Spatiotemporal variations of surface water and its response to climate change in global arid regions during 2000-2020 Post-print

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Abstract

Surface water plays an essential role in the ecohydrological cycle, especially in water-scarce regions. Changes in surface water restrict social, economic, and agricultural development. However, the patterns and underlying causes of surface water changes over varying frequencies in global arid regions remain unclear. Thus, this study investigated the changes in surface water and the underlying causes using the trend analysis and Spearman correlation coefficient on the basis of multi-source remote sensing and climate datasets across global arid regions during 2000-2020. The surface water was divided into temporary surface water (TSW), seasonal surface water (SSW), and permanent surface water (PSW) by calculating the surface water inundation frequency. Considering that surface water may be influenced by precipitation in the upper basins, we analyzed the response of surface water area to climatic factors at the basin scale. The area of all surface water (ASW) increased dramatically in global arid regions from 2000 to 2020, increasing from 61.88$×104*to*67.40×$104 km2; however, this increase was accompanied by a decrease in surface water inundation frequency. TSW increased by 55.46% relative to its area in 2000, with a net change rate of 3284.00 km2/a. Changes in surface water were predominantly observed in the Kyzylkum Desert in Central Asia, the Thar Desert in southwestern Asia, and the deserts in Oceania. Precipitation had a significant effect on SSW and TSW at the basin scale. The correlation between precipitation and SSW area can reach 0.808 in the Indus River Basin of the Thar Desert (P<0.01). The findings provide a more comprehensive understanding of surface water variability in global arid regions, carrying significant practical implications for the scientific management of surface water at different frequencies.

Full Text

Preamble

J Arid Land (2026) 18(4): 568-583 Spatiotemporal variations of surface water and its response to climate change in global arid regions during 2000-2020 TIAN Yanjun , SUN Yongqi , HOU Senlei , GAO Yongnian , ERKIN Shireli 1 School of Earth Sciences and Engineering, Hohai University, Nanjing 211100, China; College of Geography and Remote Sensing, Hohai University, Nanjing 211100, China; College of Hydraulic and Civil Engineering, Xinjiang Agricultural University, Urumqi 830052, China

Abstract

Surface water plays an essential role in the ecohydrological cycle, especially in water-scarce regions. Changes in surface water restrict social, economic, and agricultural development. However, the patterns and underlying causes of surface water changes over varying frequencies in global arid regions remain unclear. Thus, this study investigated the changes in surface water and the underlying causes using the trend analysis and Spearman correlation coefficient on the basis of multi-source remote sensing and climate datasets across global arid regions during 2000-2020. The surface water was divided into temporary surface water (TSW), seasonal surface water (SSW), and permanent surface water (PSW) by calculating the surface water inundation frequency. Considering that surface water may be influenced by precipitation in the upper basins, we analyzed the response of surface water area to climatic factors at the basin scale. The area of all surface water (ASW) increased dramatically in global arid regions from 2000 to 2020, increasing from 61.88\$×10*to*67.40×\$10 ; however, this increase was accompanied by a decrease in surface water inundation frequency. TSW increased by 55.46% relative to its area in 2000, with a net change rate of 3284.00 /a. Changes in surface water were predominantly observed in the Kyzylkum Desert in Central Asia, the Thar Desert in southwestern Asia, and the deserts in Oceania. Precipitation had a significant effect on SSW and TSW at the basin scale. The correlation between precipitation and SSW area can reach 0.808 in the Indus River Basin of the Thar Desert (<0.01). The findings provide a more comprehensive understanding of surface water variability in global arid regions, carrying significant practical implications for the scientific management of surface water at different frequencies.

Keywords

surface water area; surface water inundation frequency; temporary surface water; climate change; snow melting; global arid regions Citation:

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1 Introduction

Surface water, although only a fraction of the total water resources, has played a crucial role in the sustainable development of arid regions. The spatial configuration of surface water exhibits marked spatiotemporal heterogeneity in arid regions (Xie et al., 2016), characterized by ephemeral hydrological processes manifested in seasonal contraction–expansion cycles and channel migration dynamics (Huang et al., 2018; Wu et al., 2023). Surface water area is extremely sensitive to changes in climate and the surrounding environment (Immerzeel et al., 2010; Sheng et al., 2016). Timely, accurate, and dynamic monitoring of surface water changes is essential for understanding the spatial extent and evolutionary trends of water bodies. Such monitoring is crucial for revealing the evolving patterns of water resources and the broader water environment in global arid regions, particularly in the context of climate variability and land use changes, which significantly impact water dynamics (Tulbure and Broich, 2019). Moreover, surface water is essential for creating favorable conditions that support the healthy development of ecosystems in arid regions. It is also a vital prerequisite for maintaining the stability of social and economic systems (Huang et al., 2021; Liu et al., 2023; Zhang et al., 2023b). Spatial variability in surface water, as a significant component of arid regions, has increasingly contributed to intensified disputes over its utilization (Wang et al., 2025).

Recent studies have conducted primary evaluations of various quantitative changes in surface water. For example, a 31-a monitoring study on global surface water changes revealed that the surface water area on Earth increased by 11.50$×10between1985and2015(Donchytsetal.,2016).Pekeletal.(2016)reportedthatapproximately9.00×10ofp of PSW formed in other regions. These findings indicated that dynamic changes in surface water are more pronounced. However, research on surface water fluctuations in arid regions, particularly concerning the frequency of surface water occurrence, remains limited.

Therefore, monitoring surface water area changes in water-scarce regions is necessary to improve the understanding of this issue and facilitate the effective management of water resources in these regions.

The dynamics of surface water in arid regions play a pivotal role in shaping terrestrial ecosystems and hydrological cycles on Earth. Recent studies have highlighted an emerging warming–wetting trend in arid regions, driven by increased precipitation and rising temperatures that are linked to climate change (Chen et al., 2015, 2020; Li et al., 2024). This phenomenon gives rise to a series of critical inquiries, particularly concerning the combined repercussions of enhanced rainfall, glacial meltwater, and snow cover changes on surface water availability (Huss and Hock, 2018; Yu et al., 2019). The distribution of surface water is influenced predominantly by precipitation, temperature, and snow cover, each of which shows distinct effects (Wu et al., 2020; Sun et al., 2023; Zhang et al., 2023a).

While surface water changes in arid regions are increasingly recognized as critical indicators of ecosystem vulnerability, the divergent responses of frequency-dependent surface water to climatic drivers remain conspicuously inadequate. This study integrated the surface water inundation frequency-based classification with spatial heterogeneity analysis to investigate the spatiotemporal variation characteristics of surface water in global arid regions. Crucially, the basin-scale attribution analysis was used to reveal distinct climatic drivers (e.g., precipitation anomalies and warming-induced snow melting) that controlled the surface water variability.

These findings will establish a diagnostic framework for arid hydrology resilience, prioritizing adaptive management of ephemeral water resources in water-scarce regions. 2 Materials and methods

2.1 Study area

This study selected the global arid regions as the study area (Fig. 1 [FIGURE:1]). The study area has a typical arid climate characterized by low and highly variable annual precipitation, often less than 250 mm, and in hyperarid zones, even less than 100 mm (Abd-Elhamid et al., 2025). This climate is distinguished by its high potential for evapotranspiration, which significantly exceeds precipitation, resulting in persistent water deficits (Ajjur and Al-Ghamdi, 2021). Furthermore, it exhibits significant diurnal and seasonal temperature variations, with mean annual temperatures

typically exceeding 20.000°C in hot deserts and steppes (Zhou and Wang, 2016). The extent of surface water in global arid regions is susceptible to fluctuations in climatic factors, such as precipitation and temperature. The global arid regions mainly include the Thar Desert in western South Asia, the Kyzylkum Desert and Karakum Desert in Central Asia, the Taklimakan Desert, Gurbantunggut Desert, and Qaidam Desert in northwestern China of Asia, the Sonoran Desert in southwestern North America, the Atacama Desert in western South America, the Sahara Desert in northern Africa, the Namib Desert in southwestern Africa, the Arabian Desert in southwestern Asia, the Great Sandy Desert in northwestern Australia of Oceania, the Gibson Desert in western Australia of Oceania, the Simpson Desert in east-central Australia of Oceania, and the Great Victoria Desert in southwestern Australia of Oceania.

Spatial distribution of global arid regions

2.2.1 Köppen-Geiger data

multitude of meteorological stations (Peel et al., 2007). The Köppen-Geiger classification provides a standardized framework for monitoring surface water dynamics across the global arid regions. We extracted the vector ranges of BWh (hot desert), BWk (cold desert), BSh (hot steppe), and BSk (cold steppe), which covered 19.45% of the global regions.

Surface water data The Global Surface Water (GSW) dataset provided by the European Union’ s Joint Research extent data at a spatial resolution of 30 m. This dataset was generated from millions of Landsat images acquired since 1984 and thus could provide a comprehensive and consistent representation of global surface water extent (Pekel et al., 2016). However, the restricted global coverage of Landsat images prior to 2000 has resulted in an inherent limitation in the accuracy of surface water extraction during earlier periods (Wulder et al., 2016). Consequently, this study utilized monthly data during 2000-2020 from the GSW dataset to ensure a higher level of accuracy and to facilitate the capture of recent trends in surface water dynamics.

Temperature data ERA5 is the fifth-generation European Centre for Medium-Range Weather Forecasts (ECMWF)

climate reanalysis parameters, including 2-m air temperature and other variables. In this study, we selected 2-m air temperature during 2000-2020 with a resolution of 0.1° for global arid regions as the independent variable. The mean annual temperature was determined through the Google Earth Precipitation data The Global Precipitation Climatology Centre (GPCC) was created for climatological research according different demands. precipitation dataset is available data obtained using a large time delay. We selected monthly near real-time global precipitation data at a 1.0° resolution for the period 2000-2020, and upscaled the data to 0.1° resolution using bilinear interpolation (Beck et al., 2022), matching the temperature dataset. We utilized the precipitation data to analyze precipitation changes within global arid regions, which can provide insight into the underlying factors that influence surface water variability.

Snow cover data Snow cover is particularly important in mountains, leading to changes in surface water area. The MODIS/Terra Snow Cover Monthly L3 Global 0.05Deg CMG (MOD10CM) dataset, which can tool/MOD10CM), was selected to analyze the changes in snow cover area. The monthly average snow cover was calculated for each cell in the Climate Modeling Grid (CMG) using the daily snow cover observations. Given the missing data for certain periods in the MOD10CM product in 2000, the temporal variations in total snow cover area during 2001-2020 were calculated and used to investigate the potential drivers of surface water changes.

Basin data The HydroSHEDS (Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales) provides global basin data for hydrogeological research and applications extensive array of hydrological data products encompasses a multitude of geographical features, such as watershed boundaries, river networks, and lakes, presented at varying resolutions and scales. Additionally, it constituted a geospatial framework for a variety of assessments, such as those pertaining to hydrology, the environment, conservation, and other domains. The HydroSHEDS dataset was provided in raster and vector formats, offering a geographic reference for researchers. In this study, three-level basin data were selected for the purpose of dividing the global arid regions.

2.3 Methods

2.3.1 Calculation of surface water inundation frequency and classification of surface water We calculated the surface water inundation frequency on the Google Earth Engine platform pixel extraction and surface water inundation frequency calculation. The water pixels were extracted from the monthly GSW dataset, where water and no water were represented as 1 and 0, respectively. Equation 1 was used to calculate the water frequency at each pixel, which represents the number of times a given pixel was identified as water throughout the year.

Water Total where SWIF is the surface water inundation frequency (%); Water represents the number of pixels identified as water; and Total represents the total number of observations. Then, all surface water (ASW) with SWIF>0.00% can be divided into TSW (0.00%<SWIF$ 25.00 75.00 $100.00%) (Zou et al., 2018; Liu et al., 2024a).

2.3.2 Trend analysis of surface water and climatic factors To characterize temporal changes in surface water (ASW, TSW, SSW, and PSW) and climatic factors across multiple spatial scales, we selected trend analysis methods according to the statistical characteristics of the data. At the pixel scale, Sen’ s slope (Sen, 1968) or ordinary least squares (OLS) linear slope was used to quantify temporal trends, and the Mann-Kendall test (Mann, 1945; Hamed and Rao, 1998) was applied to evaluate their statistical significance. These methods have been frequently used to examine temporal variations in meteorological and hydrological data (Yang et al., 2020a; Meng et al., 2023). In addition, a spatial resolution of 2.5° was chosen to better reflect the spatial heterogeneity of surface water area changes (Tran Anh et al., 2019). For analyses conducted at the 2.5° grid and basin scales, the OLS linear slope was used to quantify trends, as spatial aggregation could reduce local noise and yield smoother time series. The hotspots of surface water inundation frequency changes were delineated by identifying areas with significant trends from the pixel-scale Sen’ s slope analysis, followed by kernel density analysis in ArcGIS Pro to further characterize their spatial clustering.

Sliding -test of surface water changes The surface water area is susceptible to alteration by climatic factors in arid regions. In this study, the sliding -test (Du et al., 2019) was used to identify the year in which the mutation occurred.

The sliding pointer traversed the entire time series from left to right, and the nonstationary series was partitioned into multiple stationary segments (Huang et al., 2016). By moving the sliding pointer in discrete steps along the time series, the -values were calculated to evaluate the discrepancy between the mean values of the left and right time series. Larger -values indicated a break in the data.

Correlation analysis between surface water and climatic factors To determine

Figure 2

Figure 1: Figure 2

the underlying causes of surface water area, we used the Spearman correlation coefficient (Myers and Sirois, 2006) to evaluate the strength of the monotonic relationship between changes in surface water area and influencing factors. The formula is as follows: , (2) where is the Spearman correlation coefficient; is the sample size of the data;) and represent the ranks of the observation of the influencing factor and surface water area, respectively; and represent the means of the ranks of the influencing factor and surface water area during 2000-2020, respectively.

3 Results

3.1 Temporal dynamics of surface water in global arid regions From 2000 to 2020, the ASW increased markedly in global arid regions; it increased by 8.92%, from 61.88$\times 10 to 67.40 \times$10 , at a rate of 3953.00 /a (Fig. 2

). The SSW and TSW increased by 11.53% and 55.46%, respectively. The rates of increase were 1628.00 /a for SSW and 3284.00 /a for TSW, indicating an expansion in the area of unstable surface water. In contrast, the PSW slightly decreased, at a rate of 959.00 km /a. Compared with that in 2000, the PSW in 2020 decreased by 4.07%. In summary, the findings suggested that changes in ASW were predominantly influenced by an increase in TSW within global arid regions. The accelerated transition, with increases of 8.92% in ASW and 55.46% in TSW, revealed the progressive decoupling of surface water stability regimes in arid ecosystems.

In this study, the sliding -test was used to explore the abrupt changes of surface water area in

global arid regions during 2000-2020. The ASW change was divided into four time periods (2000-2003, 2003-2005, 2005-2015, and 2015-2020) according to the abrupt change points (Fig. 3a [FIGURE:3]). The variability in SSW and TSW was greater than that in PSW, thereby increasing surface water instability (Fig. 3b-d).

Temporal variations of surface water area in global arid regions from 2000 to 2020. ASW, all surface water; PSW, permanent surface water; SSW, seasonal surface water; TSW, temporary surface water.

Abrupt changes in surface water area during 2000-2020. (a), ASW; (b), PSW; (c), SSW; (d), TSW. The blue dots indicate years in which the changes were statistically significant. 3.2 Spatial patterns of surface water changes in global arid regions 3.2.1 Spatial patterns of surface water area changes During 2000-2020, the ASW increased mainly in the Thar Desert, Sahara Desert, and Atacama Desert (Fig. 4 [FIGURE:4]). The maximum increase in ASW area can reach

258.00 km /a. The increase of ASW in the Taklimakan Desert was mainly reflected in PSW increase. ASW reduction was detected mainly in the Kyzylkum Desert, which was dominated by PSW. The maximum decrease in ASW area can reach 525.00 km /a. In addition, the regions where the decrease in ASW was primarily attributed to the reduction in both PSW and SSW were located primarily in the Great Sandy Desert and Simpson Desert.

Spatial pattern of surface water area changes in global arid regions during 2000–2020. (a1 and a2), trend and significance of ASW change; (b1 and b2), trend and significance of PSW change; (c1 and c2), trend and significance of SSW change; (d1 and d2), trend and significance of TSW change. 3.2.2 Spatial pattern of surface water inundation frequency changes In global arid regions, areas with increasing surface water inundation frequency accounted for 34.64% of ASW area, whereas areas with decreasing surface water inundation frequency made up 63.36% of ASW area. This finding proved that the surface water in the global arid regions became increasingly unstable. Spatially, the regions where the surface water inundation frequency decreased were located mainly in the Kyzylkum Desert (Fig. 5a [FIGURE:5]), and the regions where the surface water inundation frequency increased were primarily distributed in the Thar Desert and Taklimakan Desert (Fig. 5b). 3.3 Effects of climate change on surface water in global arid regions at the basin scale 3.3.1 Surface water inundation frequency-based surface water changes across diverse basins Considering that surface water may be influenced by precipitation in the upper basins, this study discussed the variation characteristics of the surface water area at the basin scale (Fig. 6 [FIGURE:6]). The

Hotspots of surface water inundation frequency decrease (a) and increase (b) in global arid regions during Spatial pattern of surface water area change in global arid regions at the basin scale during 2000-2020. (a), ASW; (b), PSW; (c), SSW; (d), TSW. basins showing increase in ASW area accounted for 27.98% of all the basins in global arid regions between 2000 and 2020. Large increases in ASW area were observed in the Indus River Basin of the Thar Desert, the Syr River Basin of the Kyzylkum Desert, and the Mesopotamia River Basin of the Arabian Desert, increased at rates of 557.00, 463.00, and 388.00 km respectively. The basins exhibiting decrease in ASW area accounted for 63.62% of all the basins in global arid regions. The Amu Darya River Basin in the Kyzylkum Desert, the Eyre Lake Basin in the Simpson Desert, and the Mackay Lake Basin in the Great Sandy Desert experienced large decreases in ASW area, at rates of 378.00, 204.00, and 128.00 km /a, respectively.

We further analyzed changes in the three types of surface water based on the six basins with significant surface water changes. The PSW area was mainly reduced in the Amu Darya River Basin at a rate of 1283.00 km /a, which contributed largely to the decrease in ASW area in the Amu Darya River Basin. The SSW area in the Indus River Basin increased at a rate of 392.00 /a, contributing greatly to the increase in ASW area in the Indus River Basin. The SSW area in the Mackay Lake Basin decreased at a rate of 136.00 km /a, which contributed to the decrease in ASW area in the Mackay Lake Basin. The TSW area in the Eyre Lake Basin decreased at a rate of 81.00 km /a, contributing to the decrease in ASW area in the Eyre Lake Basin.

3.3.2 Relationships between surface water and precipitation anomalies Figures 7 and 8 show the spatial variation characteristics of precipitation and the relationship between precipitation and surface water area during 2000–2020. In the Mackay Lake Basin, significant changes in precipitation occurred in February and March of 2000, 2001, and 2011 (Fig. 8a [FIGURE:8]), consistent with the seasonal and temporal changes in the surface water area described in Section 3.1. The results suggested that variations in precipitation were the main factors influencing changes in the areas of SSW and TSW in this basin.

The Eyre Lake Basin experienced frequent precipitation in June, July, and August (winter in Oceania) in both 2010 and 2016 (Fig. 8b), consistent with the abrupt change years observed in the areas of SSW and TSW. The results indicated that abnormal precipitation was more likely to lead to changes in surface water area with a lower cumulative frequency.

The Amu Darya River Basin experienced extreme drought with very little precipitation, which also resulted in a marked decrease in SSW area from 2002 to 2018 (Fig. 8c). Precipitation tended to decrease each month from 2003 to 2008 in this basin, leading to a reduction in PSW area.

In the Syr Darya River Basin, precipitation was relatively evenly distributed throughout the months (Fig. 8d). Despite a significant decrease in precipitation, there was a gradual trend towards increasing surface water area, indicating that the increase in surface water area was not only influenced by precipitation from 2016 to 2018.

In the Mesopotamia Basin, precipitation and ASW area exhibited generally consistent changes during 2000–2003 (Fig. 8e), implying that precipitation was a major factor to the ASW variability.

By contrast, between 2018 and 2019, ASW area increased while precipitation declined, suggesting that the increase in surface water area was not only influenced by precipitation.

The significant increase in precipitation in the Indus River Basin was primarily driven by anomalous changes in precipitation in July, August, and September (Fig. 8f). From 2002 to 2003, an abrupt increase in precipitation was observed in July, leading to corresponding changes in SSW area. A significant increase in precipitation was also observed in August from 2018 to 2019, resulting in an observable increase in SSW area.

In this study, Spearman correlation coefficient was used to analyze the influence of precipitation on the surface water area for the six basins with significant surface water changes.

Overall, strong correlations were observed between precipitation and the areas

Figure 9

Figure 2: Figure 9

of PSW, SSW, and TSW in the Mackay Lake Basin and Eyre Lake Basin, with the highest correlation coefficient of 0.773 (<0.01) between precipitation and SSW area observed in the Eyre Lake Basin (Table 1).

They were also strongly correlated in the Indus River Basin, with a correlation coefficient of 0.808 (<0.01). Moreover, a moderate correlation was observed between precipitation and SSW area in the Mesopotamia Basin, with a correlation coefficient of 0.536 (<0.05). Hence, precipitation was the primary source of surface water and had the most direct effect on the occurrence of surface water.

Spatiotemporal variations of precipitation in global arid regions during 2000–2020. (a), spatial pattern of variation in precipitation; (b), temporal variation in precipitation.

Temporal variations in surface water area and monthly precipitation for the Mackay Lake Basin (a), Eyre Lake Basin (b), Amu Darya River Basin (c), Syr Darya River Basin (d), Mesopotamia Basin (e), and Indus River Basin (f) Spearman correlation coefficient between precipitation and surface water area for the six typical basins Correlation coefficient Type of surface Mackay Lake Basin Eyre Lake Basin Amu Darya River Basin Syr Darya River Basin Mesopotamia Indus River water Basin Basin Note: "-" indicates no significant correlation. PSW, permanent surface water; SSW, seasonal surface water; TSW, temporary surface water. , significance at <0.01 level; , significance at <0.05 level; , significance at <0.10 level.

3.3.3 Relationship between surface water and temperature-induced snow melting Temperature showed an increasing trend in global arid regions from 2000 to 2020, with an increase rate of 0.026°C/a (Fig. 9

). In terms of spatial distribution, the regions with increasing temperatures were located mainly in the arid regions of Oceania, the Namib Desert, the Atacama Desert, and the Arabian Desert (Fig. 9a). Temperature decreased in the Thar Desert and Qaidam Desert. The Indus River Basin persistently exhibited the highest temperatures, with values consistently ranging from 26.420°C to 27.554°C throughout the study period. By comparison, the Eyre Lake Basin, Mackay Lake Basin, and Mesopotamia Basin were characterized by intermediate thermal conditions, with temperatures fluctuating between 20.923°C and 27.154°C.

In contrast, the Amu Darya River Basin and Syr Darya River Basin experienced the lowest temperatures, ranging from 7.647°C to 11.469°C (Fig. 9b).

The spatial distribution of snow cover in global arid regions are shown in Figure 10a [FIGURE:10]. The snow cover area in global arid regions and the global snow cover area decreased at rates of 1.27$×10and2.04×$10 /a, respectively (Fig. 10b). Relative to the 2001 baseline, the annual relative decline rates of snow cover were 0.10% and 0.02% for global arid regions and on a global scale, respectively. The snow cover area disrupted the stability of surface water in global arid regions.

Spearman correlation coefficient was also used to analyze the influence of temperature on the surface water area (Table 2). The areas of SSW and TSW were more sensitive to temperature, and increasing temperatures led to increases in SSW and TSW. A positive correlation was observed between temperature and TSW area in the Amu Darya River Basin. Specifically, the increase in temperature from 2003 to 2004 resulted in an expansion of TSW in the Amu Darya River Basin (Figs. 8c and 9b). In addition, a positive correlation was also observed between temperature and SSW area in the Syr Darya River Basin, i.e., the increase in temperature led to an increase in SSW area in the Syr Darya River Basin from 2009 to 2010 (Figs. 8d and 9b).

Spatiotemporal variations of temperature in global arid regions during 2000–2020. (a), spatial pattern of variation in temperature; (b), temporal variation in temperature.

Spatial distribution of snow cover in 2020 (a) and temporal variation in snow cover area during 2001–2020 (b)

Spearman correlation coefficient between temperature and surface water area for the six typical basins Type of surface water Correlation coefficient Mackay Lake Basin Eyre Lake Basin Amu Darya River Basin Syr Darya River Basin Mesopotamia Indus River Basin Basin Note: "-" indicates no significant correlation. , significance at <0.01 level; , significance at <0.05 level; , significance at <0.10 level.

4 Discussion

4.1 Spatiotemporal variations of surface water in global arid regions The changes in surface water were characterized mainly by an increase in TSW, and the surface water inundation frequency tended to decrease in global arid regions. The observed increase in surface water was primarily attributed to the expansion of TSW, whereas the decline in persistence indicated a reduced capacity to sustain episodic inflows. This shift was driven by seasonal dynamics and the increased frequency of extreme weather events, such as floods, which were typically concentrated in specific seasons (Xie et al., 2016). The increasing frequency of floods, particularly during the wet season, contributes to the formation of larger, but more transient, surface water bodies. During the season, rapid replenishment of water bodies occurs due to heavy rainfall, but water is also quickly lost through evaporation and infiltration, limiting the persistence of water bodies (Bertola et al., 2019). Consequently, the accumulation of water during the wet season is not sustained, leading to a reduction in the frequency of long-term water presence. The frequent occurrence of flood-driven water patches is associated with short-term inundations that expanded the TSW area, thereby exacerbating hydrological instability (Sogno et al., 2022; Mishra et al., 2024). This transition from stable water storage to altered hydrological regimes profoundly affects ecohydrological interactions (Yang et al., 2020b). The observed coupling between flood occurrence and water persistence emphasizes the response of arid region hydrology to changing hydroclimatic extremes (Dadson et al., 2019). 4.2 Response of surface water changes to climatic factors Precipitation serves as the dominant hydrological driver in arid regions, governing both the availability and spatiotemporal distribution of surface water through complex climate-hydrogeomorphic interactions (Piao et al., 2010; Li et al., 2022). The variability in precipitation intensity, seasonal fluctuations, and the occurrence of extreme precipitation events are the primary factors that dictate the dynamics of surface water. Precipitation often occurs in concentrated periods, typically in summer or autumn, when surface water bodies will expand rapidly due to intense rainfall. For instance, the heavy rainfall that occurs during the rainy season will lead to the formation of temporary ponds or wetlands (Ahmad et al., 2018; Pomee and Hertig, 2022).

However, surface water is often short-lived due to high evaporation rates, particularly during the dry season. This seasonal and intensity-driven pattern is a key driver of the changes in surface water area in arid regions (McMahon et al., 2008; Pook et al., 2014). In addition, the distribution and intensity of precipitation significantly affect surface water (Lv et al., 2018; Chang et al., 2023). For example, extreme rainfall in mountainous areas often leads to flash floods that affect surface water area downstream (Liu et al., 2024b).

Previous studies have shown that the ice and snow melting caused by global warming can increase surface water (Zhang et al., 2023a; Pandey et al., 2024; Yang et al., 2024), leading to an increase in surface water area. The melting of ice and snow is more pronounced in arid regions (Motiee et al., 2024; Soheb et al., 2024). However, the relationship between global warming and surface water area has been shown to be more complex than a mere increase in water volume. The increase in surface water area is likely temporary, as the melting of glaciers and snowpack could

primarily influence the seasonal timing and quantity of runoff rather than contributing to the creation of PSW (Liu et al., 2019; Zheng et al., 2019). While the initial increase in runoff caused by glacial retreat temporarily could increase water storage, the continuous shrinkage of glaciers is likely to reduce long-term water availability, ultimately compromising the sustainability of water resources (Immerzeel et al., 2010).

4.3 Limitations and prospects

Climate change has played a dominant role in driving surface water changes on a global scale, but regional factors such as vegetation dynamics and groundwater interactions also significantly influence surface water (Deng and Chen, 2017; Zhang et al., 2019). While the focus of this study was primarily on climatic drivers, the relationship between surface water and regional vegetation cover represents a critical area for future research, particularly in arid environments. Vegetation in these regions plays a vital role in regulating surface water availability by influencing evapotranspiration rates, infiltration, and potentially groundwater recharge dynamics (Jia et al., 2024; Xiao et al., 2024; Cao et al., 2025). Changes in vegetation cover, driven by climate change or anthropogenic activities, can significantly alter local hydrological cycles and surface water persistence. Future research should expand to quantify these complex interrelationships and integrate data on vegetation water use, groundwater levels, and surface water extent to develop a more comprehensive understanding of water resource dynamics in global arid regions under changing climatic conditions.

5 Conclusions

In this study, we analyzed the characteristics and causes of surface water changes in global arid regions on the basis of multi-source remote sensing and climate datasets from 2000 to 2020. Our analysis revealed a paradoxical expansion of surface water area in global arid regions under climate change. This expansion can be characterized by a decrease in surface water inundation frequency, despite an increase in ASW area. From 2000 to 2020, surface water area increased by 3953.00 km /a. During this period, PSW tended to decrease, whereas SSW and TSW tended to increase. TSW exhibited the most substantial increase in area, contributing greatly to the change in ASW and expanding at a rate of 3284.00 km /a. The most significant changes in surface water were observed in the Kyzylkum Desert, Thar Desert, Great Sandy Desert, and Simpson Desert in global arid regions, with a notable overall reduction in surface water inundation frequency. In light of the potential influence of precipitation in the upper basins on surface water, an examination of surface water changes at the basin scale was essential. In the Indus River Basin, ASW showed an upwards trend, with SSW contributing substantially to this increase. SSW area responded clearly to precipitation in this basin. In the Eyre Lake Basin, a robust correlation was observed between precipitation and the areas of PSW, SSW, and TSW, among which precipitation and SSW area exhibited the highest correlation. SSW and TSW were predominantly influenced by warming-induced snow melting in the Syr Darya River Basin and the Amu Darya River Basin. The findings of this study contribute to the stability assessment of water resources in global arid regions, supporting ecosystem management and informing climate adaptation strategies in these regions.

Conflict of 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.

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Figure 12

Figure 3: Figure 12

Figure 14

Figure 4: Figure 14

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Figures

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Figure 22

Figure 5: Figure 22

Figure 32

Figure 6: Figure 32

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Figure 7: Figure 50

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Figure 8: Figure 55