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Five decades of freshwater salinization in the Amu Darya River basin

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ABSTRACT

Study region: The Amu Darya River (ADR) basin in Central Asia.
Study focus: To understand the spatiotemporal patterns and underlying driving mechanisms of river salinization in arid environments, this study gathered 50 years (1970–2019) of water chemistry data from 12 locations along the ADR. The variations in discharge and salinity were assessed by a linear regression model and violin plot. The salinity-discharge relationships were evaluated by a general hyperbolic model and Spearman's rank correlation coefficient. Random forest models were also constructed to identify the predominant drivers of river water salinization. Finally, a conceptual model of river water salinization was constructed.
New hydrological insights for the region: The water salinity (S) in the upper stream of the ADR was 541–635 mg/L. Salinity showed an increasing trend along the river course, reaching 751–1560 mg/L downstream. In the downstream, the river salinity before the 1990 s (751–1128 mg/L) was slightly lower than that after the 1990 s (983–1560 mg/L). Generally, water salinity was notably correlated with river discharge (Q) in upstream, exhibiting a relationship of $S = 17{,}497Q^{-0.62}$, $p < 0.05$, before the 1990 s. Interannual variation in river salinity is mainly controlled by secondary salinization, and intra-annual variation is controlled by river flow. From upstream to downstream, the controlling salinization process changes from primary salinization to secondary salinization. Specifically, secondary salinization has accelerated due to intensified agricultural activities in recent years.

1. Introduction

Salinity is an important parameter for characterising surface and groundwater quality, and it is measured by the total concentration of inorganic ions dissolved in water (Cañedo-Argüelles et al., 2013; Williams and Sherwood, 1994). Freshwater salinization is caused by an increase in ion concentrations in freshwater (Cañedo-Argüelles, 2020), and it includes primary and secondary salinization.

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Primary salinization occurs naturally in water, while secondary salinization is mainly caused by anthropogenic activities such as irrigated agriculture (Cañedo-Argüelles et al., 2013; Kitamura et al., 2006). In the context of a warming climate and increasing human activities, freshwater salinization is an increasing global challenge (Cañedo-Argüelles, 2021; Cunillera-Montcusí et al., 2022; Thorslund et al., 2021).

Central Asia (CA) is a region with a semiarid to arid climate (Karthe et al., 2015), that is facing increasingly severe water scarcity and large-scale water pollution from agricultural and mining activities (Hao et al., 2022; Liu et al., 2021). Freshwater salinization is very severe in CA, as well as in most arid and semiarid regions of the world (Cañedo-Argüelles, 2020; Cunillera-Montcusí et al., 2022). In such regions, secondary salinization of surface/groundwater systems is most likely amplified by climate change (Cunillera-Montcusí et al., 2022). The decrease in available freshwater and deterioration in water quality associated with freshwater salinization has posed a great threat to aquatic and riparian ecosystems, human health and socioeconomic development in CA (Karthe et al., 2017; Wæhler and Dietrichs, 2017).

The ADR, one of the major Central Asian rivers, originates from the Tian Shan and Pamir-Alai Mountains. Historical observations showed that the annual upstream river flow in the ADR experienced a decreasing trend during 1951–2007 in response to the warming climate (Wang et al., 2016). Recently, several studies have analysed the variation in water salinity in the ADR and its relationship with flow during different periods. For example, Crosa et al. (2006) analysed the spatial and seasonal variations in salinity in the ADR during the 1990–1997 period. Karimov et al. (2019) evaluated the salinization dynamics upstream of the ADR in 2005–2014 using the annual average salinity. Lobanova and Didovets (2019) analysed the change trends of mean annual and monthly salinity over 1990–2015. These studies found that decreased river flow has led to increasing freshwater salinization, especially in the downstream areas of the ADR (Ahrorov et al., 2012; Gaybullaev et al., 2012). In particular, notable salinity increases in the lower ADR were observed since the 1960 s, when irrigation and agricultural activities intensified (Crosa et al., 2006; Karimov et al., 2019; Lobanova and Didovets, 2019; Rakhmatullaev et al., 2010; Yapiyev et al., 2021).

In general, current research highlights the increasing salinization in the ADR and its harmful effects. Nevertheless, long-term changes and seasonal variations in river water salinization in relation to river flow changes and anthropogenic activities are not fully understood. A few studies have focused on the spatial patterns of salinization and the identification of predominant drivers of river water salinity from the perspectives of primary and secondary salinization. These gaps likely pose great challenges to sustainable development in the ADR, partly due to the lack of long-term observational data. Therefore, this study collected monthly and annual data on river discharge and water salinity at 12 hydrological stations in the ADR over the past 50 years (1970–2019). The objectives of this study are to 1) identify the intra- and interannual changes in river salinity and discharge over the past five decades; 2) examine the relationships between river salinity and discharge for different periods; and 3) identify the possible drivers of river water salinization in the ADR basin.

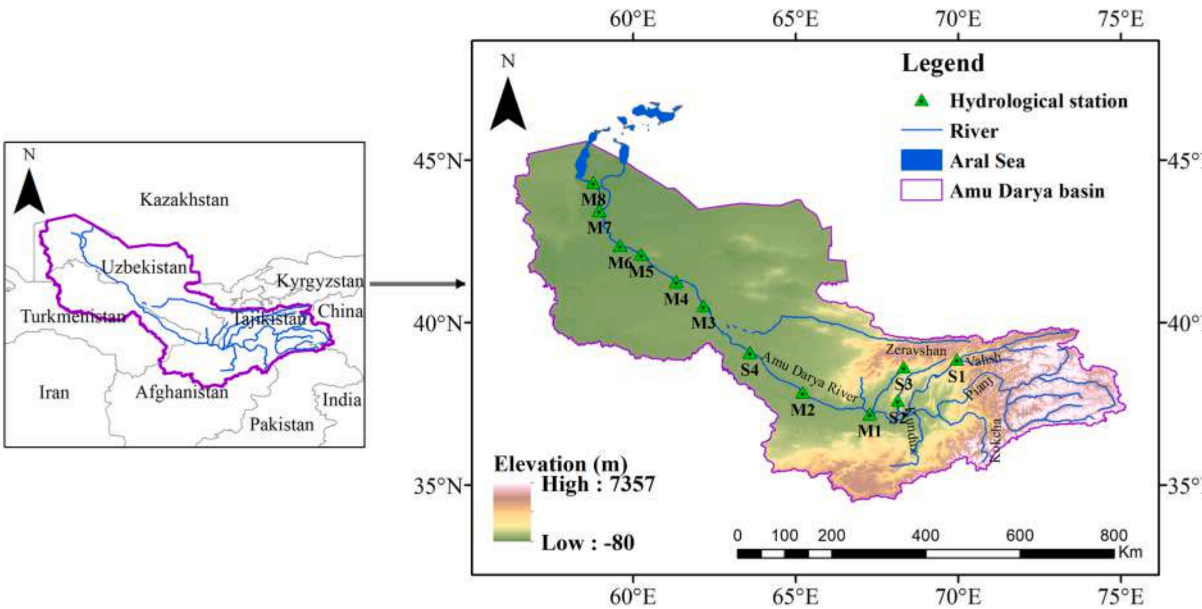

Fig. 1. Location of the ADR basin and spatial distribution of hydrological stations with water chemistry measurements. "M" indicates hydrological monitoring stations. "S" indicates stations where data are obtained from previous studies (Lobanova and Didovets, 2019). M1: Termez, M2: Kerki, M3: Darganata, M4: Tuyamuyun, M5: Kipchak, M6: Nukus, M7: Kzyldjar, M8: Temirbai, S1: Darband, S2: Tartki, S3: Karatag, S4: Chardjou. Detailed information on the hydrological stations is shown in Table S1.

2. Materials and methods

2.1. Study area

The ADR basin is characterised by a dry continental climate that is severely cold in the winter and extremely hot in the summer (Huang et al., 2021a, 2021b). Under a warming climate, this region experienced an upward trend of 0.30 °C/decade in temperature, which is much higher than the global warming rate (0.175 °C/decade) during 1960–2017 (Hu et al., 2021). Precipitation varies widely from upstream to downstream. The mean annual precipitation was greater than 1000 mm in the upstream alpine area and approximately 100–300 mm in the downstream desert steppe area, especially in Khorezm, where it was only 95 mm (Lobanova and Didovets, 2019; Wang et al., 2016). During 1960–2017, an upward trend in precipitation of 3 mm/decade was observed in the ADR basin, while a downward trend of − 10 mm/decade was observed in the southwestern part of the basin (Hu et al., 2021).

The ADR begins following the conjunction of the Vahsh and Pianj Rivers in Tajikistan and has a total length of 1415 km, excluding the Pianj River (Lobanova and Didovets, 2019) (Fig. 1). The main right bank tributaries of the ADR are the Vahsh River, Kafirnigan River, Surkhandarya River, Sherabad River and Zeravshan River (which do not reach the ADR); the main left bank tributaries are the Pianj River and Kunduz River. The mean annual discharge sum in the ADR was approximately 79 km^3 for 2000–2018 (OECD, 2020). Due to a typical continental climate, April-September runoff accounted for 77–80% of the total annual runoff, while December-February runoff accounted for only 10–13% (Agal'tseva et al., 2011). The runoff of ADR declined significantly during 1960–2017, e.g., − 0.52 mm/a and − 0.97 mm/a at the Termez and Kiziljar stations, respectively, due to climate change and increasing human activities, such as water withdrawals for agricultural irrigation (Hu et al., 2021). Recently, climate changes and increasing population density together with intensified agricultural activities have exacerbated drought in the ADR and significantly changed the quantity, salinity and quality of river water, posing a threat to human and agricultural water use.

2.2. Data

The monthly data of river discharge and river water chemistry in 1970–2002 were taken from the archives of the Centre of Hydrometeorological Service at the Cabinet of Ministers of the Republic of Uzbekistan and the Central Asian Scientific Research Institute for Irrigation, respectively. The river water salinity was calculated as the sum of the ionic composition of the major cations and anions in milligrams per litre. The mean annual salinization data from 2000 to 2015 were acquired from Lobanova and Didovets (2019).

The irrigated area, water withdrawal, drainage flow to the river and salinity of drainage flow in the ADR middle and downstream reaches were taken from the water quality dataset of the CAWater info website (SIC ICWC, 2021). The population density was downloaded from the World Bank open dataset (World Bank Group, 2021). The boundary of the ADR basin is downloaded from Ran et al. (2020). The Aral Sea boundary is downloaded from Sun (2019).

2.3. Methods

2.3.1. Methods for data selection

Monthly water chemistry data were checked using the Pauta criterion (3σ), and the observed outliers (i.e., data error exceeding 3σ) were discarded. The Pauta criterion can detect outliers under a confidence probability of 99.7% (Li et al., 2016). Furthermore, data for river discharge and water chemistry that did not appear in pairs were removed. The selected data were used to study the spatial, intra- and interannual variations in river discharge and water salinity.

The steps in the PauTa criterion are described as follows (Yao et al., 2007):

(1) The average of the N sample data for the discrete probability distribution samples

$$x = \frac{1}{N}\sum_{i=1}^{N} x_i \tag{1}$$

(2) Calculating the residual error of each sample

$$V_i = x_i - x \tag{2}$$

(3) Calculating the standard deviation

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N} V_i^2}{N-1}} \tag{3}$$

(4) Identifying the sample data that $V_i > 3\sigma$.

where N is the sample number; x_i is the value of the i-th sample; x is the average value of the N sample data; V_i is the residual error; and σ is the standard deviation.

2.3.2. Statistical analysis

A violin plot, which is a hybrid form of a box plot and a density trace, was applied to visualise and analyse summary statistics and density shapes for data exploration (Hintze and Nelson, 1998).

Spearman's rank correlation coefficient is a classical method to analyse the correlation between two variables (Hao et al., 2022). It does not require the frequency distribution of the variables and can identify nonlinear relationships very well (Hauke and Kossowski, 2011; Spearman, 1904). Spearman's rank correlation coefficient was used to explore the relationships between river discharge and salinity.

2.3.3. General hyperbolic model

The river discharge and salinity relationships are widely described by a general hyperbolic model, which can be written as follows (Meybeck et al., 1989):

$$M_i = aQ_i^b \tag{4}$$

where M_i is the instantaneous river water salinization; Q_i is the instantaneous river discharge; a is the river discharge coefficient representing the basal flow; and b is the power of the river discharge and indicates the dilution effect (Crosa et al., 2006). For a given discharge, the higher the values of the two constant parameters (a and b) are, the higher the river salinization is. Previously, the general hyperbolic model was used to investigate the relationships between salinization and discharge in the ADR (Crosa et al., 2006).

2.3.4. Random forest model

Random forest (RF) is a machine learning algorithm that is increasingly being used to identify the key drivers of environmental and freshwater salinization issues (Thorslund et al., 2021). In this study, RF models were used to analyse the effects of hydrometeorological and anthropogenic factors, including runoff (R), agricultural water withdrawal (AWW), irrigation return flow (IRF), water salinity of return flow (WS_RF), irrigation areas (IA), average nitrogen fertiliser use (N), average phosphate fertiliser use (P), population density (POP_D), precipitation (PRE), temperature (TMP), and potential evapotranspiration (PET), on water salinity (Table 1). We performed RF models at stations M2 (upstream and midstream boundary), M4 (midstream and downstream boundary), and M6 (downstream and delta zone boundary) using the annual data from 1991 to 2010. The variables were standardised and checked for collinearity before performing the random forest model (Feld et al., 2016). The collinearity was checked by the Variance Inflation Factor (VIF). According to the VIF, for sites M4 and M6, indicators of irrigation areas, average phosphate fertiliser use and population density were removed. Finally, at the three sites (M2, M4, M6), the VIF of all variables used in the random forest model was less than 10.

3. Results and discussion

3.1. Interannual changes in river discharge and salinity

As shown in Fig. 2, the river discharge of the ADR generally displayed a notable decreasing trend throughout the past five decades, especially downstream. For example, the mean river discharge at hydrological station M4 decreased from 962 m^3/s in the 1970 s to 307 m^3/s in the 2000 s. Hydrological measurements at hydrological station M6 showed that the mean river discharge decreased from 481 m^3/s in the 1970 s to 62 m^3/s in the 2000 s. The mean river discharge at hydrological station M7 decreased even faster, from 595 m^3/s in the 1970 s to 28 m^3/s in the 2000 s. However, the annual river discharge in the upstream showed less temporal variation than the river discharge in the downstream. As evidenced by the hydrological monitoring at station M1 (Surkhandarya River), the mean river discharge decreased slightly from 220 m^3/s in the 1970 s to 204 m^3/s in the 2000 s. In addition, evidence of decreased discharge was found along the river course of the ADR from station M4 (1026 m^3/s) to station M6 (272 m^3/s), where it decreased by 74% over a longitudinal distance of 228 km.

The mean river water salinity observed at eight hydrological stations was less than 1000 mg/L in the 1970 s; however, a notable increasing trend was exhibited in river water salinity from the 1970 s to the 1980 s. In the 1980 s, the average river water salinities at three sites, namely, M5 (~1038 mg/L), M6 (~1110 mg/L) and M7 (~1128 mg/L), were greater than 1000 mg/L. The river water salinity at site M4 (922 mg/L) in the 1980 s was close to 1000 mg/L. Then, river water salinity remained relatively constant from the 1980 s to the 1990 s. For example, the mean river water salinities were 1007 mg/L, 1018 mg/L and 983 mg/L at the M5, M6 and M7 sites, respectively, which were slightly different from those in the 1980 s. Furthermore, a notable increasing trend of river salinity

Table 1
Driving factors for explaining water salinity using the random forest method.

Variables	Acronyms	Data sources	Stations
Runoff	R	CAWater Info	M2, M4, M6
Agricultural water withdrawal	AWW	CAWater Info	M2, M4, M6
Irrigation return flow	IRF	CAWater Info	M4, M6
Water salinity of return flow	WS_RF	CAWater Info	M4, M6
Irrigation areas	IA	CAWater Info	M4, M6
Average nitrogen fertiliser use	N	(Lu and Tian, 2016)	M2, M4, M6
Average phosphate fertiliser use	P	(Lu and Tian, 2016)	M2, M4, M6
Population density	POP_D	World Bank open dataset	M2, M4, M6
Precipitation	PRE	Climate Research Unit (CRU) dataset	M2, M4, M6
Temperature	TMP	CRU dataset	M2, M4, M6
Potential evapotranspiration	PET	CRU dataset	M2, M4, M6

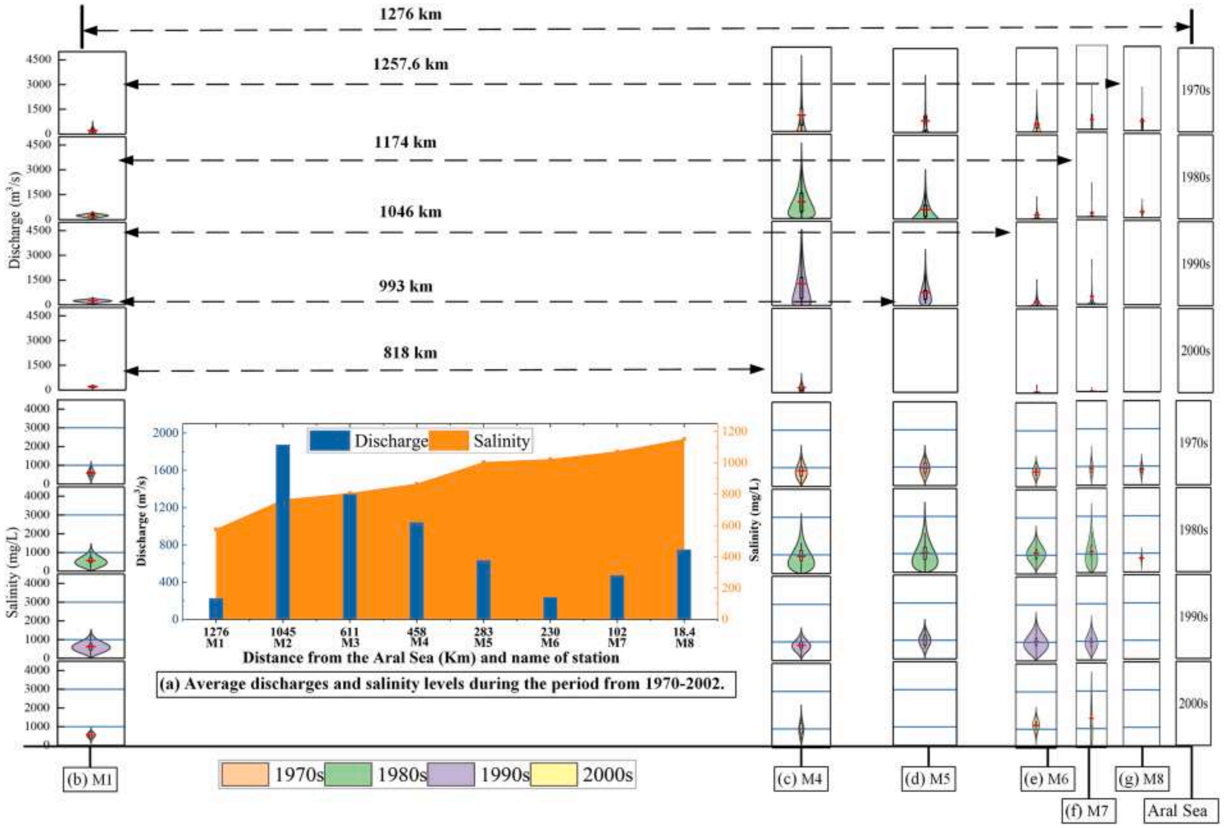

Fig. 2. Spatial patterns of discharge and salinity in the ADR during the 1970 s (1970–1979), 1980 s (1980–1989), 1990 s (1990–1999), 2000 s (2000–2002) and 1970–2002 (a). Stations M1 (b), M4 (c), M5 (d), M6 (e), M7 (f) and M8 (g) along the river are labelled on the X-axis. The lower and upper limits of 1000 and 3000 mg/L for brackish water for salinity are marked with solid blue lines.

appeared again at stations M6, M7 and M4 from the 1990 s to the 2000 s. In the 2000 s (2000–2002), the mean river salinities at sites M6 (~1211 mg/L), M7 (~1560 mg/L) and M4 (~1009 mg/L) were all higher than 1000 mg/L. Linear models between salinity and distance during the periods of 1970–1979, 1980–1989, 1990–1999, 2000–2002 and 1970–2002 were developed (Fig. 3). Spatially, a clear increasing trend pattern in river salinity was detected from upstream to downstream in the ADR basin (Fig. 2a), which was indicated by the high correlation coefficient and R squared value (Fig. 3). Brackish water (salinity higher than 1000 mg/L) mainly occurred downstream. In contrast, the water salinity at site M1 (upstream) was the lowest among the eight monitoring sites, with values below 1000 mg/L throughout the 1970–2000 s

The annual river water salinities for 2000–2015 at the survey sites are shown in Fig. 4. Compared with the other sites, the highest river water salinity during the period of 2000–2010 was observed at site M6. Notably, water salinity at site M6 experienced significant decreases with a slope of − 75.84 mg/L per year from 2000 to 2010. In particular, the annual river salinity at the M6 site declined to less than 1000 mg/L after 2008. Observations at site S2 (Kafirnigan River) also showed negative trends with a slope of − 19.49 mg/L per year in annual river water salinity, suggesting that river salinity declined from 2000 to 2015. In contrast, river salinities at sites M2 and S1 showed increasing trends with slopes of 16.22 mg/L per year and 22.26 mg/L per year, respectively. The river salinities at sites M2 and S1 nearly reached 1000 mg/L in 2015. River salinities at sites M3, M4, S4 (located between M2 and M3) and S3 (Surkhandarya River) did not show notable changing trends during the 2000–2015 period. Generally, water salinities at sites M3, M4, S4 and S3 were less than 1000 mg/L, which meets the quality requirements for drinking and irrigation. In particular, the mean annual salinities at the S3 site were less than 600 mg/L during the 2000–2015 period.

3.2. Seasonal variations in discharge and salinity

The statistics for monthly river discharge and salinity at the hydrological stations of the ADR are shown in Tables S5 and S6, and the seasonal trends for river discharge and salinity are shown in Table S7. As shown in Fig. 5, river discharge experienced notable seasonal variations. The maximum monthly river discharge usually occurred during summer (June-August) at all stations. River discharge at four hydrological stations (M1, M4, M5 and M6) had minimum values during winter (December-February).

The density shapes in the violin plots show that the distribution of monthly salinity is more uniform and symmetrical than that of river discharge, especially at hydrological stations M6 and M7 (Fig. 2). Generally, the highest monthly river salinity occurred in April,

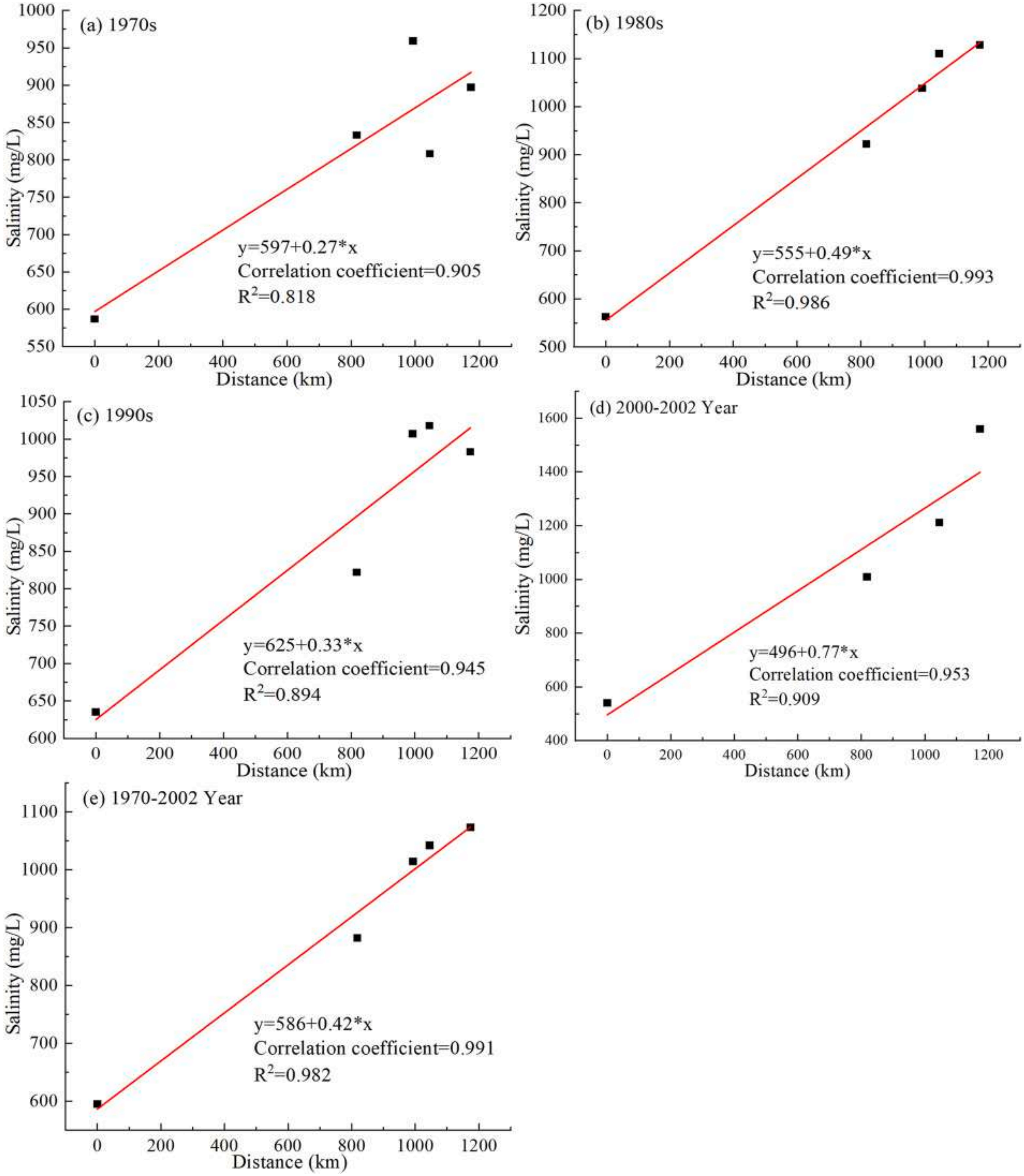

Fig. 3. Linear models between salinity and distance from upstream to downstream stations.

except for stations M1 (February) and M4 (March). The lowest river salinity usually occurred in July-September, except for station M1 (November).

Spatially, a clear pattern of increasing river salinization was detected from upstream to downstream in the ADR basin. The highest river salinity was observed at station M7, with a value of 3795 mg/L. The mean monthly water salinity increased by 80% during 1970–2002 for 1174 km from station M1 (595 mg/L) to station M7 (1073 mg/L). In terms of variations in salinity during the year, the highest monthly average salinity values at the considered stations along the river were within the ranges of 596–1378 mg/L (M1), 980–1737 mg/L (M4), 911–2105 mg/L (M5), 982–2574 mg/L (M6), 942–3796 mg/L (M7) and 724–1371 mg/L (M8).

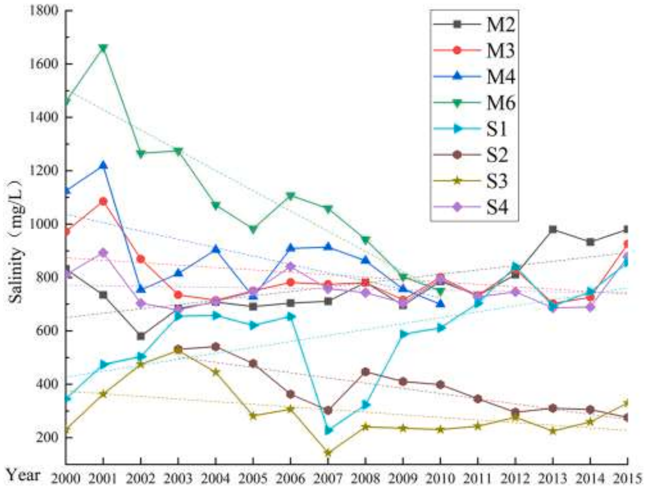

Fig. 4. Temporal variations in annual river salinity in the ADR from 2000 to 2015.

As shown in Fig. 5, monthly river salinity exhibited a negative correlation with monthly river discharge at all stations. However, the negative relationship between river discharge and river salinity became less obvious along the river. The most obvious negative relationship between river salinity and discharge was observed at hydrological station M1 (upstream) (Fig. 5a), while such a negative relationship was nonsignificant at station M8 (downstream) (Fig. 5f). Along the river course from station M4 (the boundary between the middle stream and downstream areas) to M7 (downstream; the distance between sites M4 and M7 is 356 km), the highest value of river salinity approximately doubled; however, the discharge was reduced by less than half.

3.3. Spatial patterns of river salinity-discharge relationships

River salinity-discharge relationships and their correlation coefficients are shown in Fig. 6 and Table S8, and residual plots were used to verify the reliability of the results. The results show that river salinity-discharge relationships displayed notable spatial longitudinal variations in the ADR basin. At hydrological stations M4 and M6, coefficient *b* in the general hyperbolic model (Eq. (4)) were higher than those at the other stations, indicating that the flow dilution effect had predominant influences on river salinities at these two stations during both the 1970–1980 s and 1990–2000 s. Based on the comparisons of parameters *a* and *b* in the general hyperbolic model (Eq. (4)) among all stations, we found that baseflow effects outweighed dilution effects at stations M1, M2 and M3 (with larger values of *a*). However, dilution effects outweighed baseflow effects on the river salinities (with higher values of *b*) were observed at stations M4, M6, M7 and M8. Additionally, baseflow and dilution had comparable effects on river salinities at station M5.

Compared with the 1970–1980 s period, reduced baseflow effects on river water salinities can be found during the 1990–2000 s at stations M1 and M4. However, the baseflow effects on river water salinities exhibited increasing trends from the 1970–1980 s to 1990–2000 s at stations M5, M6 and M7. As shown in Fig. 7, in general, the correlation coefficients between river salinity and river discharge during the growing season (high flow) are greater than those during the nongrowing season (low flow). It can be concluded that although the increased river salinities were mainly driven by human activities in the past decades, the seasonal variations in river water salinity are controlled by the dilution effect of the river flow. The correlation coefficients between river salinity and discharge of annual data in the 1970–1980 s are higher than those in the 1990–2000 s at stations M1 and M4, and the opposite cases are observed at stations M5 and M6.

3.4. Driving forces and conceptual model of river water salinization

3.4.1. River water salinization driven by natural processes and human activities

As noted by Cañedo-Argüelles et al. (2013) and Thorslund et al. (2021), freshwater salinization is driven by both natural (e.g., evaporation processes) and anthropogenic (e.g., agricultural activities) factors. Our results (Fig. 8) showed that the average nitrogen fertiliser use (N), agricultural water withdrawal (AWW) and water salinity of return flow (WS_RF) are the most influential factors in river salinity at stations M2, M4 and M6, respectively. Our analysis confirmed that anthropogenic factors associated with agricultural activities are predominant drivers of river water salinization in the ADR, which is consistent with previous studies in Central Asian rivers (Crosa et al., 2006; Karimov et al., 2019; Lobanova and Didovets, 2019; Rakhmatullaev et al., 2010; Yapiyev et al., 2021).

Globally, as indicated by Gibbs (1970), river water chemistry is generally controlled by atmospheric precipitation, rock dominance, and the evaporation-crystallisation process. For rivers in Central Asian arid regions, ion concentrations in river water are increasing due to intensified evaporation from upstream to downstream. The evaporation in the northwestern (middle and downstream) is higher than that in the southeastern (upstream) of the ADR basin; therefore, this may be one of the reasons why the river salinity in the middle and downstream is greater than that in the upstream. On the other hand, river salinity can be reduced by dilution during periods of

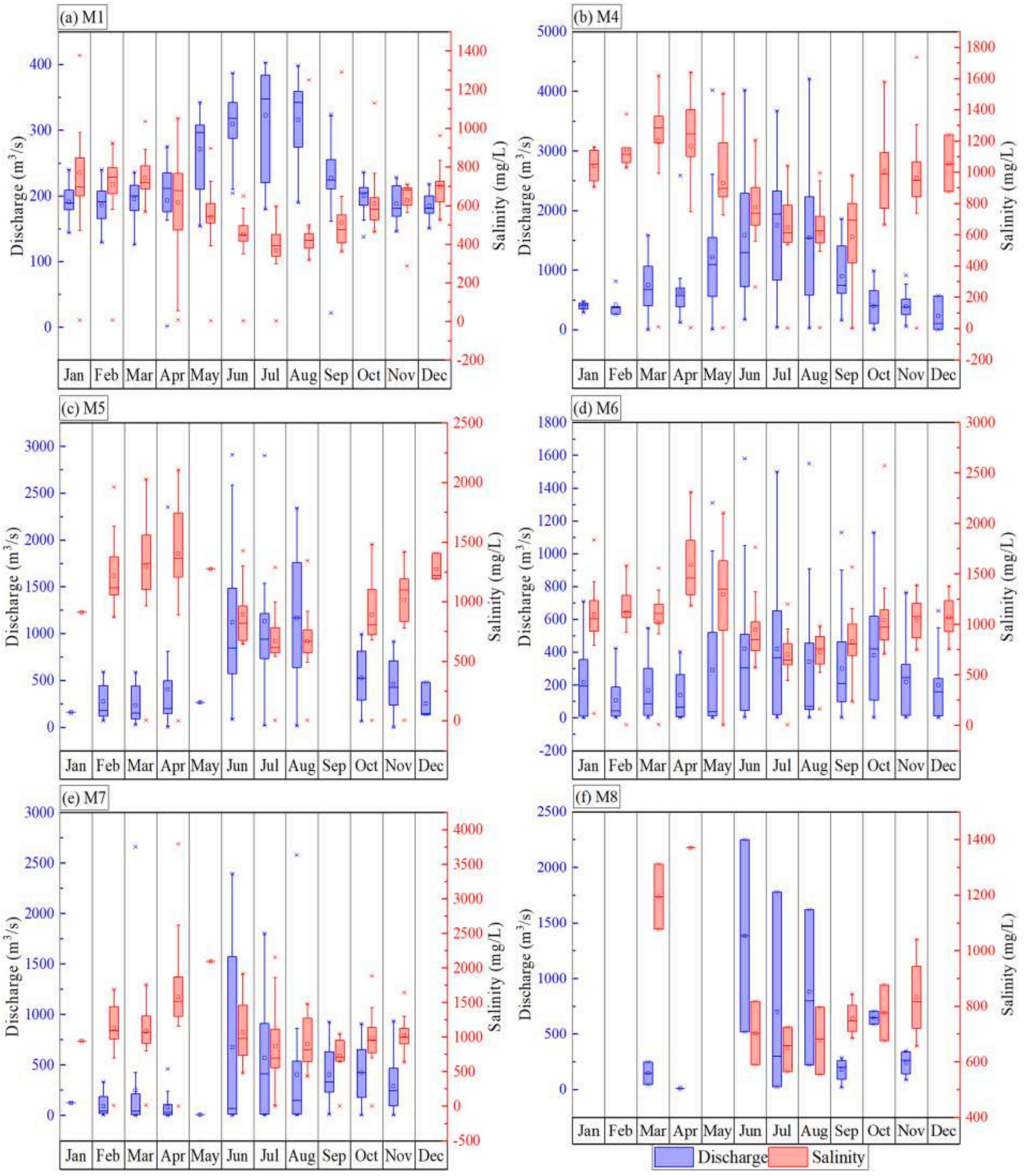

Fig. 5. Intra-annual variability in river discharge and salinity for the hydrological stations of the ADR during the 1970–2002 period. Box plots represent the monthly data distribution.

rainfall (Cañedo-Argüelles, 2020; Thorslund et al., 2021). Generally, salinity is low where precipitation is greater. Spatially, precipitation was higher in the southeastern ADR basin than in the northwestern part. Temporally, the annual precipitation exhibited an increasing trend (3 mm/decade) during 1960–2017, except for the southwestern part of the basin (approximately −10 mm/decade) (Hu et al., 2021). The effect of precipitation dilution on freshwater salinization is opposite to that of the enrichment of river water salinity by evaporation. However, the river water salinity in the ADR did not decrease during the 1970–1990 s. Therefore, increased precipitation failed to reduce the water salinity due to other factors, e.g., water withdrawal for irrigation, fertiliser usage and return

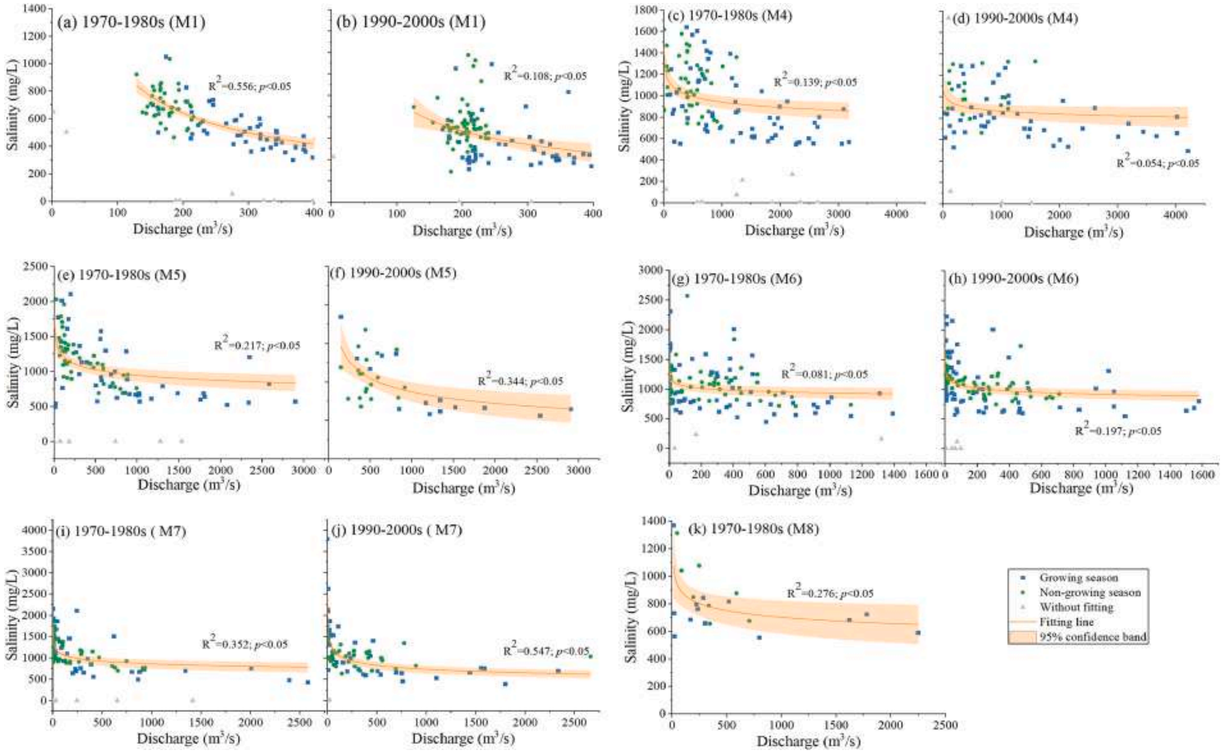

Fig. 6. River salinity-discharge relationships at stations M1, M4, M5, M6, M7 and M8 during the 1970–1980 s and 1990–2000 s. R^2 and *p* values and confidence intervals (95%) are also provided for both periods. The growing season (April-September) is the period of the year when crops and other plants grow successfully; the nongrowing season (October-March) is the opposite of the growing season.

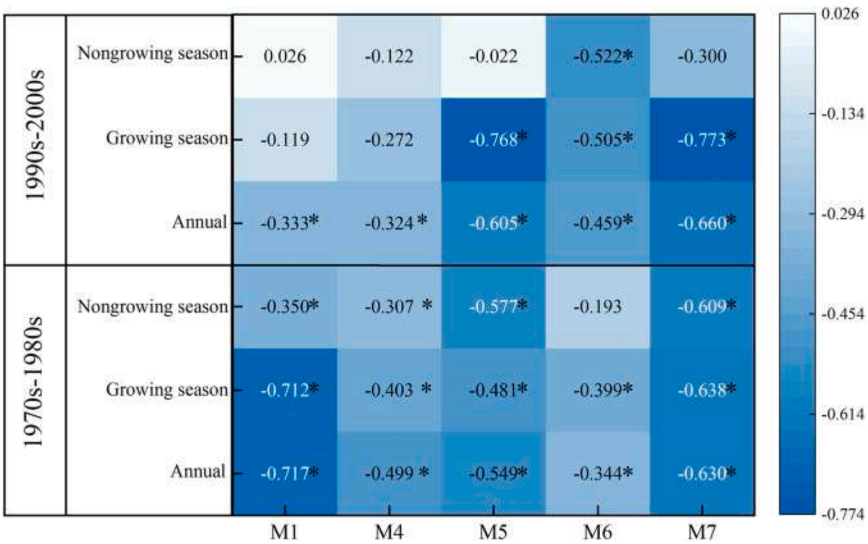

Fig. 7. Spearman's rank correlation coefficient between river salinity and discharge at stations M1, M4, M5, M6 and M7. "* " indicates a correlation with a *p*-value less than 0.05.

flow.

A recent study has shown that human activities may be an important cause of temporal dynamics in river salinity (Moyano Salcedo et al., 2022). In the ADR basin, river salinization can also be caused by enhanced human activities, which is evidenced by the fact that the population density increased approximately threefold in riverine countries throughout 1960–2020 (Fig. S3). There have been no considerable increasing trends in urban and cropland areas during the past 50 years (Fig. S4; Shi et al., 2021; Yapiyev et al., 2021).

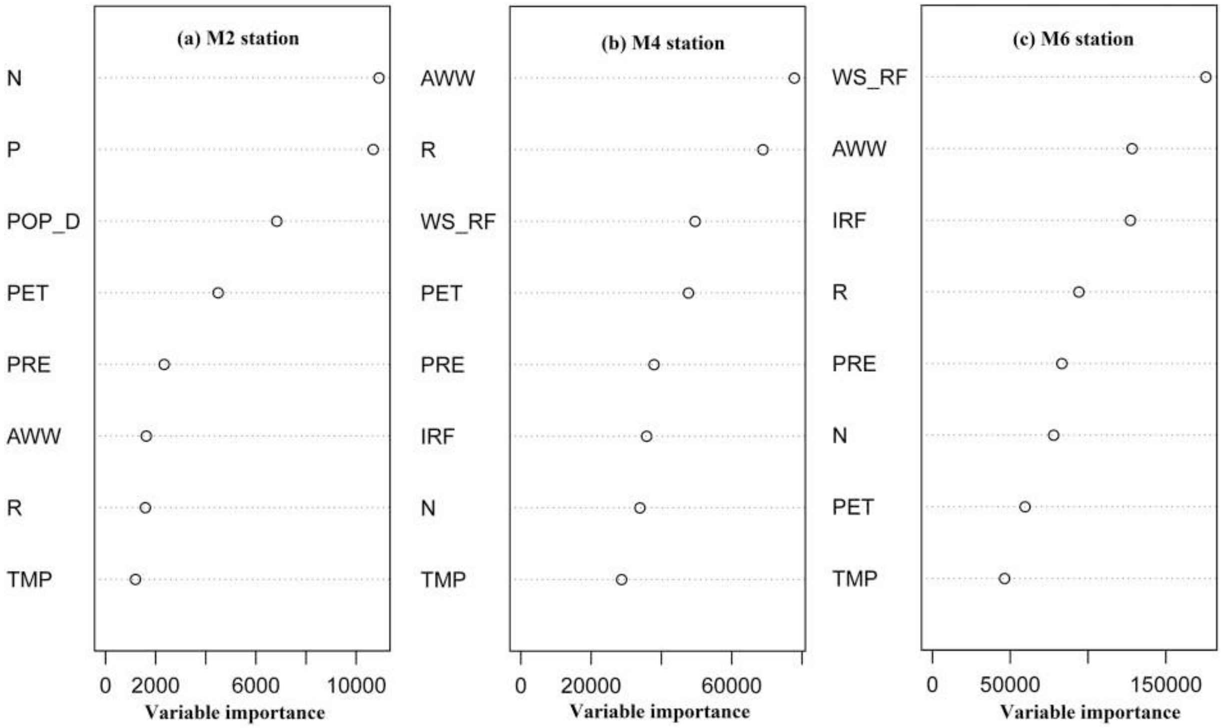

Fig. 8. Random forest plot representing the relative importance of the drivers explaining water salinity.

Nevertheless, agricultural activity intensified after the 1970–1980 s in the ADR basin due to increased irrigation for water-intensive crops, elevated usage of pesticides and fertilisers, and degraded irrigation and drainage canals (Shi et al., 2021; Törnqvist et al., 2011; Yapiyev et al., 2021).

Our analysis showed that the irrigated areas in the downstream of the ADR basin remained almost constant from 1991 to 2010; however, the irrigated areas exhibited a slightly increasing trend in the middle stream (Fig. S5). Water withdrawal showed a slight decreasing trend in the middle and downstream areas during the period from 1991 to 2010 (Fig. S5). Moreover, the river water salinity showed negative trends from 2000 to 2015 at most sites (Fig. 4). Irrigation and drainage activities in the ADR basin are the main processes governing the spatial-temporal pattern of salt content in the river. Together, the volume and salinity of return flow likely shape the spatial and temporal patterns of freshwater salinization, which is indicated by the consistent trends in the river water salinity of the considered stations during 1990–2010. In particular, the return flow with a high salt load from drainage systems into the river is the major factor that shapes the salt dynamics.

In general, river runoff in the ADR has experienced a notable declining trend over the past half-century and is expected to decrease by 10–20% by the end of the 21st century due to the influences of climate change and human activities in the ADR basin (Hu et al., 2021; White et al., 2014). Freshwater salinization has been exacerbated by decreased water volume and weakened dilution in the middle and downstream reaches of the ADR due to increased water demands and withdrawals by agricultural and domestic users (Cañedo-Argüelles, 2020). As noted by Niedrist et al. (2021), water resource extraction or agriculture are the main drivers of secondary salinization in arid and semiarid regions. Similarly, secondary salinization is likely the main process of water salinization in the ADR. However, in terms of the seasonal changes in salinity, the main controlling factor of intra-annual variation in salinity in the ADR is flow. Salinity does not increase in April-September, which is the growing season when agricultural activities intensify (e.g., increased pesticide use, fertiliser use and irrigation water return flow). In contrast, water salinity decreases in the basin due to the high flows, even in the lower reaches. Therefore, in the ADR, intra-annual variation in salinity is dominated by natural factors, and simultaneously, it is regulated by human activity (Timpano et al., 2018).

3.4.2. Conceptual model of river water salinization

There is significant spatial heterogeneity in freshwater salinization and salinity-discharge relationships and their drivers in the ADR basin under the combined effect of human activities and climate change. Fig. 9 shows the processes and drivers of river water salinization in the ADR basin. In the upstream, where river flows are high and the intensity of human activity is low, the salinity of the water is mainly controlled by primary salinization (e.g., snow melting, precipitation). Although hydroelectric plant operations and mining can regulate water salinity, they do not lead to a significant deterioration of salinization. In the middle stream, human activity is gradually intensifying, and the salinity of the water is influenced by a combination of natural processes (e.g., increased temperature and evaporation) and human activity (e.g., industrial and agricultural activities). In the downstream and delta areas, high-intensity agricultural activities (e.g., pesticides, fertilisers, irrigation water return flow) control the process of water salinization. In addition,

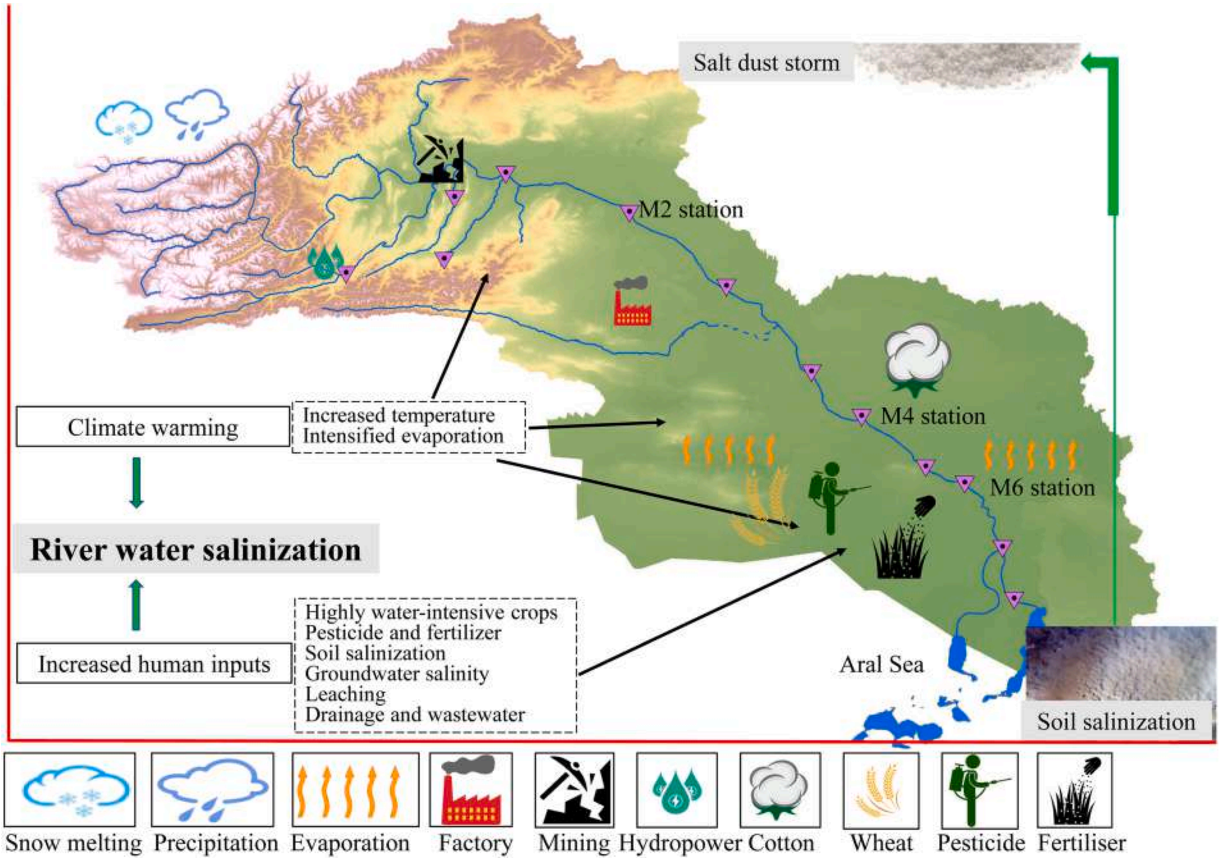

Fig. 9. A conceptual model of river water salinization in the ADR basin.

salinity accumulation also contributes to increasing salinization due to the flow concentration process. This conceptual model can be applied to analyse the freshwater salinization processes in agriculturally dominated inland rivers recharged by snowmelt in semiarid to arid areas.

3.5. Uncertainties and limitations

In this study, we attempted to analyse the long-term change patterns of salinity and flow in the ADR based on a large amount of observational monthly data for water salinity and discharge. However, the data series were not consistent and varied year by year (Table S2). Although we used a time step of a decade to reduce the potential random errors, these uncertainties could not be eliminated entirely. In addition, data from different seasons may introduce uncertainty in the interpretation of the results.

Estimated general hyperbolic models provided us with general knowledge about the spatiotemporal patterns of salinity-discharge relationships in the ADR. Although river discharge is the main driving factor for seasonal variation in river water salinity in the ADR, freshwater salinization is certainly influenced by other natural and human factors (Crosa et al., 2006). In this study, the potential drivers of river water salinity such as soil salinity and irrigation schemes, were not considered in the RF models due to the lack of such data.

4. Conclusions

In this study, the spatial and temporal patterns of streamflow and river salinity in the ADR basin during the past five decades were analysed comprehensively. The results revealed that river salinity generally increased along the river course, and the river water salinity exceeded the safe drinking and irrigation standard (1000 mg/L) in the middle and downstream areas, especially in the downstream area. Temporally, during the 1970–1990 s, the river water salinity experienced a notable increasing trend; however, it gradually decreased after 2000. Apart from natural salinization processes, the increasing intensity of human activities, including water withdrawal for crop irrigation and high salinity drainage and wastewater flows into the river, is the predominant driver of river water salinization. Although limited success was achieved in controlling river water salinity during the 21st century, more efforts are needed to mitigate challenges related to freshwater salinization and to realise regional SDGs.

Recognising that freshwater salinization from agricultural activities is a growing problem (Thorslund et al., 2021), a detailed analysis of freshwater salinization at subbasin or irrigated agricultural region scales is needed. Equally important, such analyses require detailed irrigation data, such as irrigation schemes and the location and quantities of return flow from main drains. In terms of research methodology, water quality modelling approaches can be performed to understand the salt dynamics in river reaches, and Bayesian model approaches can be applied to quantify the contributions of freshwater salinization drivers (Huang et al., 2021a, 2021b). Moreover, the breakpoints in both trend and seasonal components can be detected by the break for the additive season and trend (BFAST) method based on long-term consecutive data (Verbesselt et al., 2010). In addition, more efforts are needed to analyse the interactions between freshwater salinization and the SDGs and to mitigate the potential trade-offs among SDGs using the nexus approach (Flörke et al., 2019; Liu et al., 2018).

CRediT authorship contribution statement

Lingang Hao: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Visualization, Writing – original draft preparation. **Ping Wang**: Conceptualization, Resources, Validation, Writing – review & editing. **Boris Gojenko and Shavkat Kenjabaev**: Resources, Validation, Writing – review & editing. **Jingjie Yu**: Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing. **Aifeng Lv and Fadong Li**: Data curation, Writing – review & editing. **Rashid Kulmatov and Fazliddin Khikmatov**: Writing – review & editing.

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

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2023.101375.

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