

Research Article

Influence of lake basin topography on the differential shrinkage of lakes on the Inner Mongolia Plateau, China

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Abstract: The driving mechanisms behind the differential shrinkage of lakes on the Inner Mongolia Plateau under similar climatic and anthropogenic pressures remain unclear, hindering targeted ecological restoration. This study investigates two adjacent lakes, the bowl-shaped Daihai (DH) and the dish-shaped Huangqihai (HQH), to reveal the dominant role of lake basin topography. Integrating remote sensing, field data, and numerical models, we analyzed the hydrological evolution of both lakes from 1987 to 2008. Key findings: (1) HQH's shallow, dish-shaped basin is more sensitive to hydrological changes than DH's deeper, bowl-shaped basin; (2) For an equivalent decline in the regional groundwater table, HQH's groundwater recharge area (GRA) decayed at 2.01 times the rate of DH's, and its groundwater recharge (GWR) loss was 2.10 times greater; (3) HQH's shallow morphology triggered a vicious cycle of shrinking recharge area and decoupling of its recharge system, accelerating desiccation, whereas DH's bowl structure demonstrated greater resilience. These results demonstrate that basin morphology critically modulates groundwater recharge, explaining divergent shrinkage trajectories and highlighting the need for morphology-specific conservation strategies in arid regions.

Keywords: Lake basin morphology; Lake shrinkage; Groundwater recharge; Water balance; Water management

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Introduction

As a crucial ecological barrier in northern China, the lake ecosystems of the Inner Mongolia Plateau play an irreplaceable role in maintaining the regional water balance (Danyang et al. 2022), supporting agricultural and pastoral production (Ren et al. 2022), and preserving biodiversity (Zhai et al. 2022). However, under the influence of

climate evolution (Wang et al. 2022) as well as agricultural activities and coal mining (Zhang et al. 2023), the number of lakes with an area greater than 1 km² on the plateau decreased sharply from 354 in 1991 to 195 in 2009, a reduction of 159 lakes, or 44.9% (Zhou et al. 2019). The total lake area shrank from 4984 km² in 1990 to 3880 km² in 2021 (Feng et al. 2024). Although the lakes on the Inner Mongolia Plateau show an overall trend of shrinkage and degradation, their evolutionary rates exhibit significant differences (Luo et al. 2024). Notably, Xu et al. (2022) revealed that lake basin morphology strongly influences the pattern of shrinkage. When comparing the bowl-shaped Hulun Lake with the dish-shaped Hasu Lake, although Hulun Lake had higher absolute shrinkage rates owing to its much larger size (area: 1.93 km²/a vs. 0.13 km²/a; water storage: 0.067 km³/a

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vs. $0.001 \text{ km}^3/\text{a}$), the dish-shaped Hasuhai Lake lost 4.51 times more area per unit volume of water lost than the bowl-shaped Hulun Lake, indicating that shallow, dish-shaped basins are far more sensitive to water loss. However, this cross-regional comparison is confounded by differences in climatic conditions and human activity intensity between the two lake basins, making it difficult to isolate the effect of basin morphology. A more controlled comparison can be found in the central Inner Mongolia Plateau, where Daihai Lake (DH) and Huangqihai Lake (HQH), separated by only 47 km and sharing similar climatic and anthropogenic pressures, show markedly different shrinkage trajectories. DH decreased in area from 112.59 km^2 in 1990 to 47.11 km^2 in 2022, with an average annual shrinkage rate of $1.98 \text{ km}^2/\text{a}$ (Jiang et al. 2025), while HQH experienced a shrinkage rate of $3.29 \text{ km}^2/\text{a}$ and had dried up completely by 2008 (Ma et al. 2024).

Current research primarily focuses on identifying the causes of lake shrinkage from a macro-scale perspective, including climate evolution and the intensity of water resource development. There has been limited investigation into the driving mechanisms of micro-scale lake structure on its evolution. This has led to ecological restoration strategies for the Inner Mongolia Plateau that primarily focus on reducing groundwater extraction, without highlighting the unique characteristics of different lakes. As a result, it is difficult to truly implement the approach of "one lake, one policy; precise governance."

The influence of lake basin morphology on hydrological stability has gradually gained attention (Qiao et al. 2019). It is generally considered that, compared to deeper lakes, wide and shallow lakes are more vulnerable to external disturbances, such as climatic drought and declining water levels (Crossman et al. 2016). This pattern has been corroborated across diverse arid and semi-arid regions worldwide, including the western United States (Fergus et al. 2022) and the Burdur basin in Turkey (Çolak et al. 2022).

However, when applying this principle to explain the differential evolution of lakes in a specific region, a quantitative analysis of how lake basin morphology affects lake evolution through its impact on groundwater recharge (GWR) is still lacking. Furthermore, the influence of a lake's intrinsic morphology is often conflated with that of external driving factors, making them difficult to disentangle effectively. Together, these two issues have hindered a deeper understanding of the mechanisms behind differential lake shrinkage.

Based on the perspective of lake basin topography, this study selects two lakes in the central Inner Mongolia Plateau, Daihai and Huangqihai, which share similar climatic conditions and intensity of human activities but possess vastly different lake basin structures. By constructing a numerical model of the ellipsoidal surface area, this study aims to investigate the differences in groundwater recharge mechanisms between Daihai and Huangqihai, as influenced by their respective basin topographies. This will further reveal the intrinsic mechanism explaining why shallow, dish-shaped lakes in Inner Mongolia are more prone to shrinkage than bowl-shaped lakes, thereby providing a more targeted basis for lake conservation efforts on the Inner Mongolia Plateau. This research not only enriches the theoretical framework of lake evolution mechanisms in Inner Mongolia but also contributes to a better understanding of the complexity of lake ecosystems in arid regions, thus providing solid scientific support for regional ecological conservation and sustainable development.

1 Study area

The Daihai watershed is situated within Liangcheng County, Ulanqab City, in the central part of the Inner Mongolia Autonomous Region (Fig. 1), with geographic coordinates ranging from $112^\circ 17'$ to $112^\circ 48'$ E and $40^\circ 29'$ to $40^\circ 45'$ N. The watershed is situated in a fault-subsidence basin at the southern foot of the Yinshan Mountains, exhibiting an overall topography that is high in the northwest and low in the southeast. The northern part of the watershed is a region of low mountains and hills characterized by significant topographical undulation and fragmented terrain, with bedrock composed mainly of granite and metamorphic rocks. The central area contains the Daihai lake basin, which is the lowest-lying region within the watershed.

The Huangqihai watershed borders the Daihai watershed and is also located within a fault-subsidence basin. Its topography is generally high in the northeast and low in the southwest. The northeastern part consists of low mountains and hills, while the southeastern part contains the Huangqihai lake basin, where the terrain is comparatively flat. The groundwater aquifers surrounding both the Daihai and Huangqihai lake basins are dominated by pore water, while the outer areas primarily contain fissure and pore water in volcanic lava, as well as bedrock fissure water. The two watersheds share fundamentally similar hydrogeological conditions,

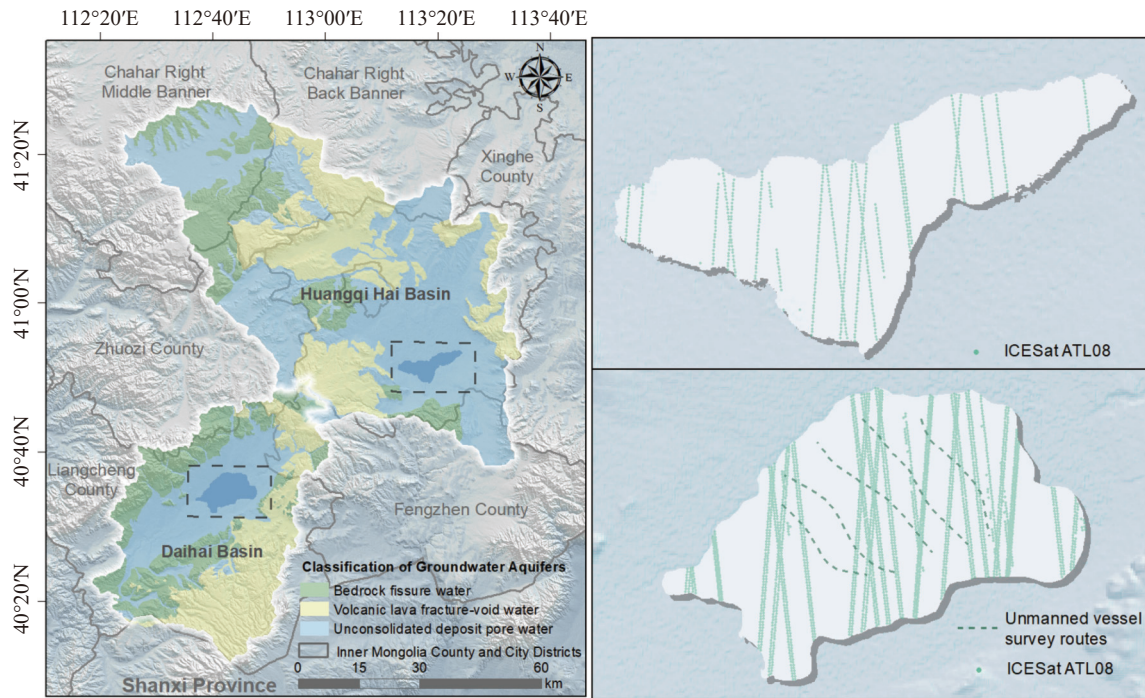


Fig. 1 Overview of the Daihai and Huangqihai study areas and the ICESat-2 data footprints

climate, and patterns of water resource development and utilization. This provides a foundation for the subsequent comparative analysis of the influence of their respective basin structures on lake shrinkage.

2 Materials and methods

2.1 Materials

2.1.1 Elevation data

This study utilized the 30 m resolution version of the DEM released by NASA in 2020, which is based on SRTM (Shuttle Radar Topography Mission) data (<https://www.earthdata.nasa.gov/>), as the foundational data for reconstructing the lake basin topography. This version offers significant improvements in denoising, gap-filling, and global accuracy compared to earlier DEM datasets. Since the SRTM source data were acquired in February 2000, when both lakes were inundated, the DEM does not capture the underwater lakebed topography. Therefore, separate reconstruction of the submerged terrain is required to complete the full lake basin model.

Underwater topographic elevation data were primarily sourced from laser altimetry satellites and sonar measurements from an unmanned surface vehicle (USV). Since Huangqihai became a seasonal lake after 2007, we collected ICESat-2 (Ice, Cloud, and Land Elevation Satellite-2)

ATL08 data (<https://nsidc.org/data/icesat-2>) from the dry seasons of 2020–2023 to serve as its surface elevation reference. Since HQH has been dry or only seasonally inundated since 2008, the exposed lakebed elevation has remained relatively stable; cross-validation with the SRTM DEM at overlapping non-submerged locations confirms the temporal consistency of these elevation data. The collection was focused on the lake's water extent as it was in 2000 (Fig. 1b–c). For Daihai, the underwater elevation data within its 2023 water extent were collected using a USV (Fig. 1c).

2.1.2 Water body area

Lake area extraction was performed using two approaches: Annual minimum area extraction and monthly average area extraction. Extracting the annual minimum lake area helps to minimize the effects of short-term surface expansion caused by precipitation during the wet season. Compared to other periods within the year, the annual minimum area is more reflective of groundwater recharge conditions. To avoid the influence of ice and snow reflectance, this study generated a maximum value composite from Landsat data for the period from March to November each year. A maximum value composite of surface reflectance was used to determine the minimum water surface extent. For the monthly area, an average value composite of all images within each month was used to calculate the mean extent of the water body. The Modified Normalized Difference Water Index (MNDWI)

was calculated from the composite images, and the area was then extracted using Otsu's Thresholding Method (Otsu). Due to the impacts of cloud cover and damage to the Landsat 7 sensor, Landsat 5 was used for the years 1990–2000 and 2003, while Landsat 7 was used for the remaining years. For years relying on Landsat 7 data (post-SLC failure in May 2003), multi-temporal image compositing was employed to minimize the impact of SLC-off data gaps, as the gap locations vary across different acquisition dates, enabling effective spatial coverage when multiple scenes are combined. All the aforementioned Landsat data were acquired from the Google Earth Engine (<https://earthengine.google.com/>).

2.1.3 Hydrological and meteorological data

The temperature and precipitation data used in this study were obtained from local meteorological stations, and surface runoff data were collected from monitoring stations. Given the significant discrepancy between evaporation pan data and actual lake evaporation, and because evaporation is influenced by meteorological factors such as air temperature, humidity, wind speed, and solar radiation, this study employed the Priestley-Taylor (P-T) model to ensure the accuracy of the results. The model was used to calculate monthly evaporation, which was then aggregated to determine the annual evaporation. The daily net radiation flux and lake temperature data required for the model were sourced from the European Centre for Medium-Range Weather Forecasts (ECMWF). Furthermore, groundwater depth data for Huangqihai were obtained from the groundwater depth monitoring network surrounding the lake. Groundwater depth data for Daihai Lake were derived from the interpolation of monitoring data from the Sansumu station and an open-source dataset (Wang et al. 2025). No additional processing was applied to the raw meteorological data beyond standard quality control procedures (removal of erroneous records and gap-filling via linear interpolation for isolated missing days).

2.2 Methodology

This study first reconstructs the underwater topography of the two lakes using ICESat laser altimetry data and a DEM, thereby creating a complete three-dimensional model of the lake basins to calculate the absolute annual water storage of each lake. Based on the lake basin's topographic parameters, an ellipsoidal model is constructed. This model, combined with groundwater level data, is used to calculate the groundwater recharge area

(GRA) for each lake. Subsequently, the groundwater recharge volume (GWR) is calculated using the water balance equation. This allows for an analysis of the impact of different lake basin structures on the evolution of GWR and an investigation into the trends of lake shrinkage.

2.2.1 Lake basin topography reconstruction

The method for reconstructing the lake basin topography primarily involves using a Long Short-Term Memory (LSTM) model to predict elevations at fishnet points, followed by interpolation to generate the underwater terrain (Jiang et al. 2025). The model training accuracy and topographic validation results have been detailed in Jiang et al. (2025), to which interested readers are referred for comprehensive documentation of the reconstruction methodology and its precision assessment. To ensure the continuity of the predicted topography, the data from the USV and ICESat are first corrected, and outliers are removed. A nearest-neighbor analysis is performed on the data, and the resulting dataset is used as the training set for the model. Finally, the Kriging interpolation method is applied to the predicted points to generate the terrain, which prevents abrupt transitions at the water-land boundary.

2.2.2 Ellipsoidal model

The key to calculating the lake's groundwater recharge area is to generalize the lake basin into a suitable ellipsoidal model. The generation of the ellipsoid involves two steps: first, constructing an ellipse based on the lake area, and second, creating the basin ellipsoid from this ellipse and the maximum water depth. The ellipse is built based on the maximum value of the lake's annual minimum areas. This involves first calculating the minimum bounding rectangle of the ellipse and then determining the maximum inscribed ellipse within that rectangle. The lake's maximum water depth serves as the c-axis of the ellipsoid. The formula for calculating the ellipsoid surface area is presented in Appendix 1.

2.2.3 Priestley-Taylor model

Daihai and Huangqihai are inland terminal lakes, with their primary sources of replenishment being atmospheric precipitation, surface runoff, and groundwater recharge. The main form of discharge is atmospheric evaporation. In this study, based on daily meteorological data, the P-T model was used to calculate the evaporation from both Daihai and Huangqihai. The formula for calculating the monthly evaporated water volume using the P-T model is given by:

$$E = \alpha \times \frac{\Delta}{\Delta + \gamma} \times \frac{R_n - G}{\lambda} \quad (1)$$

$$W_E = E / 1000 \times n \times A \quad (2)$$

Where: E represents the daily evaporation (mm/day), W_E is the monthly evaporated water volume (m^3), n is the number of days in the month, A is the monthly lake area (m^2), α is the P-T coefficient, set to the accepted standard value of 1.26 (McMahon et al. 2013), Δ is the slope of the saturation vapor pressure curve ($\text{kPa}/^\circ\text{C}$), γ is the psychrometric constant ($\text{kPa}/^\circ\text{C}$), R_n is the net radiation flux ($\text{MJ}/\text{m}^2/\text{day}$), G is the heat flux into the water body ($\text{MJ}/\text{m}^2/\text{day}$), λ is the latent heat of vaporization (MJ/kg).

2.2.4 Water balance equation

The water balance equation, based on the principle of water equilibrium, is used to describe the changes in a lake's water resources over a specific period. For closed-basin inland lakes like Daihai and Huangqihai, the water balance can be expressed as (Rasheed et al. 2024):

$$\Delta WS = (P + R + G) - (E + W) \quad (3)$$

$$G = \Delta WS + E + W - P - R \quad (4)$$

ΔWS represents the annual change in the lake's water storage; a positive value indicates an increase in water volume, while a negative value indicates a decrease, P is the volume of direct

precipitation onto the lake surface, R is the volume of surface runoff entering the lake, G is the net groundwater recharge to the lake (inflow positive). Given that both DH and HQH are terminal lakes at the lowest positions within their fault-subsidence basins, outward seepage from the lake is negligible, and G effectively represents gross groundwater inflow. E is the volume of water evaporated from the lake, W is the volume of water directly extracted from the lake by human activities.

3 Results

3.1 Lake basin reconstruction and water storage calculation

Fig. 2a-b illustrate the three-dimensional (3D) underwater topography of DH and HQH. The topography reveals that DH's lakebed progressively deepens from west to east, with the deepest area located on the eastern side. In contrast, the underwater topography of the HQH basin becomes shallower from west to east. By overlaying the extracted area data onto the lake basin topography, the water storage corresponding to each year's area was calculated. Fig. 2c-d display the area and water storage for DH and HQH from 1987 to 2008. DH and HQH exhibit a significant downward trend; however, compared to DH, the fluctuations

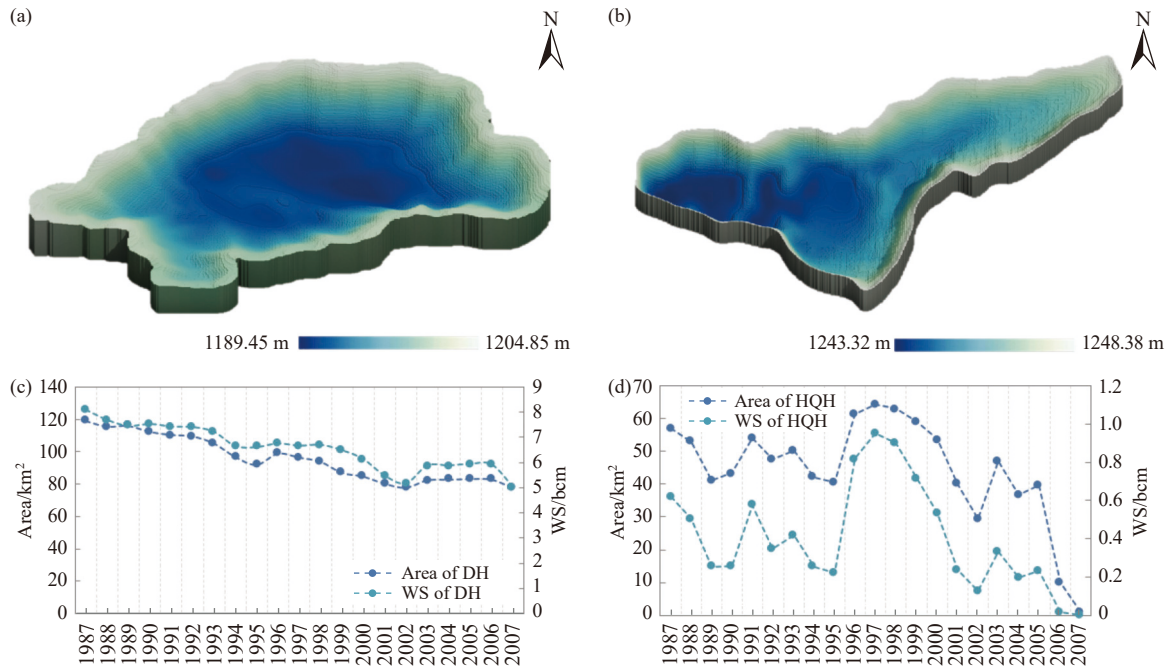


Fig. 2 Reconstructed lake basin topography and the evolution of lake area and water storage (WS) from 1987 to 2008

Notes: (a) 3D underwater topography of the Daihai (DH) basin; (b) 3D underwater topography of the Huangqihai (HQH) basin; (c) Time series of area and WS for DH; (d) Time series of area and WS for HQH

in HQH's area and water storage are more pronounced. Between 1987 and 2008, the area of DH decreased from 118.92 km² to 75.79 km², representing a cumulative reduction of 36.28% with an average annual decline rate of 1.65%. Concurrently, its water storage decreased from 9.96×10^8 m³ to 5.59×10^8 m³, representing a 43.88% reduction. Notably, a brief but significant recovery occurred between 1995 and 1996, with the area increasing by 7.50%. This event was primarily attributed to an increase in local precipitation recharge. After 2000, the rate of shrinkage accelerated, with the most significant single-year decline occurring between 2001 and 2002, when the area decreased by 3.04% and water storage by 4.76%, primarily due to climatic aridification during that period.

The fluctuations in HQH's area and water storage were more dramatic and can be divided into three main stages (Fig. 2d). From 1987 to 1995, the area of HQH decreased from 56.95 km² to 40.59 km², representing a 28.73% reduction, accompanied by a corresponding loss of 64.23% in water storage. In 1996 and 1997, the area grew contrary to the overall declining trend to 64.42 km², with a relative annual growth rate of 59.72%, and water storage recovered to 0.95×10^8 m³. Between 1998 and 2008, the lake underwent a period of rapid shrinkage. Following a brief expansion in 2003 and 2004, the lake's area plummeted from 39.62 km² to 4 km² between 2005 and 2007. By 2008, it had become a seasonal lake, completely dry during the dry season.

DH's area expanded by 0.35 km², 6.90 km², 3.74 km², 1.16 km², and 0.38 km² in 1989, 1996, 2003, 2004, and 2005, respectively, with relative inter-annual rates of change of 0.30%, 6.97%, 4.57%, 1.40%, and 0.45%. In 1996, 2003, and 2005, HQH also experienced expansion to varying degrees, with relative inter-annual rates of change of 50.96%, 58.97%, and 7.98%, respectively. The magnitude of expansion for HQH was considerably more intense than that for DH. For both lakes, the relative rates of change in 1996 and 2003 were significantly higher than in 2005.

In summary, under the influence of the same macro-scale factors, such as climate evolution and agricultural irrigation, the shrinkage trends of DH and HQH exhibit significant similarities. This is particularly evident around the time points of 1990, 1996, and 2004, when both lakes experienced expansion to varying degrees. However, due to differences in micro-scale factors, namely their lake basin structures, the magnitude of HQH's evolution was more dramatic than that of DH.

3.2 Ellipsoidal model calculation results

The historical maximum water area of both DH and HQH was selected as the reference plane to generalize each lake basin into an ellipsoidal model. For DH, the major axis (x-axis) of the ellipse is 16,730.43 m, and the intermediate axis (y-axis) is 10,086.21 m (Fig. 3a). Based on the basin topography, the water surface elevation at the maximum area was calculated to be 1204.85 m, and the lowest point of the lakebed has an elevation of 1189.45 m. Therefore, the semi-minor axis (z-axis) is 15.40 m, and the ratio of the major axis to the semi-minor axis is 1086.39. For the HQH ellipsoidal model, the major axis is 16,972.26 m, and the intermediate axis is 7,653.58 m. The water surface elevation corresponding to its maximum area is 1248.38 m, with the lowest point of the lakebed at an elevation of 1243.32 m, making the semi-minor axis of its ellipsoid 5.06 m. The ratio of the major axis to the semi-minor axis is 3354.20. Using the ellipses calculated above as the X-Y plane, with the center of the ellipse as the origin (0,0) and the maximum lake depth as the z-value, an ellipsoid encompassing the lake basin can be constructed (Fig. 3c-d), which displays the proportionally scaled model ellipsoids. As can be seen from the figures, the ellipsoid generalized from the HQH basin is significantly shallower and flatter than that of DH, classifying it as a dish-shaped lake. In contrast, the DH basin corresponds to a bowl-shaped lake.

Increased groundwater exploitation within the watersheds has induced a gradual decline in regional water tables, resulting in progressively diminished groundwater recharge to the lakes. Since both DH and HQH are terminal lakes situated at the lowest points of their respective watersheds, their groundwater levels have remained consistently higher than their lake levels throughout the process of shrinkage. Groundwater primarily recharges the lakes through seepage across the entire ellipsoidal surface area.

DH and HQH exhibit comparable hydrogeological conditions with identical groundwater development intensities. During 1990–2008, the average groundwater extraction modulus (watershed groundwater extraction volume/watershed area) for both watersheds was 0.006 m. Consequently, the changes in the groundwater table within the two watersheds are considered to be uniform. To investigate the evolution of the recharge area during the decline of the groundwater table, the maximum

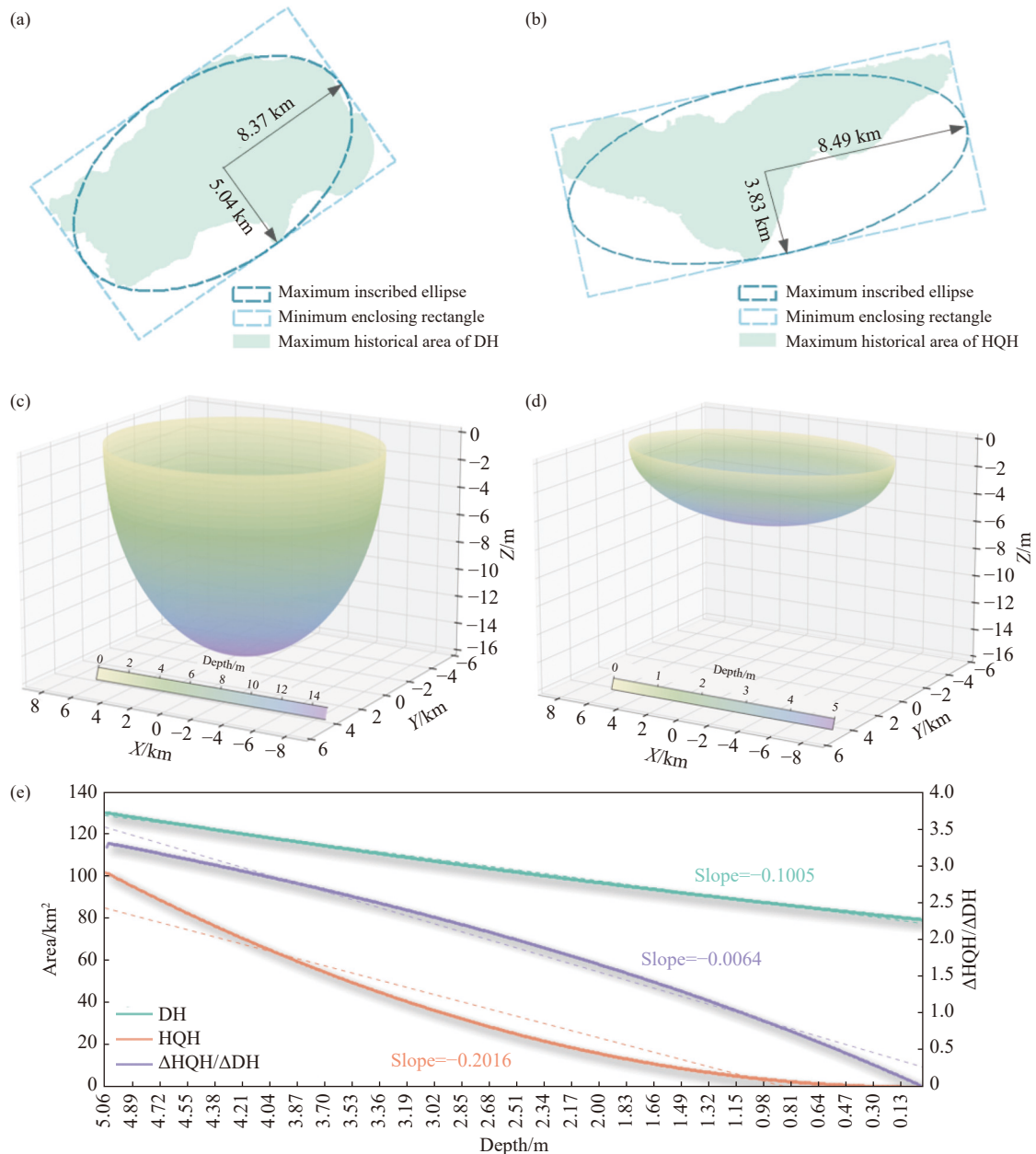


Fig. 3 Ellipsoidal model analysis of the Daihai (DH) and Huangqihai (HQH) lake basins

Notes: (a), (b) The maximum inscribed ellipse derived from the maximum historical area for DH and HQH, respectively; (c), (d) The proportionally scaled, generalized ellipsoidal models for DH and HQH; (e) The evolution of the ellipsoidal surface area (Groundwater Recharge Area, GRA) and the ratio of change ($\Delta\text{HQH}/\Delta\text{DH}$) as a function of declining water level. (Note: The major and intermediate axes of the ellipsoids were scaled (x, y axes in km) relative to the vertical axis (z-axis in m) for visualization purposes due to the large differences in their domains.)

water depth of HQH was used as the initial water level to model the evolutionary process of the lake recharge area for both lakes as the water table drops (Fig. 3e). As the groundwater level declines, DH's groundwater recharge area shows a linear decrease with a rate of -0.1005 . In contrast, HQH exhibits a trend where the rate of decline first accelerates and then decelerates, with an overall rate of -0.2016 , which is 2.01 times that of DH.

When the groundwater level has declined by more than 5.06 meters, it drops below the bottom

of the HQH lakebed, at which point groundwater recharge to the lake ceases. By this stage, the GRA for HQH has decreased by 102.02 km^2 . In comparison, DH's GRA decreases from 132.55 km^2 to 89.29 km^2 , a reduction of only 43.26 km^2 , which is 39.01% of its original area. Furthermore, the ratio of the change in GRA area between HQH and DH for every 0.01 m drop in the groundwater level exhibits an overall linear decreasing trend, with the process initially slowing down before accelerating at a rate of 0.0064. This indicates that during the

initial stages of groundwater level decline, the rate of decrease in the GRA is faster for HQH than for DH. Compared to DH, the impact of groundwater evolution on HQH is more intense.

3.3 Water balance of DH and HQH

3.3.1 Evaporation calculation results

Fig. 4a-b display the monthly area data for DH and HQH, along with the monthly evaporation values calculated by the P-T model. The intra-annual evaporation for both lakes exhibits a distinct cyclical pattern. Evaporation approaches zero in January and December of each year, primarily due to low winter temperatures and an ice cover that impedes water vapor exchange. The evaporation reaches its annual maximum between June and September.

Fig. 4c shows the annual evaporation, obtained by aggregating the monthly values, while Fig. 4d presents the absolute value of the Relative Annual Change Rate (absolute annual difference/mean). Overall, the evaporation from both lakes shows a declining trend in correspondence with the lake area. A strong positive correlation exists between the area of DH and its evaporation, with a correlation coefficient of 0.84. The correlation coefficient

between the area of HQH and its evaporation is 0.95. This indicates that the lake area is the dominant factor influencing evaporation volume.

DH's area experienced notable fluctuations, with shrinkage rates of 8.74% in 1994 and 7.14% in 1999, though the rate of change in most years remained within 5%. Its annual evaporation decreased from $1.70 \times 10^8 \text{ m}^3$ in 1987 to $1.04 \times 10^8 \text{ m}^3$ in 2008, with the relative rate of change generally below 15%, except for significant drops of 12.16% in 1992 and 13.11% in 2000. In contrast, the annual rate of change in HQH's area exceeded 10% in most years, such as a 69.68% decrease in 2006 and a 40.96% increase in 2003. Its annual evaporation fell from $0.11 \times 10^8 \text{ m}^3$ in 1987 to $0.02 \times 10^8 \text{ m}^3$ in 2008.

A comparative analysis reveals that for DH, the mean Relative Annual Change Rate for the area was 3.54%, with a standard deviation of 2.48%. For evaporation, the mean rate was 5.94%, with a standard deviation of 4.61%. The corresponding values for HQH were higher: the mean annual rate of change for its area was approximately 19.7% (standard deviation: 17.2%), and for evaporation, it was approximately 17.0% (standard deviation: 11.4%). Although DH showed an overall declining trend, its inter-annual fluctuations were relatively small, resulting in a more gradual shrinkage

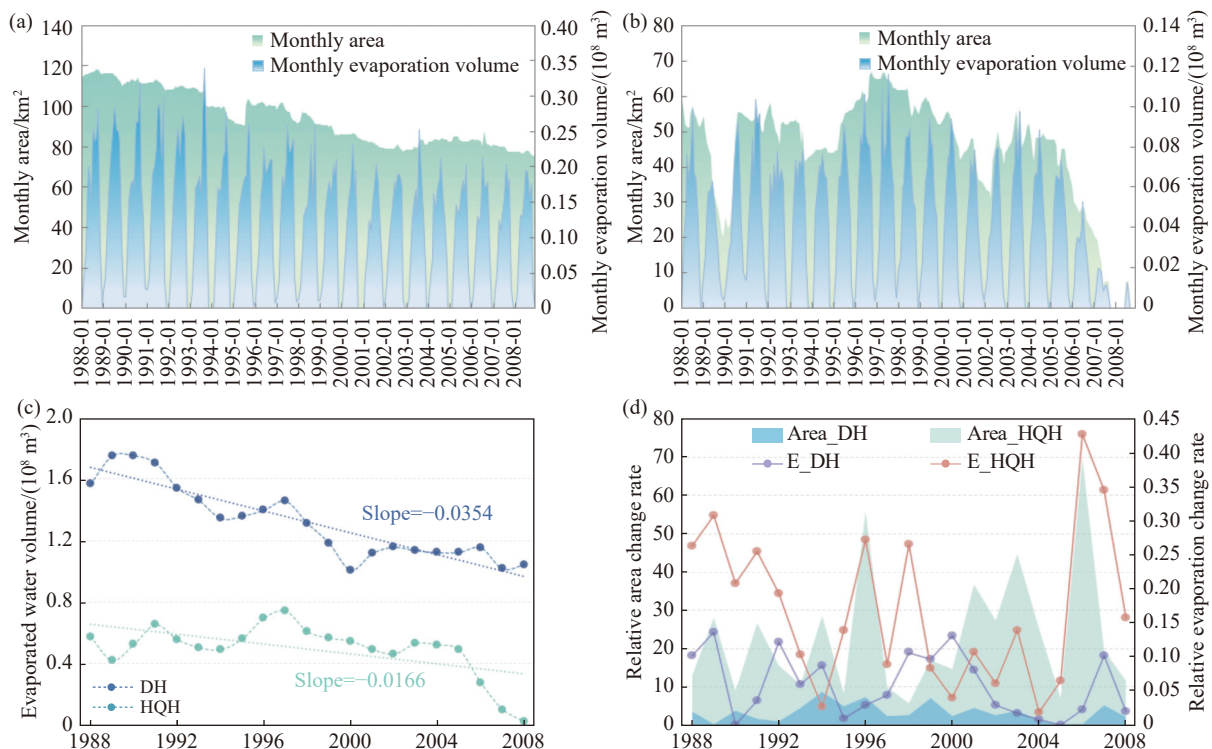


Fig. 4 Lake evaporation results calculated using the P-T model

Note: (a), (b) Monthly area and evaporated water volume for Daihai (DH) and Huangqihai (HQH), respectively; (c) Time series of annual evaporated water volume for both lakes; (d) Relative annual change rates of area and evaporation for both lakes

process and more stable changes in evaporation. Conversely, HQH was characterized by high inter-annual rates of change and intense fluctuations in both area and evaporation, culminating in its rapid desiccation in the later period. This suggests that the dish-shaped HQH lake is more sensitive to climate change compared to the bowl-shaped DH lake.

3.3.2 Groundwater recharge calculated from the water balance

The water balance sources and sinks show that for DH, precipitation recharge and inflow runoff are comparable. Excluding GWR, these two sources account for 54% and 46% of the total recharge, respectively, and both exhibit an overall downward trend (Fig. 5a). Furthermore, since 2005, the fixed annual water withdrawal of $0.095 \times 10^8 \text{ m}^3$ by the DH Power Plant, an anthropogenic factor, has exacerbated water consumption. For HQH, the average surface runoff inflow was $0.483 \times 10^8 \text{ m}^3$, peaking at $1.42 \times 10^8 \text{ m}^3$ in 1995 before declining significantly in the later period. The average precipitation recharge was $0.148 \times 10^8 \text{ m}^3$, indicating that the primary source of replenishment for HQH was surface runoff inflow (Fig. 5b). The precipitation recharge for HQH fluctuated considerably, decreasing from a maximum of 0.293×10^8

m^3 in 1998 to $0.011 \times 10^8 \text{ m}^3$ in 2007, with a particularly sharp decline after 2000, leading to a significant reduction in the direct precipitation recharge volume.

Based on the water balance equation, GWR for DH ranged from a minimum of $0.017 \times 10^8 \text{ m}^3$ in 2000 to a maximum of $0.833 \times 10^8 \text{ m}^3$ in 1989. The GWR was positively correlated with precipitation recharge, indicating that precipitation enhances groundwater recharge to the lake. The GWR for HQH peaked at $0.821 \times 10^8 \text{ m}^3$ in 1996 and fell to just $0.03 \times 10^8 \text{ m}^3$ by 2007. Overall, the rate of GWR shrinkage for DH was $0.0041 \times 10^8 \text{ m}^3/\text{a}$, while for HQH it was $0.0109 \times 10^8 \text{ m}^3/\text{a}$, making the shrinkage rate of GWR 2.66 times that of DH.

The GRA for DH contracted by 22.9%, from 131.13 km^2 in 1988 to 101.14 km^2 in 2008. Based on the groundwater recharge volume, the mean recharge rate (RR) for DH was calculated to be 0.34 m/a . It reached a maximum of 0.616 m/a in 1991 and fell to a minimum of 0.0146 m/a in 2000, a 98% decay in recharge intensity. The RR for DH showed a significant positive correlation with lake area ($r = 0.61$, $p = 0.003$), suggesting that the recharge intensity per unit area has a controlling effect on maintaining the lake's area. In contrast, the GRA for HQH completely disappeared

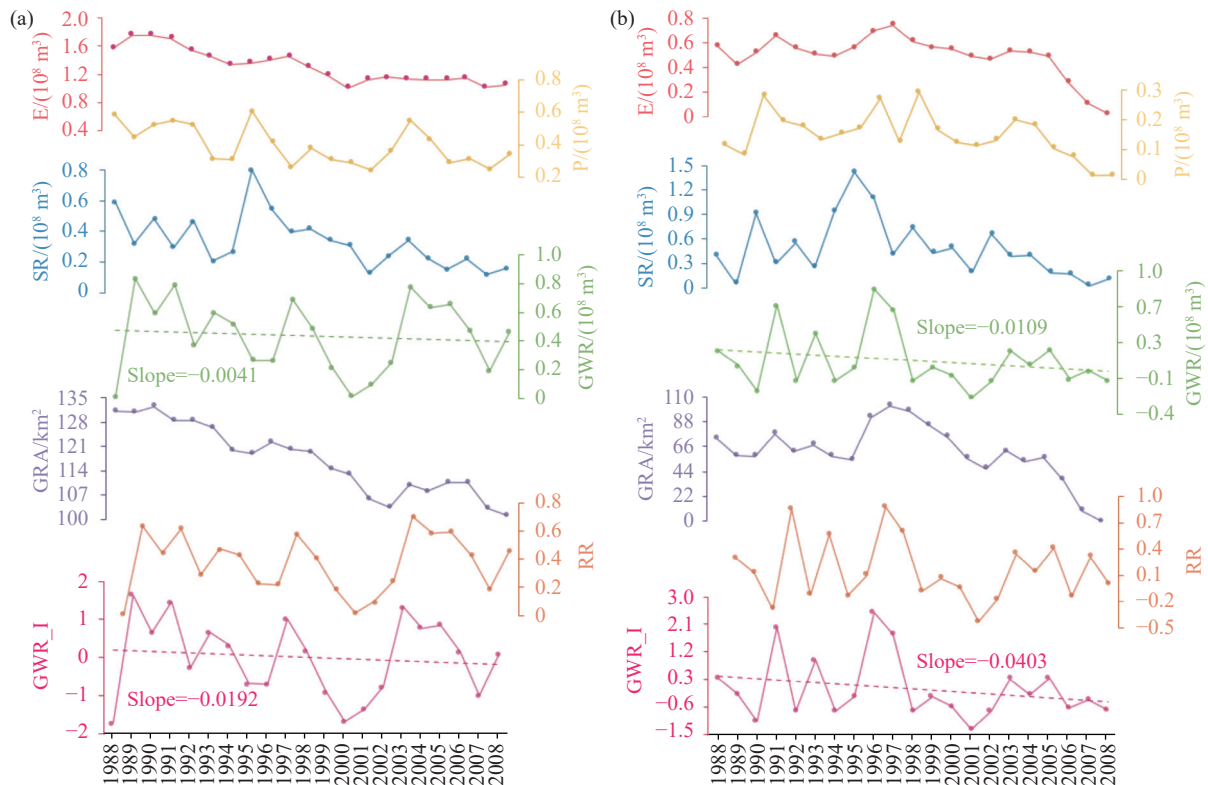


Fig. 5 Temporal evolution of water balance components and groundwater recharge dynamics

Notes: (a) Daihai and (b) Huangqihai (1988–2008). Key variables include: Evaporation (E), Precipitation (P), Surface Runoff (SR), Groundwater Recharge (GWR), Groundwater Recharge Area (GRA), Recharge Rate (RR), and the standardized recharge index (GWR_I)

between 1988 (72.99 km²) and 2008. Its RR had a maximum value of 0.89 m/a, a minimum of −0.44 m/a, and an average of 0.16 m/a. The quartile coefficient of variation was 3.33, far greater than DH's 0.81, indicating intense fluctuations. Throughout its shrinkage process, the calculated GWR for HQH was negative on nine occasions, suggesting a change in the mode of interaction with groundwater. However, actual groundwater level monitoring data show that the groundwater table near HQH remained consistently higher than the lake level during its desiccation, making it impossible for the lake to recharge the groundwater. This implies that the negative values are primarily due to cumulative calculation errors across multiple recharge and discharge terms in certain years (e.g., runoff, precipitation, evaporation). A more significant reason is that as the dish-shaped lake shrank, large areas of the lakebed were exposed, and the evapotranspiration from this moist lakebed was not included in the calculations, leading to an underestimation of groundwater recharge.

To accurately depict the impact of GRA changes on GWR, we constructed the GWR_I index (GWR/i) to eliminate the influence of the hydraulic gradient (i) on GWR. Since the aquifers surrounding both lake areas consist of lacustrine sediments with similar lithology, the permeability coefficient was treated as a constant. By removing the effect of the hydraulic gradient, the relationship between groundwater seepage and area can be examined. Fig. 5 presents the standardized GWR_I values (mean: 0, standard deviation: 1). Overall, the trend of GWR_I is consistent with that of GWR. The rate of decline for HQH's GWR_I (Fig. 5b) is 2.10 times that of DH's (Fig. 5a), which is nearly identical to the ratio of their ellipsoidal area decline rates (2.01). This provides strong evidence that, during the lake shrinkage process, the differential decay of the GRA, caused by differences in lake basin topography, is a critical factor in the differential

shrinkage of the lakes.

To further analyze the relationship between GWR_I and GRA, we employed the Pettitt test for change-point detection to identify abrupt shifts in the GWR_I and GRA (mean: 0, standard deviation: 1) time series (Fig. 6), which enabled us to divide the entire evolutionary process into two distinct stages.

For the bowl-shaped DH, the coupling relationship between its GWR_I and GRA was consistently weak and unstable. In Stage I (1988–1999) and Stage II (2000–2008), the Pearson correlation coefficient between DH's GWR_I and GRA was only 0.26 and 0.18, respectively, with the R^2 from linear regression being as low as 0.07 ($p = 0.41$) and 0.03 ($p = 0.64$). This indicates that the GWR of DH is not sensitive to changes in its GRA.

In contrast, the dish-shaped HQH exhibited a strong correlation in Stage I (1988–1996), with $r = 0.91$ and $R^2 = 0.83$ ($p < 0.001$), suggesting that GRA was the primary factor controlling GWR during this period. However, during the rapid shrinkage of Stage II (1997–2008), the correlation weakened significantly, to $r = 0.41$ and $R^2 = 0.17$ ($p = 0.19$). The simultaneous sharp reduction in both the slope and R^2 indicates a decoupling of the relationship between GRA and GWR. Furthermore, the recharge intensity per unit area for HQH in the second stage was 0.08 m/a, a 68% decay compared to the 0.25 m/a of the first stage. This demonstrates that after the lake's rapid shrinkage, the groundwater recharge capacity had severely degraded.

To further investigate the temporal heterogeneity in the relationship between GWR and GRA for the two lakes, we employed the Empirical Mode Decomposition (EMD) method to decompose the GWR_I and GRA time series into components of different periodicities for analysis (Fig. 7).

For DH, the EMD analysis confirms and deepens the understanding of its recharge system's

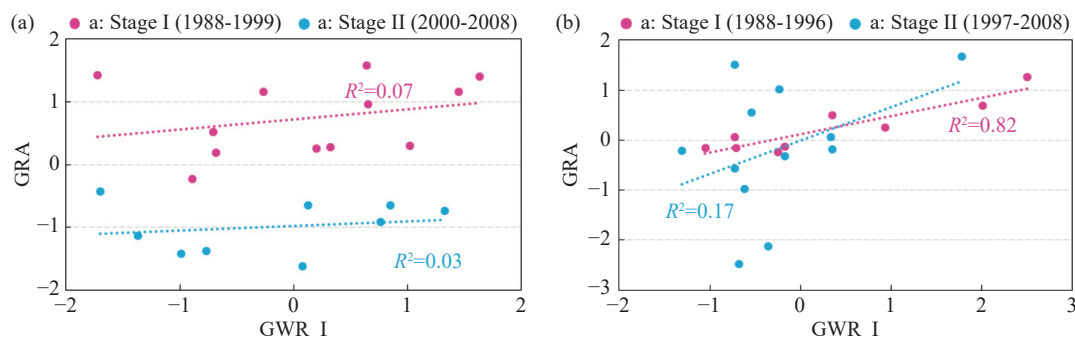


Fig. 6 Staged scatter plots of Groundwater Recharge index (GWR_I) and Groundwater Recharge Area (GRA) for (a) Daihai and (b) Huangqihai

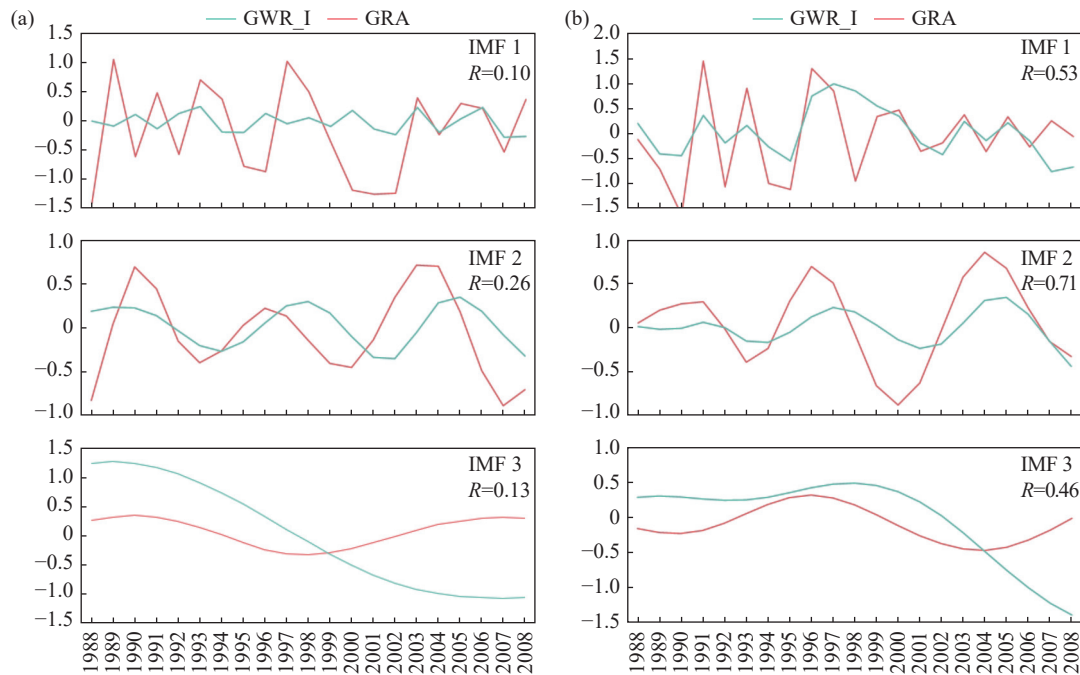


Fig. 7 Empirical Mode Decomposition (EMD) of the standardized Groundwater Recharge index (GWR_I) and Groundwater Recharge Area (GRA) time series

Notes: (a) Daihai and (b) Huangqihai. IMF1, IMF2, and IMF3 are the primary decomposed components

stability and buffering capacity. Across all primary decomposed time scales (IMF1, IMF2, IMF3), the coupling relationship between GWR_I and GRA was exceptionally weak; the strongest correlation, found in IMF2 (representing approximately 3–9 years), was only 0.261. Even in the residual component, which represents the long-term trend, the correlation was merely 0.11. This indicates that the bowl-shaped structure of DH provides a significant hydrological buffering capacity. Its deeper water body and relatively steep banks enable it to effectively resist inter-annual (IMF1), multi-year (IMF2), and even longer-period hydrological fluctuations, causing the groundwater recharge process not to respond synchronously to short-term changes in the recharge area. This corresponds to the overall weak correlation shown in Fig. 6a and reflects its general insensitivity across all time scales.

In contrast, the EMD analysis for HQH reveals that GWR_I and GRA exhibit significant synchronicity across multiple time scales, underscoring the sensitivity and vulnerability of its recharge system. The coupling relationship was strongest in IMF2 ($r = 0.71$), indicating that medium-term regional hydrological fluctuations primarily control HQH's water balance. Concurrently, moderate to strong coupling was also present in the short-term, rapid fluctuations (IMF1, $r = 0.53$) and in the long-term trends (IMF3 and the residual component, $r = 0.46$). This demonstrates

that the dish-shaped structure of HQH is highly sensitive, directly translating external disturbances at any time scale into intense fluctuations in the lake's area. This synchronous response across multiple scales ultimately led to the rapid decoupling and collapse of HQH's recharge system under the dual pressures of a warming, drying climate and intense human activities.

4 Discussions

4.1 Lake basin construction and water storage analysis

This study further quantifies the differences in basin morphology between DH and HQH through an ellipsoidal structure model analysis (Fig. 3a-d). The semi-major axis of the generalized ellipsoid for HQH is 0.12 km longer than that of DH. However, its intermediate semi-axis is 1.21 km shorter, and its semi-minor axis is also 10.36 m shorter than DH's. These dimensions render the generalized ellipsoid for HQH significantly flatter. The average ratio of water surface area to volume is 12.34 for DH, while for HQH it is 185.90. The higher ratio for HQH means that, for a given volume of water, it possesses a significantly larger surface area for evaporation, which has a critical impact on its water balance in arid to semi-arid climates.

Overall, the area and water storage of both DH and HQH exhibit a significant declining trend (Fig. 2c, 2d), which is consistent with the background of regional climate aridification and intensified human activities. The area of DH decreased from 118.92 km² to 75.79 km², representing a 36.28% reduction in area and a 43.88% decrease in water storage. Its absolute inter-annual change was relatively small, indicating a more gradual shrinkage process. In contrast, HQH experienced dramatic fluctuations in both area and water storage. After a substantial recovery between 1996 and 1997, it underwent rapid shrinkage from 1998 to 2008 until it desiccated, with its relative inter-annual rate of change far exceeding that of DH. This marked difference in volatility is directly rooted in their basin topographies. The dish-shaped morphology of HQH implies gentle shoreline slopes and a wide, shallow basin. Consequently, even minor fluctuations in water level can lead to substantial advances or retreats of the shoreline, making the lake area extremely sensitive to short-term changes in water storage. In contrast, the bowl-shaped structure of DH features relatively steep banks, which lessen the impact of water level changes on the lake's area and water storage, thereby exhibiting a stronger buffering capacity and greater hydrological stability. This confirms that lake morphology is a key intrinsic factor that modulates the intensity of a lake's response to hydrological fluctuations, with shallow lakes typically being more sensitive to environmental changes and having lower resilience.

4.2 Water balance and recharge area analysis

Evaporation is the primary pathway for water loss from lakes in arid regions. The results of this study (Fig. 4a-d) show that annual evaporation from both lakes decreased as their areas diminished, with strong positive correlations between area and evaporation ($r = 0.84$ for DH; $r = 0.95$ for HQH), confirming that water surface area primarily controls evaporation volume. The mean relative inter-annual rate of change in evaporation for HQH ($17.0\% \pm 11.4\%$) was far higher than for DH ($5.94\% \pm 4.61\%$), reflecting the highly volatile nature of HQH's area driven by its shallow, dish-shaped morphology. This morphology exposes a disproportionately larger surface area per unit volume of water, and as demonstrated by Sacks et al. (1994), shallower lakes experience faster heat transfer and more rapid warming, further enhancing evaporation. Thus, basin topography exacerbates

HQH's water deficit by amplifying both the magnitude and inter-annual variability of evaporation loss in a drying climate.

The interaction between groundwater and lakes is a key link in the lacustrine hydrological cycle, and the basin structure influences the effectiveness of groundwater recharge in this process (Li et al. 2024; Chen et al. 2019). Using the water balance approach and the ellipsoidal structure model, this study calculated GWR and GRA for both lakes. Due to large-scale groundwater extraction for agricultural irrigation, the regional water table has declined (Guo et al. 2022), causing DH's GRA to steadily decrease from 130.39 km² in 1988 to 79.52 km² in 2008, with GWR showing a corresponding decay rate of $-0.0041 \times 10^8 \text{ m}^3/\text{a}$.

In contrast, the GRA of HQH shrank from 72.99 km² to complete disappearance, causing its recharge to drop from a peak of $0.821 \times 10^8 \text{ m}^3$ in 1996 to zero by 2008, drastically accelerating the lake's desiccation into a seasonal lake. The difference in recharge intensity is even more striking: DH had a mean RR of 0.34 m/a with a quartile coefficient of variation of 0.81, whereas HQH had a mean RR of 0.16 m/a with a highly volatile coefficient of variation of 3.33. The decay of HQH's GWR is primarily due to large-scale agricultural pumping, which has lowered the shallow groundwater table, causing the groundwater that previously seeped into the lake basin to weaken and cease seepage gradually. Furthermore, the exposure of a large area of the lakebed increased the degree of evaporation from the groundwater discharge zone, weakening the groundwater recharge intensity. The wide, shallow basin and gentle slopes of HQH make its groundwater exchange interface extremely sensitive to minor changes in water level; its rapid area reduction directly limits effective groundwater recharge, and under arid, high-evaporation conditions, recharge efficiency declined sharply. In contrast, DH's steeper slopes and deeper water body helped maintain a more stable recharge area, demonstrating greater resilience.

The differences in the recharge efficiency and stability of the two lakes are primarily caused by the sensitivity of their GRA, which is driven by topographical differences. Fig. 3e clearly illustrates the changes in the GRA for both lakes as the groundwater level declines, based on the ellipsoidal structure model. The GRA decay rate for DH was -0.1005 , whereas the average decay rate for HQH was -0.2016 , 2.01 times that of DH, exhibiting a faster, non-linear decline. The GWR, inverted from the water balance equation, was used

to calculate the GWR_I index after removing the influence of the hydraulic gradient. This index showed that the seepage rate of HQH was 2.10 times that of DH, which is nearly identical to the ratio of their ellipsoidal area decline rates. This demonstrates that the difference in GWR changes is primarily caused by the difference in GRA, which is in turn controlled by the lake basin structure.

The coupling between GWR_I and GRA also differs between the two lakes. For DH, the correlation between GWR and GRA in the two analysis stages (1988–1999 and 2000–2008) was 0.26 and 0.18, respectively, both of which are statistically insignificant (Fig. 6). This indicates that the GWR of DH is relatively insensitive to changes in its GRA. This is mainly because its bowl-shaped structure provides a stable hydraulic connection and recharge mechanism: DH has a large water depth and vertical recharge area, and its sides and bottom are primarily in hydraulic connection with deeper phreatic aquifers. The sedimentary layers at the bottom of DH act as a buffer, further contributing to the poor correlation between GWR and GRA. In contrast, HQH exhibited a very strong positive correlation between GWR and GRA in Stage I (1988–1996) ($r = 0.91$, $R^2 = 0.83$), indicating that the recharge area was the key factor controlling recharge volume during this period. However, upon entering Stage II (1997–2008), the period of rapid lake shrinkage, the correlation dropped significantly ($r = 0.41$). The recharge intensity per unit area decayed by 68% in this stage. This is because when the lake entered the second stage of rapid shrinkage, the large exposed lakebed experienced intense evaporation, leading to salinization. Salt crystals cemented the soil, reducing the permeability of the surface layer and thus impeding groundwater discharge. More critically, the exposed lakebed enhances phreatic evaporation, depleting shallow groundwater and disrupting effective recharge from adjacent aquifers. HQH's shallow saucer-shaped basin drives these dual mechanisms, triggering accelerated GRA shrinkage and consequent RR attenuation during Phase II. This feedback loop between lakebed desiccation and intensified evaporation ultimately leads to the decoupling of the GRA-GWR relationship at this stage.

The EMD analysis (Fig. 7) further elucidates the multiscale synchronicity between groundwater recharge volume and recharge area. For DH, the primary time scale for GWR_I and GRA is IMF2, and the correlation coefficients for this and the residual component representing the long-term

trend are both very low. This proves that the insensitivity of DH's GWR to changes in GRA is a phenomenon that exists across different time scales, owing to lakebed sediments that effectively buffer vertical hydraulic exchange. For HQH, GWR and GRA show moderate to strong positive correlations in the short-term IMF1 and medium-term IMF2, with a weaker correlation on longer time scales. This indicates that the changes in HQH's GWR and GRA exhibit strong synchronicity on short and medium time scales, particularly in the 3–9 year medium-term fluctuations. Combined with the results of the staged correlation analysis (Fig. 6), this coupling relationship weakened significantly in its later shrinkage period. This suggests that on an inter-annual scale, the effect of precipitation recharge is transmitted through groundwater, causing the lake area to fluctuate synchronously. On a decadal scale, the cumulative surplus or deficit of groundwater caused by cycles of climate drought and human activities is largely consistent with the trend in the lake's area. Although HQH is highly coupled on short and medium time scales, its correlation in the component representing the long-term trend is weaker. This does not mean the long-term trend is irrelevant; rather, it reflects the inherent instability of the GWR-GRA relationship itself. The EMD, as an analysis of the entire study period, averages the response characteristics of these two distinctly different stages in its extracted long-term trend component, thus appearing as a seemingly weaker overall correlation. This, precisely from a frequency-domain perspective, confirms that HQH's recharge system underwent an irreversible collapse under sustained pressure, rather than a stable, linear decay like that of DH.

In conclusion, under similar external hydrogeological features, climatic conditions, and human activity impacts, the lake basin topography is also a key intrinsic factor that regulates the lacustrine hydrological dynamics, particularly the groundwater recharge process. The bowl-shaped structure of DH possesses a relatively strong stability; its groundwater recharge is insensitive to changes in area, and it exhibits a more gradual rate of shrinkage. The shallow, dish-shaped topography of HQH makes its area and water storage highly sensitive to water level changes, leading to intense fluctuations and relatively greater evaporation. This caused the coupling between its groundwater recharge and recharge area to rapidly decouple in the later stages of shrinkage, resulting in a sharp decline in recharge efficiency and thereby accelerating its shrinkage in a drying climate. In particu-

lar, shallow, dish-shaped lakes require more attention to cope with potential future environmental changes.

5 Conclusions

Through a comparative analysis of the bowl-shaped Daihai Lake and the dish-shaped Huangqihai Lake on the Inner Mongolia Plateau, this study systematically reveals the dominant role of lake basin topography in the differential shrinkage process of lakes. The main conclusions are as follows:

(1) Huangqihai exhibits the characteristics of a typical dish-shaped lake, with a wide and flat basin. In contrast, Daihai has a bowl-shaped structure with relatively steep banks and greater water depth. Under similar climatic conditions and intensity of human activities, this topographical difference is the key factor influencing the lakes' shrinkage processes.

(2) Due to the differences in their basin structures, as the regional groundwater table declined, the loss of groundwater recharge for the dish-shaped Huangqihai was 2.10 times that of the bowl-shaped Daihai. This led to the dish-shaped Huangqihai becoming a seasonal lake in 2008. In contrast, the bowl-shaped Daihai, despite a shrinking trend, still maintained a water area of 47 km² in 2023. This is primarily because the dish-shaped morphology of Huangqihai results in a more severe relative evaporation loss. More critically, as the regional groundwater table falls, its groundwater recharge area decays at a rate 2.01 times faster than that of the bowl-shaped lake. In contrast, the bowl-shaped structure of Daihai allows its groundwater recharge to maintain a consistently weak coupling with changes in its area, demonstrating a stronger buffering capacity. This structure effectively resists the impacts of external environmental fluctuations, resulting in a more gradual shrinkage process.

(3) As a key intrinsic factor, lake basin topography governs the different shrinkage outcomes of Daihai and Huangqihai under similar external pressures by shaping the stability of the lake's groundwater recharge area and its evaporation efficiency. Therefore, in water resource management, ecological conservation, and climate change impact assessment of lakes in arid regions, analyses based on lake basin topography and ellipsoidal models can effectively estimate the decline in a lake's groundwater recharge. This allows for the development of differentiated response strategies tailored to the vulnerability characteristics of differently shaped lakes.

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Availability of data and material

Landsat 5 and Landsat 7 imagery used in this study were obtained from the Google Earth Engine platform (<https://earthengine.google.com/>). Underwater topographic elevation data were derived from ICESat-2 ATL08 data (<https://nsidc.org/data/icesat-2>) and sonar measurements from an unmanned surface vehicle (USV). The digital elevation model was sourced from the 30 m resolution version released by NASA in 2020, based on Shuttle Radar Topography Mission data (<https://www.earthdata.nasa.gov/>). Daily net radiation flux and lake temperature data were obtained from the European Centre for Medium-Range Weather Forecasts (<https://cds.climate.copernicus.eu/>). The USV bathymetric survey data are proprietary and cannot be shared publicly due to laboratory policy and confidentiality agreements. These data may be available from the corresponding author upon reasonable request and with permission from the data owner.

The code implementing the ellipsoidal model is available from the corresponding author upon reasonable request.

Appendix 1. Numerical method for calculating the surface area of the Ellipsoidal model

The core concept for calculating the surface area of the ellipsoid is to first divide the ellipsoid into $(2n_1) * n_2$ regions, then calculate the area of each region, and finally obtain the approximate area of the ellipsoid through cumulative summation. The purpose of dividing it into multiple small regions is to prepare for subsequent calculations at specific declining water levels or angles.

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1 \quad (1)$$

Where: c represents the depth, a and b repre-

<http://gwse.ihg.org.cn>

sent the major and intermediate axes of the ellipse at the maximum horizontal interface.

Establish a planar Cartesian coordinate system with the center of the ellipsoid as the origin. The depth h (infinitely close to c) is divided into n_2 equal parts. The function equation for each slice is:

$$\frac{x^2}{a^2 * \frac{(n_2 * c)^2 - (i * h)^2}{(n_2 * c)^2}} + \frac{y^2}{b^2 * \frac{(n_2 * c)^2 - (i * h)^2}{(n_2 * c)^2}} = 1 \quad (2)$$

Where: i represents the i -th slice, $i = 0, 1, 2 \dots, n_2 - 1$.

Each slice is divided into $2 * n_1$ equal parts by angle. When n_1 is sufficiently large, the arc corresponding to each angle can be approximated as a straight line. The length of each straight line is calculated using the coordinate formula and is used as the approximate "length" of each region. The specific process is as follows: Assume the dividing angle is ψ . The intersection points (x, y) are found by solving the simultaneous equations of the dividing line and the ellipse of the slice:

$$\begin{cases} x = \frac{a * b}{n_2 * c} * \sqrt{\frac{(n_2 * c)^2 - (i * h)^2}{b^2 + (a * \tan(p * \psi))^2}} \\ y = \tan(p * \psi) * \frac{a * b}{n_2 * c} * \sqrt{\frac{(n_2 * c)^2 - (i * h)^2}{b^2 + (a * \tan(p * \psi))^2}} \end{cases} \quad (3)$$

Where: p is the p -th dividing angle, $p = 0, 1, 2 \dots, 2 * n_1 - 1$. The x and y values are stored in two arrays, x_array and y_array . This is looped for p to find the value of each segment in the ring.

As i increases from 0 to $n_2 - 1$, the above steps for finding the segments of each ring are repeated to obtain the segment values for all slices of the ellipsoid. These values are stored in a two-dimensional array, arc_length_array , with n_2 rows (number of slices) and $2 * n_1$ columns (number of segments). This completes the calculation for the "length" of all regions.

The calculation for the "height" of each region is as follows: The depth h (infinitely close to c) is divided into n_2 segments. The arc length corresponding to each drop of h/n_2 is approximated as a straight line, which serves as the "height" of each region. The calculation method also uses the coordinate distance formula to find the intersection point coordinates of each drop h/n_2 with the ellipsoid:

$$\begin{cases} x = \frac{(i * h)}{n_2 * \frac{(c * i * h)}{(a * \sqrt{((c * n_2)^2 - (i * h)^2)})}} \\ y = \frac{i * h}{n_2} \end{cases} \quad (4)$$

Where: $i = 0, 1, 2 \dots, n_2 - 1$. The x and y values of the intersection points are stored in two arrays. As i increases from 0 to $n_2 - 1$, the above steps are repeated to find the height of each layer, which are stored in the $high_array$.

The area of each ring is the sum of each row in the arc_length_array multiplied by the corresponding element in $high_array$. The total area of the ellipsoid is the cumulative sum of these ring areas, multiplied by 2.

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