increased, and the extent of the decline also increased. The average depth of decline was −0.07 m (Drainage-2), −0.1 m (Drainage-2.5) and −0.15 m (Drainage-3).

3.5. Mixed scenario

To evaluate the combined influence of the aforementioned scenarios, three levels of mixed cases were investigated, and detailed information is listed in Table 4. The groundwater mainly declined on the sides of the drainage, with an average decline of −0.3 m (Mixed-low), −0.25 m (Mixed-medium), and −0.43 m (Mixed-high). A regional increase in the groundwater table was also observed in the Mixed-medium and Mixed-high scenarios, with a maximum increase of 1.32 m and 0.76 m, respectively. The spatial patterns are shown in Fig. 7, the Mixed-medium and Mixed-high scenarios are particularly interesting because the areas in which the groundwater increases are completely different. In the Mixed-medium case, increases in groundwater are mainly distributed in irrigation areas, which means that these changes are related to mulched drip irrigation and changes in recharge and ET conditions. In the mixed-high case, the areas of increase are distributed on the sides of the Amu Darya River, which means that these changes are related to the rise of the river stage.

4. Discussion

4.1. Characteristics of groundwater dynamics under different improved irrigation method scenarios

Groundwater dynamics are a result of the combined influence of both natural and anthropogenic activities, especially in irrigated areas. These dynamics are influenced by the coaction of precipitation, ET, leakage from river and drainage, recharge to the water body, irrigation, groundwater extraction, etc. As shown in Fig. 3 - Fig. 6, the simulated groundwater levels under the different scenarios indicate substantial spatial variability. Drip irrigation scenarios primarily affected the irrigation area, while drip irrigation with pumping well scenarios show the opposite behavior, and groundwater typically declines in non-irrigation areas. The groundwater level significantly responds to irrigation events,

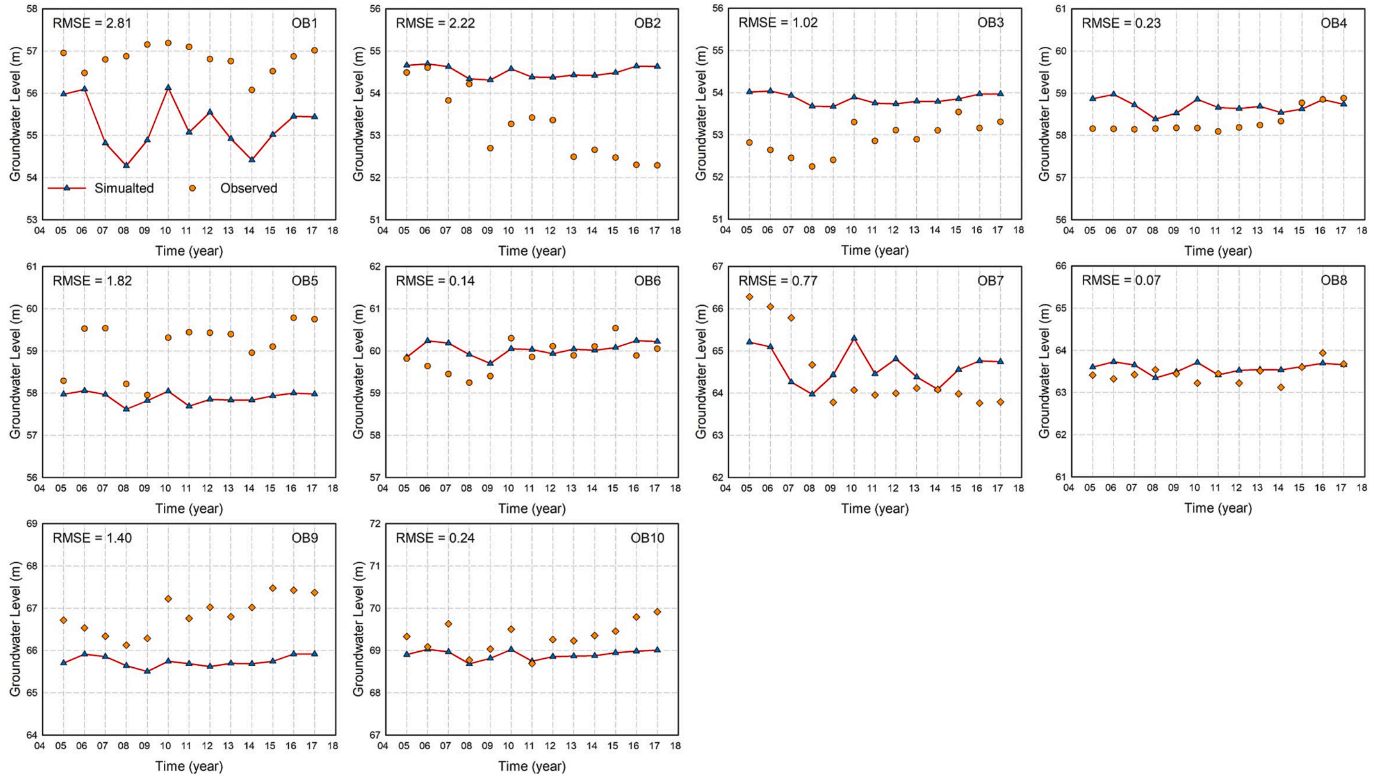

Fig. 3. Comparison of the observed (yellow circles) and simulated (blue triangle with red line) hydraulic heads (m a.s.l.) in ten observation wells (OB1 to OB10) during the period 2005–2017. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

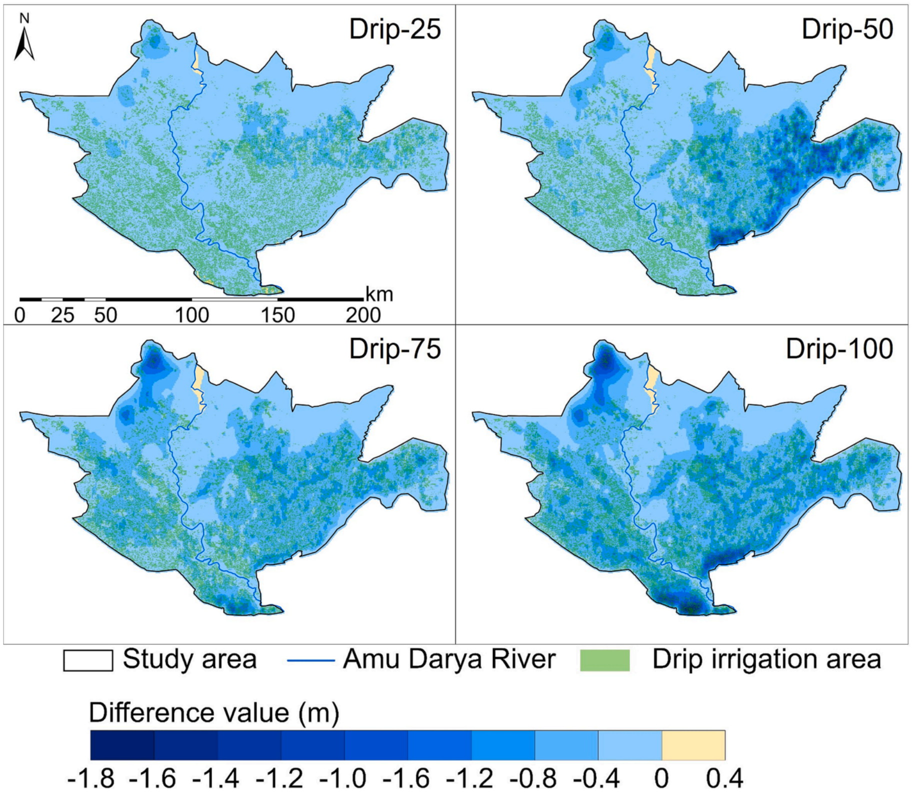

Fig. 4. The average simulated groundwater heads difference between current irrigation efficiency and mulched drip irrigation scenario during the study period.

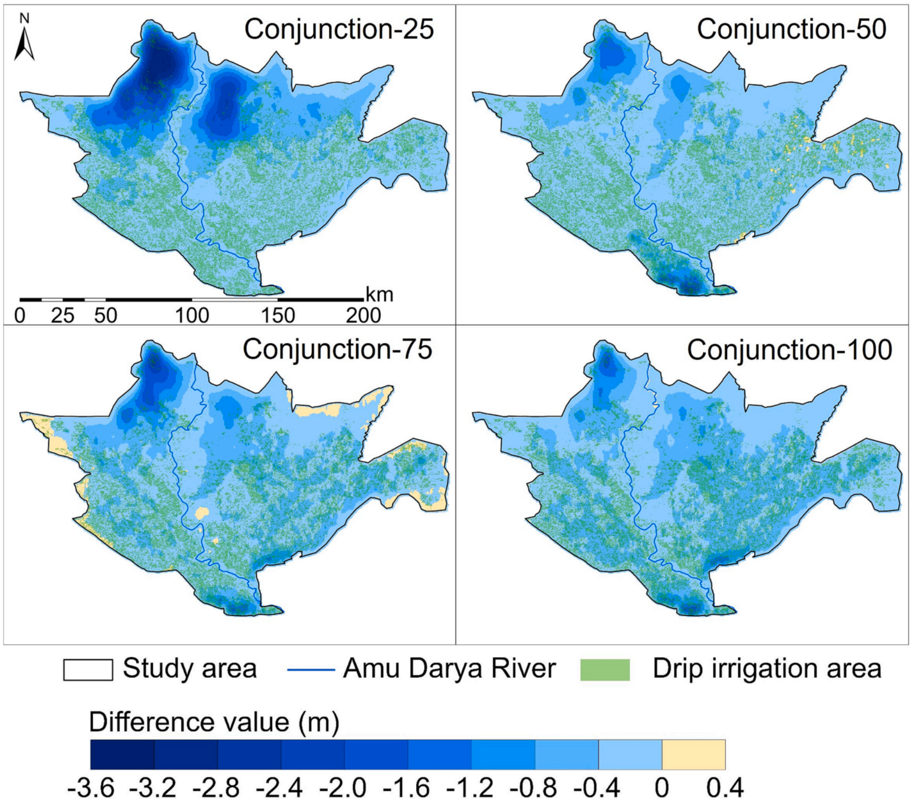

Fig. 5. The average simulated difference in groundwater heads between the current irrigation efficiency and surface water-groundwater conjunctive irrigation scenario during the study period.

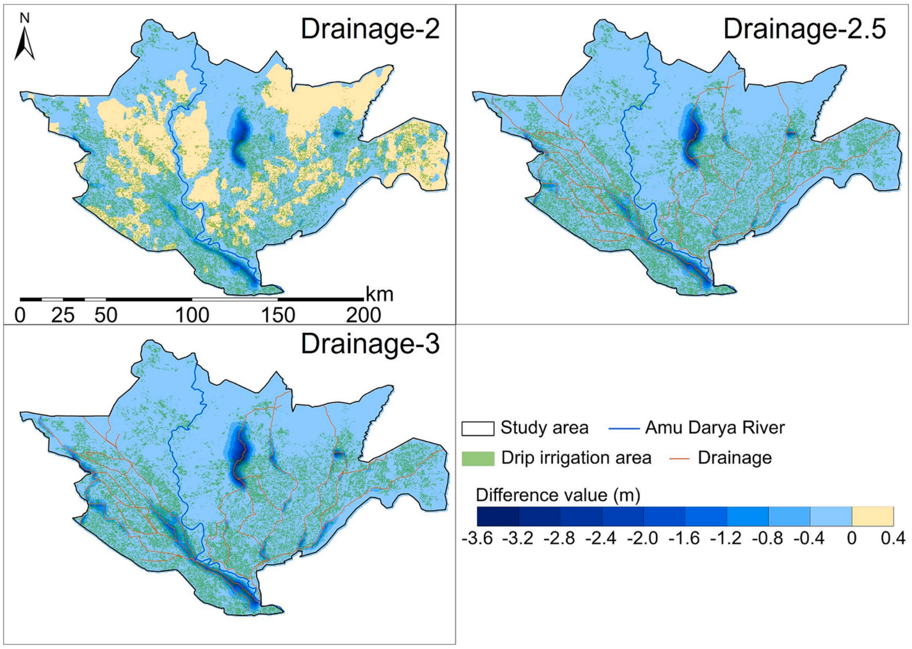

Fig. 6. The average simulated difference in groundwater heads between current irrigation efficiency and drainage system scenarios during the study period.

and mulched drip irrigation reduced both potential groundwater recharge and ET consumption over flood irrigation. However, in arid and semi arid regions, irrigation return flow is a primary resource of aquifer recharge, drip irrigation may disconnect the flow dynamic relationship between the root zone and unsaturated zone, potentially impacting long-term agricultural activities (Porhemmat et al., 2018). Field experiments conducted by Li et al. (2016) in arid regions have demonstrated that crop transpiration accounts for 34.3% of irrigation water, and deep percolation accounts for 53.2%, which indicates that half of the irrigation water ends up in the aquifer. Meanwhile, the abstraction was evenly distributed across the entire area, yet the groundwater level showed a considerable decline in the non-irrigation

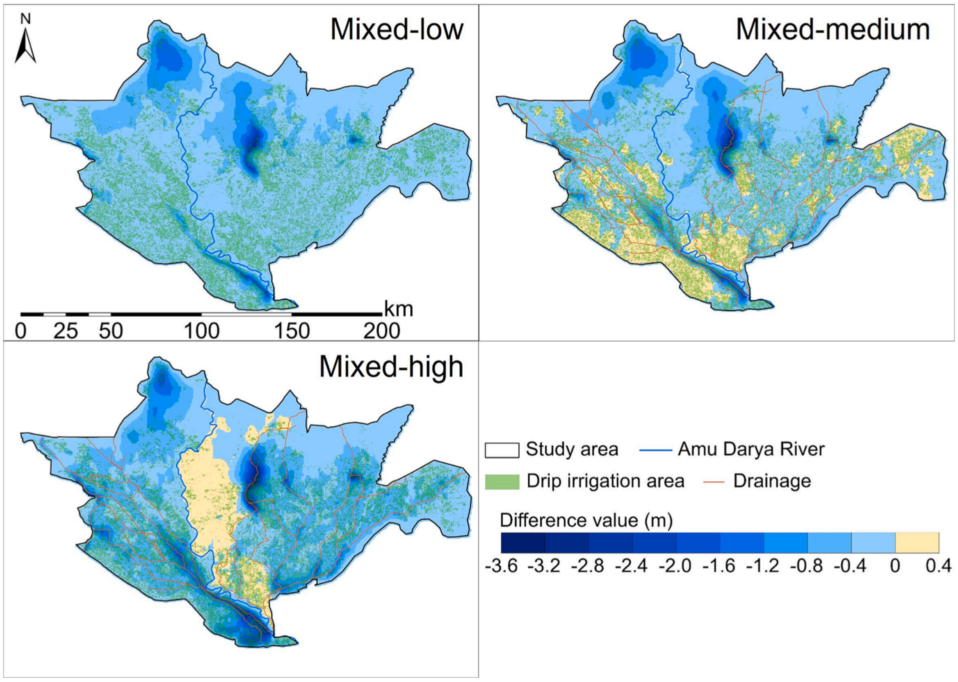

Fig. 7. The average difference in simulated groundwater heads between current irrigation efficiency and mixed scenarios during the study period.

area. Increasing groundwater abstraction for irrigation poses a practical issue regarding the limit of groundwater abstraction and the specific location of the pumping well, which is crucial for the future sustainability of groundwater use in the basin. Not only the location of the pumping wells, but also the percentage could be fine-tuned, because the simulation results of the junction scenario and the mixed scenario show that the groundwater level change does not show a monotonic trend, but rather reaches a turning point between 75% and 25%. This indicates that with a more detailed investigation and finer resolution of the coverage percentage, the optimum point could be revealed.

As shown in Fig. 8, a global decline can be observed in all scenarios, and this decline is more drastic in the Conjunction and Mixed scenarios, and least drastic in the Drainage scenario. The difference between the growing and non-growing seasons was much smaller than the general variation among the scenarios. Owing to the limited area of influence in the drainage, the overall water table variation was the smallest among

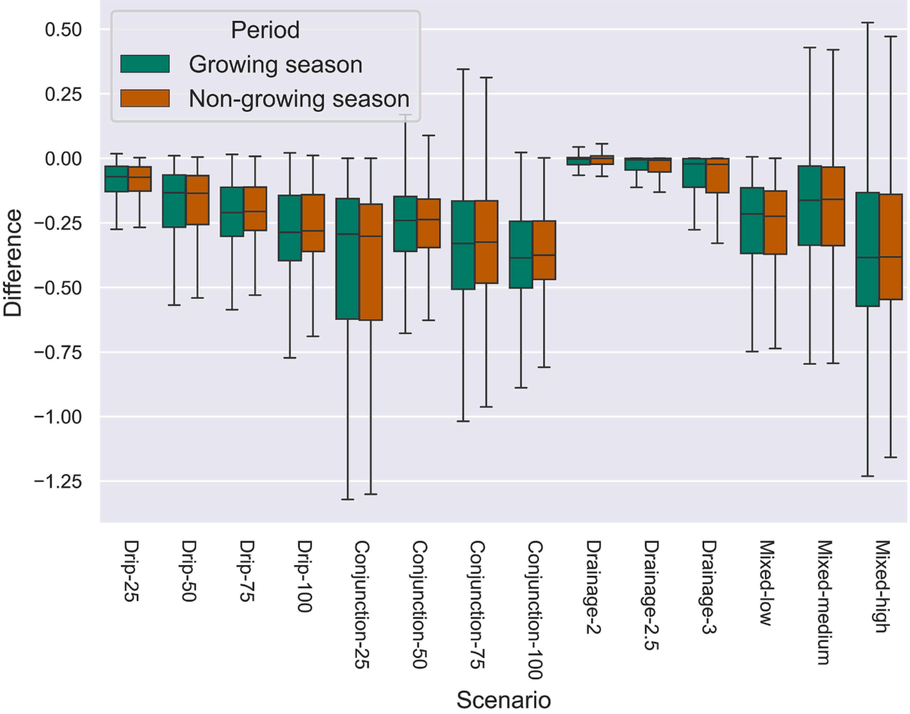

Fig. 8. The boxplot of the average difference in simulated groundwater heads between the current irrigation efficiency and improved irrigation method scenarios. The green box represents the difference in the growing season and the brown box represents the difference in the non-growing season. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

all scenarios. The water table in drip irrigation showed a monotonic decrease as coverage increased. This could be attributed to an over-paced decrease in recharge, even when ET drops at the same time. The abstraction of groundwater had a greater impact on the shallow aquifer in both the Conjunction and Mixed scenarios. Since the 20th century, the demand for groundwater irrigation has significantly increased, leading to exploration exceeding natural aquifer recharge rates in many cases (Siebert et al., 2010).

4.2. *Impact of improved irrigation methods on the interactions between surface water and groundwater*

The response of groundwater systems to local agricultural activities was evaluated based on the multi-year average water balance, as shown in Fig. 9, which shows that recharge and ET are the most prominent factors. Precipitation normally contributes little in arid regions, while irrigation is important in arable land. Constant head refers to the continuous lateral flow of groundwater, conceptualized by the flow from the fixed water heads at the model boundary. It is represented in the water balance by the recharge from the model boundary. Constant head contributes a small amount of recharge to the aquifer. Mulched drip irrigation may simultaneously decrease the volume of both recharge and ET, which compete to either generate an increase or decrease in the local groundwater table. A side effect of the mulched layer is that it may substantially reduce soil evaporation and capillary groundwater rise, which can lead to a reduction in the leaching of salts from the root zone. Over time, this can result in the accumulation of salts in the soil, leading to secondary soil salinization (Forkutsa et al., 2009). Groundwater extraction, leakage into the drainage, and ET consumption accounted for approximately 6.9%, 23.5%, and 52% of the groundwater system outflows, respectively. A recent study in the Nukus irrigation area showed that ET consumption was 9.87 km^3 in 2005, based on the SEBAL model (Liu et al., 2020); our simulated annual ET consumption was 7.31 km^3.

Since 1960, the Aral Sea has experienced an abrupt decrease in area and salinization, overwhelming the effects of rapid expansion in irrigation that depleted the two tributary rivers (Micklin, 2010). As shown in Fig. 10, an improvement in irrigation systems could substantially increase surface water resources. Both drip irrigation and groundwater extraction would strongly alleviate irrigation water stress and increase runoff in the Amu Darya River. Groundwater leakage into the drainage system could further contribute to surface runoff. In recent years, historical river runoff measured at the Kiziljar station occasionally fell to zero, whereas in the M scenario, the annual surface water resources may potentially increase to 19.16 km^3.

The trends of the South Aral Sea volume and Amu Darya River runoff are distinct. There was rapid desiccation of the lake until 2008, during which the lake’s water balance suffered a severe deficit. After 2008, the lake seemed to have reached a relatively stable period and varied over a smaller range. Two peaks in the Amu Darya River runoff were observed in 2005 and 2010. In 2010, a heavy flow from the river partially restored the lake, which experienced the highest runoff in two decades (14.82 km^3) (Micklin et al., 2018). Given the relatively high volume of surface water resources generated by improved irrigation systems, the ecological environment of the South Aral Sea is expected to improve.

The maximum predicted runoff (19.16 km^3/yr), which is merely 29% higher than the high flow year in 2010 (14.82 km^3), will provide limited replenishment to the lake, and the water demand of a full restoration is not realistic in the foreseeable future. Furthermore, groundwater is another critical component of the lake’s water balance under current conditions (Jarsjö and Destouni, 2004). The estimated groundwater flux to the lake is 2.73 km^3, and the lowest flux occurs in the Conjunction-25 case and is 2.67 km^3. This difference indicates that the scenario hypothesis in this study had little effect on the groundwater system. Recent simulations imply that groundwater is a vital resource for the South Aral Sea, with a recharge flux between 5.5 and 7.7 km^3 (Pan et al., 2022). Owing to the stable recharge of irrigation, groundwater from irrigation area is a critical water resource for the recharge of the South Aral Sea.

Local farmers face high uncertainty in irrigation water supply (Forkutsa et al., 2009), and despite this concern, the actual water

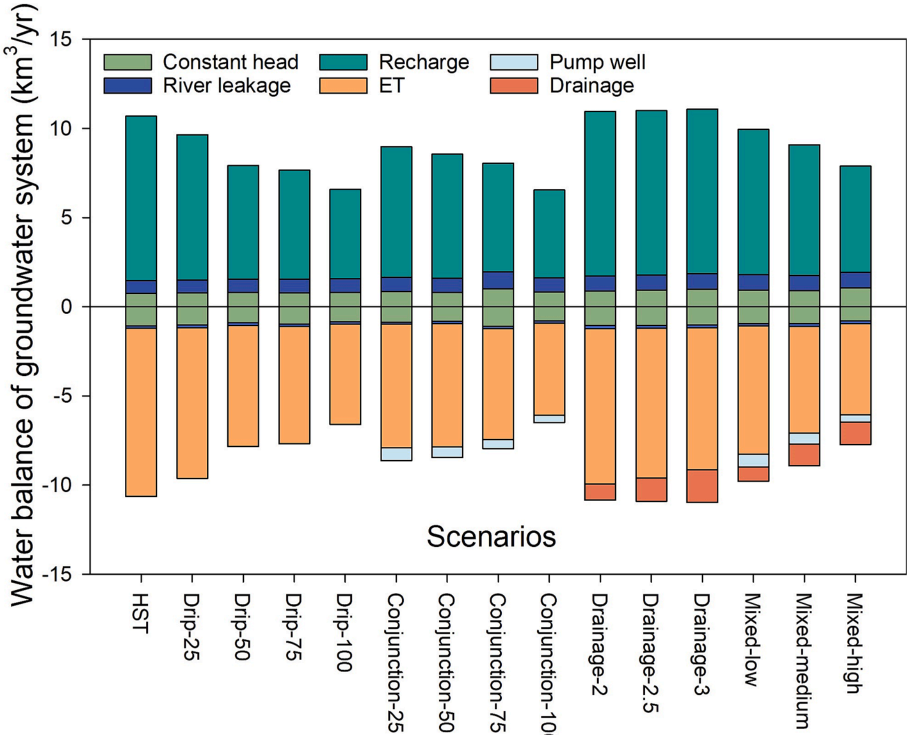

Fig. 9. The water balance of the groundwater system in the Nukus irrigation area produced by the MODFLOW model, which was simulated under improved irrigation method scenarios during the study period.

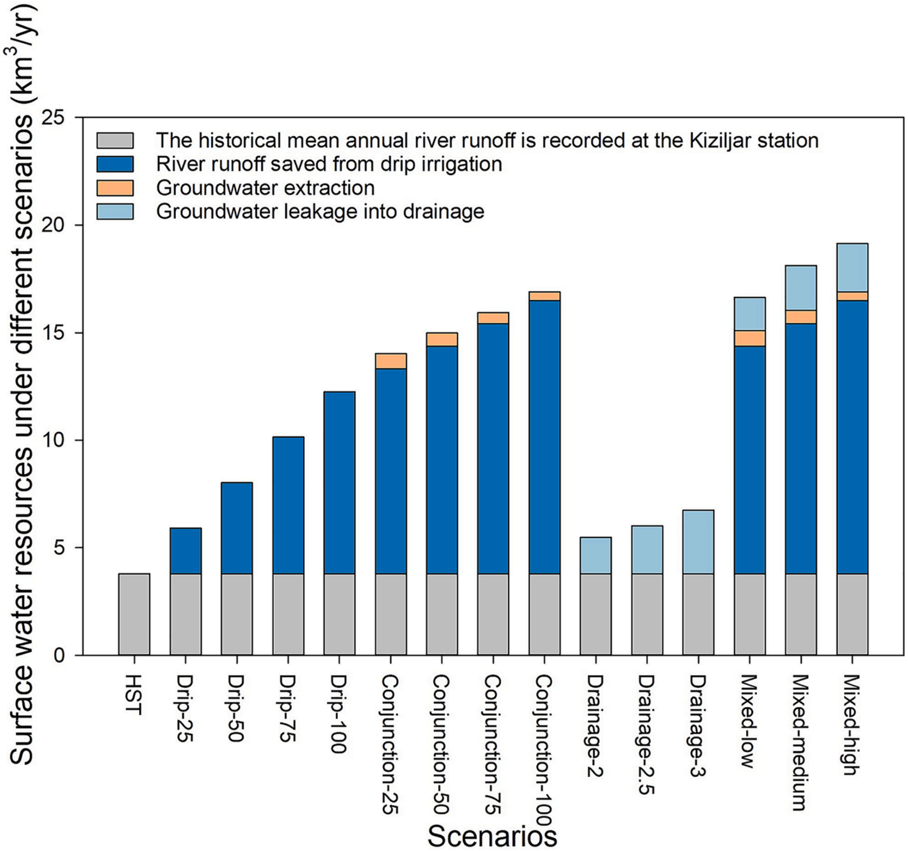

Fig. 10. Surface water resources under improved irrigation management, the grey histogram is the historical average river runoff recorded by the Kiziljar station during 2005–2017, the light blue histogram is the groundwater leakage into the drainage estimated by the MODFLOW model. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

delivery of each irrigation district was used in this study, which ensures the reliability of the simulation quantity. However, the absence of irrigation water usage at high resolutions contributes to uncertainty in the distribution of the simulated water heads. In addition, limited ground-based observations may have influenced the accuracy of the calibration.

5. Summary

To assess the impact of improved irrigation methods on the interactions between surface water and groundwater, a MODFLOW model for the Nukus irrigation area was developed and applied to simulate groundwater level variations. The hydrological scenarios were based on improved irrigation efficiency and water-saving practices in arid regions. The MODFLOW model was automatically calibrated using PEST based on ten in-situ groundwater monitoring wells. The simulation incorporated the key components of the hydrologic cycle that influence groundwater and surface water interactions, such as uneven spatial distribution in the irrigation rate, transpiration with evolving vegetation, and changing river stages based on each scenario. The model was forced with 13-year monthly hydrometeorological data such that the influence of the growing season was captured in the simulations. Both the spatial and temporal variability in irrigation rate, as well as changes in irrigation behavior during the growing and non-growing seasons, were reproduced with an acceptable degree of accuracy.

The simulation results demonstrate that improved irrigation management could increase surface water flow into the South Aral Sea. Variations in the groundwater level for the improved irrigation method scenarios indicate a unanimous groundwater level decline. Compared to the irrigated area, which has a sustained irrigation recharge, the non-irrigated area showed a greater decline. Conversely, the simulated results demonstrated few differences between the growing and non-growing seasons. In the Mixed-high scenario, which includes the most intensive water-saving measure, the mean groundwater level declined by 0.43 m. The majority of cases show that the mean groundwater level declined less than 0.3 m, which implies that a rational intensity of agricultural activities is sustainable. Therefore, in most hypotheses, the decline in the groundwater level is acceptable; however, the dynamics of the groundwater level would exacerbate secondary salination and extensive contamination (MacDonald et al., 2016).

Based on the water balance method, the groundwater storage in the irrigated area was controlled by ET and irrigation rate. In M3, ET consumption accounted for 52% of the total outflow of the groundwater system, and recharge accounted for 55% of the total inflow of the groundwater system. Furthermore, recharge from groundwater in the irrigated area had identifiable effects on the South Aral Sea; the groundwater flux into the lake decreased by only 2% in the simulated scenarios. Meanwhile, the simulated results provide evidence that increased surface water flow could cause the Amu Darya River to reach its largest runoff in nearly two decades. The Amu Darya River currently vanishes before reaching the South Aral Sea; however, based on the historical status of the lake volume (40.92 km^3) and the annual river runoff (14.82 km^3) in 2010, this study illustrates that excess water from the river and drainage, with a total runoff of 19.16 km^3, could extend sufficiently far north to release to the lake.

Here we present, for the first time, a quantified estimation of the influence of improved irrigation management on the Nukus irrigation area and the South Aral Sea. Hypothetical modeling scenarios explored practical methods of anthropogenic intervention. The study was constrained by poor ground-based observations in this arid region. Groundwater has great potential for supporting ecosystems (Lubczynski,

2009) and providing available water resources for agricultural and domestic use (Al-Katheeri, 2008; Tang et al., 2004). This study contributes to the formulation of water management strategies for drought resistance. However, resolving the Aral Sea crisis requires vast long-term investment as well as sustainable policy support. To meet the requirements of ecological water, future studies should be devoted to developing a zonal regulation plan to restore unreasonable groundwater to an ecological water level.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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