Reply to Reviewers' comments (Reviewer#1)

Ref: Manuscript ID egusphere-2025-4778

Title: Disentangling the Key Drivers of Water Balance in Central Asia's Lake Balkhash: A Relative Contribution Assessment (Original title: Revealing the Driving Factors of Water Balance in Lake Balkhash Through Integrated Attribution Modeling)

Dear Reviewer,

We sincerely thank you for your positive evaluation of our work and for your detailed and thoughtful comments. We have incorporated your suggestions, including changing the title, restructuring the results, and adding necessary climate context. Below is our point-by-point response to your specific comments. The reviewer's comments are highlighted in red, and our responses are highlighted in black.

General comments

Comment 1: recommend removing "integrated attribution modelling" from the title and being cautious with the use of the term "attribution" throughout the manuscript. This terminology may cause confusion with established climate and impact attribution studies (e.g. Pietroiusti et al., 2024), which are not conducted here. More neutral wording such as "disentangling drivers" or "assessing relative contributions" would be clearer.

Pietroiusti, R., Vanderkelen, I., Otto, F. E. L., Barnes, C., Temple, L., Akurut, M., Bally, P., van Lipzig, N. P. M., & Thiery, W. (2024). Possible role of anthropogenic climate change in the record-breaking 2020 Lake Victoria levels and floods. Earth System Dynamics, 15(2), 225-264. https://doi.org/10.5194/esd-15-225-2024

Response: Response: We greatly appreciate the reviewer's insightful and expert suggestion. We fully agree that the term "attribution" has a specific connotation in the field of climate science, and its use in our research could cause confusion. To ensure accuracy and clarity in terminology, we have adopted your suggestion and systematically revised the relevant terminology throughout the text.

Specific revisions are as follows:

(1) Title Revision: The paper title has been changed from "Revealing the Driving Factors of Water Balance in Lake Balkhash Through Integrated Attribution Modeling" to "Disentangling the Key Drivers of Water Balance in Central Asia's Lake Balkhash: A Relative Contribution Assessment."

(2) Terminology Adjustment: Throughout the text, we have replaced "attribution" with more neutral terms such as “disentangling drivers,” “separating contributions,” and “contribution assessment.”

(3) Framework Renaming: The research framework name has been changed from “Hydrological Attribution and Analysis Framework (HAAF)” to “Hydrological Analysis and Disentanglement Framework (HADF)” and updated uniformly throughout the text.

We believe these modifications have clarified our research focus and avoided confusion with classic attribution studies.

Comment 2: The manuscript would benefit from a clearer description of observed climatic changes in the basin, including precipitation characteristics (mean annual values and seasonality) and documented trends such as warming or enhanced glacier melt in upstream mountain regions. Where possible, summary statistics or maps (e.g. in an appendix) would improve context.

Response: We appreciate the reviewers' valuable suggestions. We recognize the importance of providing readers with a detailed climatic background of the study area. Therefore, we have added quantitative descriptions and visualizations of the climatic characteristics of the Lake Balkhash Basin to the manuscript.

Specific revisions are as follows:

(1) Added Appendix Figure: We have added a new figure (Appendix Figure A1) to the appendix, which contains three parts: (a) spatial distribution of the basin's annual mean precipitation; (b) a comparison of seasonal variations in monthly mean precipitation and temperature in the mountainous (upstream) and plain (downstream) regions; and (c) long-term trends in annual mean temperature and precipitation in the mountainous areas from 1931 to 2024.

(2) Added Text Description: In the section “2.1 Study Area and Historical Periodization”, we have added detailed textual descriptions of these climatic characteristics and referenced the new Appendix Figure A1. For example, we now explicitly state: “The mountainous upper reaches receive significantly higher precipitation, averaging 725 mm/year, compared to the arid plains and lake surfaces, which average only 235 mm/year (Appendix Fig. A1a). Precipitation exhibits strong seasonality, with approximately 71.2% of the annual total occurring during the spring and summer months (Appendix Fig. A1b). Observed climatic changes from 1931 to 2024 indicate a pronounced warming trend, particularly in the upstream mountain ranges, with a significant temperature increase of 0.30 °C/decade and a precipitation increase of 1.11 mm/decade (Appendix Fig. A1c).”

These additions provide a solid foundation for readers to understand the hydroclimatic background of this watershed.

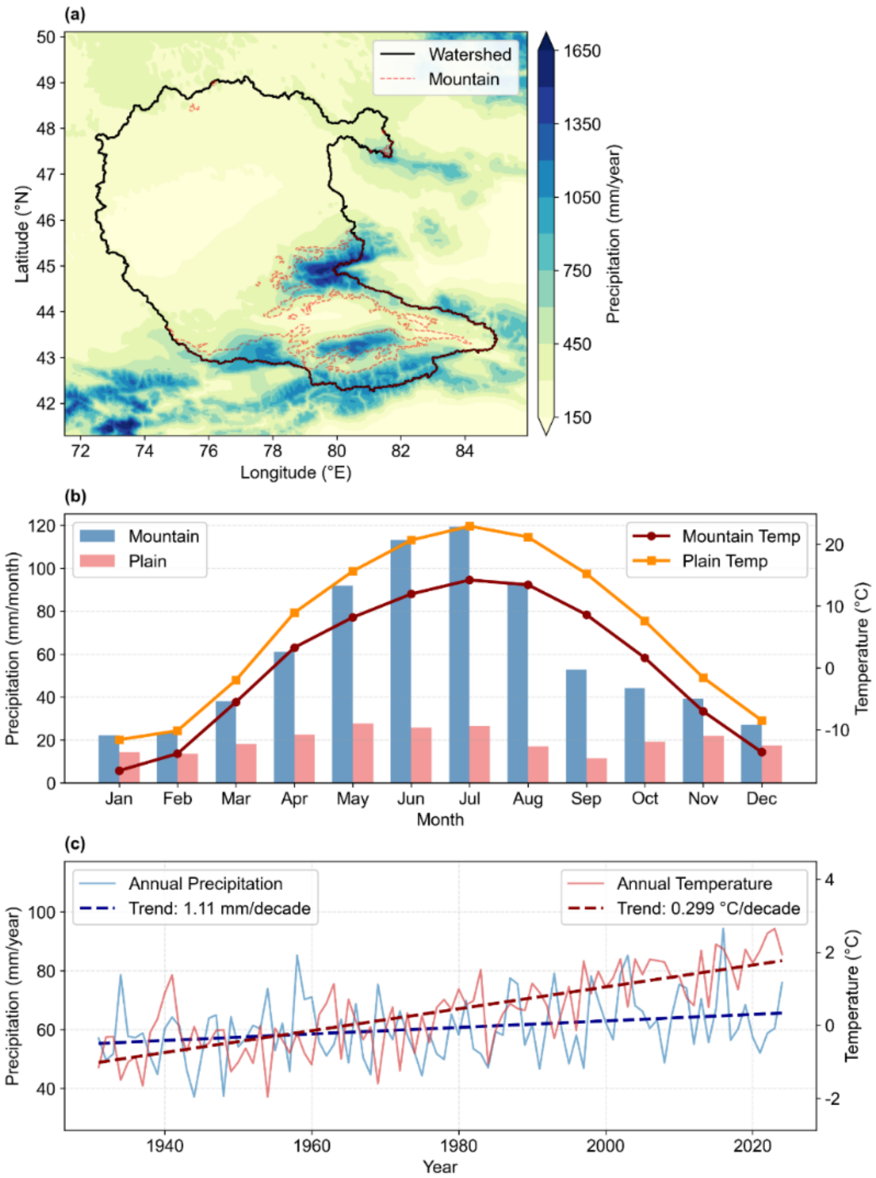

Figure A1. Spatiotemporal characteristics of climate variables in the Lake Balkhash Basin. (a) Spatial distribution of Mean Annual Precipitation (MAP) across the basin, highlighting the contrast between the mountainous upstream regions and the arid plains. (b) Seasonal cycle of monthly mean precipitation (bars, left axis) and temperature (lines, right axis), comparing the Mountainous (upstream) and Plain (downstream) regions. (c) Long-term trends in annual mean temperature and precipitation for the mountainous region from 1931 to 2024. The dashed lines represent the linear trends, with statistical significance indicated in the legend. Note the accelerated warming trend observed in recent decades.

Comment 3: The role of the machine-learning component following the hydrological model simulations requires clearer justification. At present, it appears to function primarily as a bias-correction step. The manuscript should explain why this additional step is necessary, how overfitting is avoided, and why the direct hydrological model outputs are insufficient.

Response: We appreciate the reviewer's key question, which prompted us to more clearly articulate the advantages and design philosophy of our hybrid model approach. We have already provided a detailed explanation of the role, necessity, and methods for avoiding overfitting in the manuscript.

Specific revisions are as follows:

(1) Clarifying Necessity: In section "2.3.1 Hybrid Hydrological Reconstruction Model", we explained the limitations of using the physical model alone (SEGSWAT+), especially regarding structural biases that may exist in sparse data regions. We explicitly state that the ML module, as a nonlinear error correction tool, can learn and correct these systematic residuals caused by model structure and driving data uncertainties, thereby significantly improving simulation accuracy.

(2) Explanation of Overfitting Avoidance: In the same section, we further explain how this hybrid strategy effectively mitigates the risk of overfitting: "Overfitting, a common concern in ML, is mitigated here because the ML component targets only the residuals rather than the total flow. Since the residuals from a calibrated physical model are inherently bounded and smaller in magnitude than the total runoff, the search space for the ML model is constrained, preserving the physical plausibility of the final output."
(3) Demonstrating Performance Improvement: To quantitatively demonstrate the effectiveness of ML calibration, we have added a new performance comparison table (Appendix Table B3). This table compares in detail the performance metrics (KGE, NSE, PBIAS) of the original SEGSWAT+ model and the ML-calibrated hybrid model during the calibration and validation periods. The data shows that the hybrid model has significant improvements across all metrics, thus demonstrating the value of this additional step.

Table B3. Performance comparison of SEGSWAT+ (Raw) and the Hybrid Model (Corrected) across calibration and validation periods

River	Station	Period	Metric	SEGSWAT+ (Raw)	Hybrid Model (Corrected)
Ili	Ushzharma	Calibration	KGE	0.68	0.89
			NSE	0.72	0.93

			PBIAS(%)	-9.5	3.2
		Validation	KGE	0.65	0.85
			NSE	0.68	0.88
			PBIAS(%)	-16.8	5.1
Karatal	Ushtobe	Calibration	KGE	0.74	0.89
			NSE	0.76	0.91
			PBIAS(%)	11.2	6.4
		Validation	KGE	0.71	0.86
			NSE	0.72	0.85
			PBIAS(%)	18.5	7.5
Aksu	Chann	Calibration	KGE	0.66	0.83
			NSE	0.64	0.84
			PBIAS(%)	-9.3	-2.8
		Validation	KGE	0.62	0.80
			NSE	0.60	0.78
			PBIAS(%)	-13.5	-3.4
Lepsy	Lepsinsk	Calibration	KGE	0.70	0.82
			NSE	0.71	0.84
			PBIAS(%)	9.8	-5.1
		Validation	KGE	0.68	0.80
			NSE	0.67	0.77
			PBIAS(%)	11.5	-6.2
Ayaguz	Ayaguz	Calibration	KGE	0.63	0.89
			NSE	0.61	0.88
			PBIAS(%)	-15.4	-0.5
		Validation	KGE	0.71	0.86
			NSE	0.68	0.83
			PBIAS(%)	-8.45	-1.8

Comment 4: The analysis of future lake level projections is introduced for the first time in the Discussion section. Given its relevance, this analysis should be presented in the Results section and clearly introduced in the Introduction and Methods. The climate data sources (e.g. selection of CMIP6 models) should be explicitly described and referenced, and model performance in simulating precipitation and evaporation in the basin should be assessed or supported by existing literature. The role of glacier melt in future changes also warrants more explicit discussion.

Response: We fully agree with the reviewers' points. Future scenario predictions are a crucial component of this study and should rightfully be presented in the results section, with clear background information provided earlier. We have made significant adjustments to the article's structure and content to better integrate this section.

Specific revisions are as follows:

(1) Structure Adjustment: We have moved the entire section on future lake water level predictions from the discussion section to the results section, and established a new subsection, “3.4 Changes in Lake Water Levels Under Future Scenarios.”

(2) Additional Introduction and Methodology: In the introduction, we explicitly list predicting future lake water levels as the third core objective of this study. In section “2.2 Datasets,” we detail the climate data sources used for future predictions (NEX-GDDP-CMIP6), the six GCM models selected (and their selection criteria), and the SSP scenario settings.

(3) Further Discussion: In the Discussion section (now “4.3 Future Vulnerabilities and Uncertainties”), we explored the impact of future glacial meltwater changes (such as the “peak water” problem) on lake levels in greater depth and discussed the uncertainties associated with GCM predictions.

Through these revisions, the future scenario analysis has been seamlessly integrated into the overall logical framework of the paper.

Comment 5: The frequent use of the term “runoff” appears inconsistent with the processes described, where “inflow” (i.e. water actually entering the lake after upstream losses) would often be more appropriate. This distinction should be clarified and terminology applied consistently throughout the manuscript.

Response: We thank the reviewers for their meticulous corrections. We agree that "inflow" is a more accurate term than "runoff" when describing the volume of water entering lakes, as it takes into account headway losses such as deltaic seepage. We have carefully reviewed and revised the terminology throughout the paper to ensure consistency and accuracy. We retain the terminology "streamflow" when discussing watershed runoff processes, but consistently use "inflow" when specifically referring to the volume of water entering lakes.

Comment 6: The multi-step procedure used to derive naturalized streamflow is not sufficiently clear. In particular, using parameter sets calibrated for the first period (including snow and glacier parameters) may not capture climate-driven changes in snow and glacier dynamics in the most recent period. This assumption and its implications should be discussed more explicitly.

Response: The reviewer raised a profound question regarding our methodological assumptions. Using fixed parameters (calibrated based on the P1 time period) in the "natural runoff" simulation is indeed an important assumption, and its potential impact warrants further investigation. We have addressed and discussed this more clearly in the manuscript.

Specific revisions are as follows:

(1) Clarified Method Description: In section "3.2 Quantification of The Impacts on Variations in Streamflow", we have more clearly described the method for simulating "natural runoff" (Q_{nat}) and explicitly stated that it is "a standard 'fixed parameter' method designed to effectively separate climate signals."

(2) Added Discussion Section: We have added a new subsection, "4.2 Cryospheric Dynamics and Methodological Limitations," to the Discussion section specifically to discuss this assumption and its impacts. We acknowledge that using mid-20th-century glacier parameters to simulate recent runoff may underestimate the "glacier surplus" effect resulting from accelerated glacier melting.

(3) Clarifying the Impact: In this section, we further argue that this limitation actually makes our attribution of the impacts of human activities conservative. Because if the actual natural runoff (considering accelerated meltwater) is higher than our simulations, then the amount of water consumed by human activities (the difference between natural and actual runoff) would actually be greater than our estimates. Therefore, this uncertainty reinforces our core conclusion that human activities are the dominant force suppressing watershed water supply.

Comment 7: The manuscript uses overly strong or promotional language throughout the results, discussion and conclusion section (e.g. "powerful," "massive increase," "overwhelmingly," "immense," "enormous potential," "exceptionally favorable"). I recommend moderating this wording and adopting a more neutral, quantitative scientific tone throughout the manuscript.

Response: Thank you very much for the reviewer's reminder. We have carefully polished the entire paper, removing or replacing overly emotional or exaggerated words such as "powerful," "massive," and "immense." We strive to use more objective, neutral, and quantitative scientific language to present our findings, letting the data and results speak for themselves.

Specific comments

(1) Title: I suggest removing “integrated attribution modelling”. This is not a standard modelling term, and given the existence of established fields such as climate attribution and climate impact attribution, its use may be confusing for readers (see also general comment above).

Title: Please consider adding the country or region to the lake name to help readers geographically locate the study area, e.g. “Lake Balkhash (Kazakhstan)”.

Response: As mentioned in the reply to General Comment 1, we have removed "integrated attribution modelling" as suggested by you. We have also adopted your second suggestion, adding geographic location information to the title, changing it to "...in Central Asia's Lake Balkhash...", to facilitate readers' quick location of the study area.

(2) L90–99: Are lake level observations available for Lake Balkhash? If not, please state this explicitly and explain why. If such data exist, a plot of lake level and/or lake extent evolution and variability over this period would be highly informative. Datasets such as DAHITI or G-REALM may be relevant.

Response: Thank you for your suggestion. We recognize that showing the historical changes in lake levels is crucial for understanding the context. We have added a new figure (Figure 2) to the revised manuscript, showing the interannual water level changes of Lake Balkhash from 1931 to 2024. Regarding the data sources, we have provided detailed explanations in the "2.2 Datasets" section and in the captions of Figure 2: historical water level data (1931–2015) are from published literature (Duan et al., 2020), while recent data (2016–2024) have been supplemented and calibrated using G-REALM satellite altimetry data.

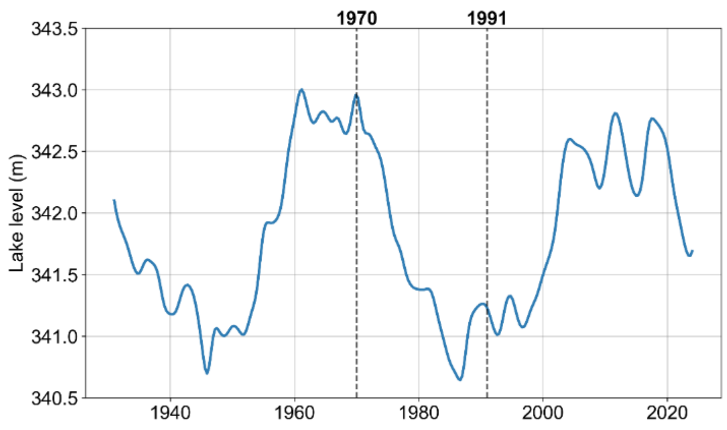

Figure 2. Water Level of Lake Balkhash, 1931–2024 (Water levels from 1901 to 2015 are based on actual observational data, while those from 2016 to 2024 are derived from the G-REALM dataset. The latter was calibrated against observed data from 2001 to 2015. Specific sources are detailed in the following subsection)

(3) L87–89: Could you provide quantitative information or maps on mean annual precipitation (e.g. in an appendix) and precipitation seasonality? In addition, a description of observed climatic changes in the region is missing (e.g. warming, enhanced glacier melt in upstream mountain ranges, changes in precipitation patterns). Where possible, briefly mentioning projected future changes under different scenarios would further strengthen the context.

Response: As stated in the reply to General Comment 2, we have fully responded to your request by adding Appendix Figure A1 and supplementing the quantitative description in the “2.1 Study Area…” section.

(4) Table 2 (datasets): Please provide full references for all datasets listed under Source. In line with HESS guidelines, these datasets should also be included in the reference list, and their URLs should be provided in the Data availability section.

Response: Following your instructions, we have improved Table 2. The “Source” column in the table now provides complete references for each dataset (e.g., Harris, 2024; Zhang et al., 2024). All these references have also been added to the reference list at the end of the document. Furthermore, we have added a “Data availability” section at the end of the document, providing access links (URLs) for all public datasets.

Table 2. Summary of datasets used in this study

Dataset	**Key Variables**	**Spatial Resolution**	**Temporal Coverage**	**Source (Reference)**
Copernicus GLO-90 DEM	Elevation	90 m	Static	European Space Agency (2019)
DSOLMap	Bulk density, hydraulic conductivity, available water capacity	250 m	Static	Lopez-Ballesteros et al. (2023)
GLC_FCS30D	Land cover classes (35 subcategories)	30 m	1985–2022	Google Earth Engine(Zhang et al., 2024)
Randolph Glacier Inventory (RGI v7.0)	Glacier outlines, attributes	Vector	Target year: 2000 (varies by region)	RGI Consortium (2023)
SWORD v15	River reaches, nodes, hydrological networks, lake boundaries	~10 km reaches, 200 m nodes	Static	(Altenau et al. (2021)
Glacier mass loss	Glacier elevation change rates (dh/dt)	100 m	2000–2019	Hugonnet et al. (2021)
CRU JRA v3.0	Temperature, precipitation, wind speed, vapor pressure, etc.	0.5° (downscaled to 0.05°)	1901–2024 (daily)	Harris (2024)
TerraClimate	Max/min temperature, precipitation, solar radiation, vapor pressure deficit	1/24°	1958–2024 (monthly)	Abatzoglou et al. (2018)
NEX-GDDP-CMIP6	Daily temperature (max/min), precipitation	0.25°	2015–2100 (Daily)	Thrasher et al. (2022)
Observations	Discharge, water level	Point	1931–2024 (monthly)	NCDC (2024); Duan et al. (2020)

Data availability. All underlying data used in this study are publicly accessible. The specific sources and access links are as follows: Copernicus GLO-90 DEM is available via OpenTopography (https://doi.org/10.5069/G9028PQB). DSOLMap soil properties are accessible through the WateriTech platform (https://www.wateritech.com/data). GLC_FCS30D land cover data can be downloaded from the Zenodo repository (https://zenodo.org/records/8239305). RGI v7.0 glacier data are provided by the GLIMS initiative (https://doi.org/10.5067/f6jmovy5navz). SWORD v15 hydrological networks are available at the SWOT mission river database (https://zenodo.org/records/10013982/). CRU JRA v3.0 and TerraClimate datasets are accessible via the CEDA Archive (https://catalogue.ceda.ac.uk/uuid/90a87c8fd63c4520a33445e7b6a20688/) and the Climatology Lab (https://www.climatologylab.org/), respectively. NEX-GDDP-CMIP6 projections are hosted by the NASA Earth Exchange (https://nex-gddp-cmip6.s3.us-west-2.amazonaws.com/index.html). Observed streamflow and lake level data were obtained from the National Cryosphere Desert Data Center (http://www.ncdc.ac.cn) and previously published literature (Duan et al., 2020). The model outputs and customized processing codes developed in this study are available from the corresponding author upon reasonable request.

(5) Table 2: Please clarify what is meant by “~2000 snapshot” for the glacier dataset.

Response: We have revised the description of the Glacier dataset in Table 2 from “~2000 snapshot” to the clearer statement: “Target year: 2000 (varies by region)” to accurately reflect the characteristics of the RGI v7.0 dataset.

(6) L123: The phrase “enhance precision” should be replaced by “increase resolution”, as downscaling does not increase the precision of the original dataset. Please also clarify whether the downscaling approach is validated against precipitation observations and whether total precipitation amounts are conserved.

Response: Thank you for your precise correction. We have changed "enhance precision" to the more accurate "increase resolution". Additionally, in section "2.2 Datasets", we have added details about the downscaling method: "This downscaling procedure strictly enforces mass conservation, ensuring that the area-weighted sum of the fine-resolution precipitation matches the total water volume of the original coarse-resolution forcing." This ensures water conservation during the downscaling process.

(7) L126: Please provide more details on the observed streamflow dataset, including which stations are available (preferably shown on a map) and their periods of record. If historical lake level or extent data are unavailable, could the streamflow observations be used to illustrate the periods defined in Table 1?

Response: We have provided a more detailed explanation of the runoff observation data in the revised draft. On the map in Figure 1, we have marked the locations of the 16 hydrological stations with triangles. In Appendix Table B1, we have provided a detailed table listing the name, latitude and longitude, observation period, and resolution of each station. This information provides readers with a comprehensive data background.

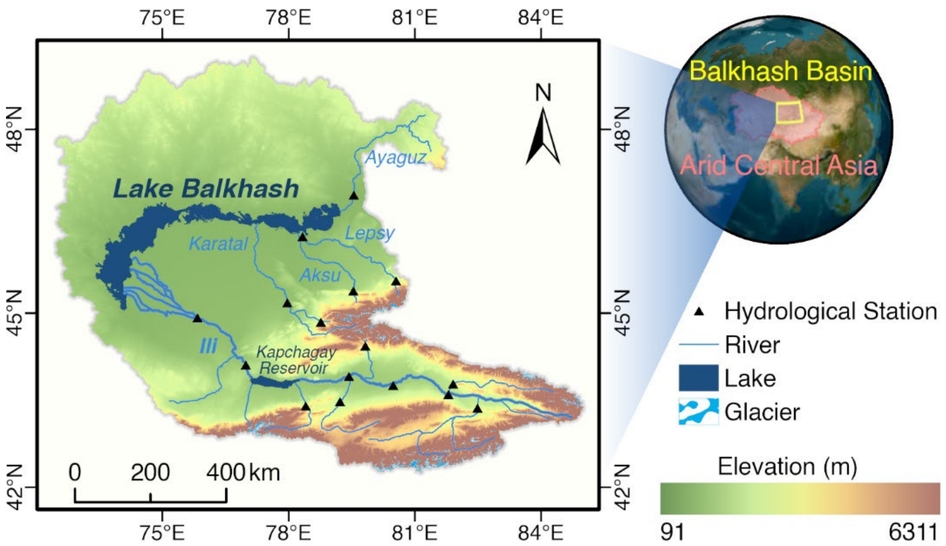

Figure 1. Geographic location of the study area.

Table B1. Details of the 16 hydrological stations used in this study

River System	Station Name	Longitude (°E)	Latitude (°N)	Site Elevation (m)	Drainage Area ($\times 10^2$ km^2)	Observation Period & Resolution
Ili	Ushzharma	75.83	44.93	381	1311.7	1939-1989 (monthly); 1931-2020 (yearly)
	Kapchagay	76.98	44.13	431	1141.0	1935-1989 (monthly); 1931-2000 (yearly)
	Dobyn	79.43	43.94	498	756.4	1931-2020 (yearly)
	Kairgan	80.48	43.78	529	630.6	1931-2020 (yearly)
	Yamate	81.8	43.63	692	476.2	1953-1980,2005-2008 (monthly)
	Tuohai	81.91	43.81	804	95.4	1953-1980 (monthly); 1931-2015 (yearly)
	Qiafuqihai	82.49	43.4	878	275.2	1958-1980 (monthly)
	Sliyaniya Su	79.82	44.47	1226	11.3	1936-1952, 1959-1986 (monthly)
	Sarytogay	79.22	43.51	760	77.8	1935-1989 (monthly)
	Malybay	78.4	43.43	879	42.5	1936-1989 (monthly)
Karatal	Ushtobe	77.97	45.19	422	128.0	1936-1989 (monthly)
	Tekeli	78.78	44.87	1022	11.7	1940-1955, 1959-1986 (monthly)
Aksu	Chann	79.54	45.38	667	13.4	1937-1983 (monthly)

Lepsy	Lepsy	78.33	46.28	346	101.9	1936-1989 (monthly)
	Lepsinsk	80.55	45.55	936	12.2	1931-1975 (monthly)
Ayaguz	Ayaguz	79.56	46.96	364	125.9	1949-1986 (,yearly)

(8) L146: Streamflow and runoff are not equivalent terms; please clarify and use consistent terminology.

Response: Thank you for the reminder. As stated in our response to General Comment 5, we have differentiated and standardized the use of "runoff," "streamflow," and "inflow" throughout the text.

(9) L150: Please clarify why overfitting is not an issue in the machine-learning approach. As implemented, it appears to function as a form of bias correction—this should be stated explicitly and justified.

Response: As stated in our response to General Comment 3, we have detailed in section "2.3.1 Hybrid Hydrological…" how hybrid models effectively avoid overfitting risks by learning only from bounded residuals, and clarified their function as a nonlinear "error correction" or "bias correction" module.

(10) L176: How is the parameter n calculated? Is it static in time? What data sources are used to determine n? Please also specify which data are used to estimate potential evaporation and actual evaporation.

Response: We have detailed in section "2.3.2 Budyko-based Contribution Analysis" the method for calculating parameter n in the Budyko framework. We explained: "In this study, the parameter n was calibrated for each period by solving Equation (1) inversely, using the period-averaged P, ET_0, and observed ET…." Meanwhile, we clarified that potential evapotranspiration (ET_0) was calculated using the Penman-Monteith method, while actual evapotranspiration (ET) was back-calculated on a long-term scale using the water balance equation (ET = P - Q). All meteorological data required for the calculations were derived from the datasets described in "2.2 Datasets".

(11) L188: Please explicitly describe how lake precipitation and lake evaporation are determined, including data sources and assumptions.

Response: We clarified the sources of lake surface precipitation and evaporation in the

"2.3.3 Lake System Response Linkage" section. Meteorological variables (such as temperature, wind speed, etc.) required for calculating lake surface precipitation and evaporation were derived from the CRU JRA v3.0 climate dataset. We assumed that the meteorological conditions on the lake surface were consistent with the neighboring grid data.

(12) L191: For the level-to-area conversion, please provide the conversion function or a plot of the hypsometric relationship. Additional methodological details from Wang et al. (2022) should also be summarized.

Response: Thank you for your suggestion. We have added Figure A2 to the appendix, showing the water level-area-storage capacity curve of Lake Balkhash, which is derived from Myrzakhmetov et al. (2022). Meanwhile, in the main text, section "2.3.3 Lake System…", we directly present the formula for calculating lake water volume changes (Equation 5), which originates from Zhang et al. (2013), and its applicability in this region has been verified by previous studies.

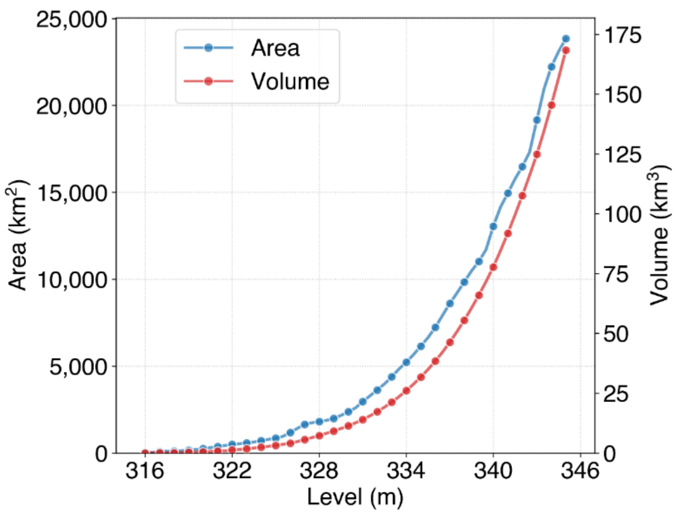

Figure A2. Stage-area and stage-volume relationships for Lake Balkhash. The blue line represents the relationship between water level and surface area (left axis), while the red line indicates the relationship between water level and storage volume (right axis). Data derived from Myrzakhmetov et al. (2022).

(13) L207: This equation appears to repeat a previous one; please update to the correct formulation.

Response: We sincerely apologize for this oversight. The formula was indeed repeated in the original manuscript. We have checked and corrected the error here, ensuring that the formula numbers and contents in the manuscript are correct. The correct formula is as follows: $\Delta V_h = \Delta Q_h$

(14) L239: Please be precise about which input data are used here and repeat the product names (either here or in the Methods; see also comment above).

Response: We have clearly defined the input data used for model parameterization in section "3.1 Hydrological Model Performance Evaluation": "Parameterization of the process-based SEGSWAT+ module was conducted by integrating the topographic, soil, and land use datasets described in Section 2.2."

(15) L274: Please clarify how the deltaic water consumption method works and which data sources are used.

Response: We have provided a more detailed explanation of the method for calculating delta water consumption. In section 3.2 Quantification of the Impacts..., we explained that "Deltaic water consumption was estimated using the empirical function derived by Xie et al., (2011), which correlates water losses with inflow volume based on historical observations (detailed equation provided in Appendix equation C1)." We have added Appendix C to fully present the empirical formula proposed.

C1. Estimation of Deltaic Water Consumption

According to Xie et al., (2011), the annual water consumption in the Ili Delta (Y_i) is estimated using a multi-linear regression framework based on lake levels, river discharge, and hydro-climatic variables. The empirical equations are defined for two distinct historical periods to account for changes in the delta's eco-hydrological state:

$$Y_i = 540.5868 - 2.2890X_{i-1}^{bl} - 0.2976X_i^{be} - 0.0684X_i^{U_1} + 0.0062X_i^{U_2} + 0.0191X_i^{U_3} - 0.1496X_i^{U_4} + 0.0296X_i^{U_5} + 0.0036X_i^{U_6} + 0.0303X_i^{U_7} + 0.0308X_i^{U_8} - 0.0453X_i^{U_9} - 0.0506X_i^{U_{10}} + 0.0876X_i^{U_{11}} - 0.0051X_i^{U_{12}} + 0.2074X_i^{R} + 25.0280X_i^{T}$$

Variable Definitions and Units:

Y_i: Annual water consumption of the Ili Delta in year i(10^8m^3);

X_{i-1}^{bl}: Water level of Lake Balkhash in the preceding year ($i-1$, in meters);

X_i^{be}: Total open-water evaporation of Lake Balkhash from May to September in year i (10^8m^3);

$X_i^{U_1}$ ... $X_i^{U_{12}}$: Monthly river discharge from January to December at the Ushzharma hydrological station in year i (10^8m^3);

X_i^R: Total precipitation in the delta from May to August in year i (mm);

X_i^T: Average air temperature in the delta from May to August in year i (°C).

(16) L276: The multi-step procedure is not sufficiently clear. Moreover, using the same parameter set (including snow and glacier module parameters) calibrated for an early period (1931–1969) may not account for climate-driven changes in snow and glacier dynamics in later decades. As a result, the naturalized streamflow may implicitly assume pre-1970 climatic conditions, despite substantial climate change in more recent decades. This assumption and its implications should be discussed.

Response: As in the detailed response to General Comment 6, we fully recognize the importance of this methodological assumption and have discussed it in depth and frankly in section 4.2 Cryospheric Dynamics and Methodological Limitations, analyzing its potential impact on the final conclusions (i.e., making the conclusions more conservative).

(17) L279: For how many years does this apply? An overview figure showing data availability by year and tributary would be helpful.

Response: This is a good suggestion. To clearly demonstrate the availability of observational data, we have listed the start and end years and time resolutions of the observations for each of the 16 hydrological stations in Appendix Table B1, allowing readers to easily understand the data coverage for each period.

(18) Figure 6: The term "real runoff" is confusing and potentially misleading (e.g. with respect to observed values). Please revise this terminology. In addition, "inflow" may be more appropriate than "runoff" here and throughout the manuscript.

Response: Thank you for your suggestion. We have revised "Real Runoff" in the figure to the more accurate "Actual Inflow" and maintained consistency throughout the text.

(19) L296: What evidence supports the statement regarding "more extreme events"? Please clarify or provide supporting references or analysis.

Response: This is a good question. Regarding the statement "increased extreme events," our original intention was to refer to the intensification of interannual hydrological variability. To make the statement more rigorous, we have revised it to "...increased inter-annual variability," a conclusion directly based on the larger range of fluctuations shown in our reconstructed runoff series (as shown in Figure 7) during the P3 period.

(20) L284–295: The reported values in $km^3\ yr^{-1}$ do not appear to correspond to the absolute values shown in Figure 6; please check for consistency.

Response: Thank you for the reviewer's careful review. You are correct; the km^3/yr values in the original manuscript refer to the annual average variation between different periods, not the absolute values shown in Figure 6. We have carefully checked and confirmed the accuracy of the values and ensured this in the text of the "3.2 Quantification…" section to avoid ambiguity.

(21) Table 3: Does x represent precipitation (P) here? If so, please replace x with P and add units to the relevant columns.

Response: I apologize for the ambiguous notation. x_i in the table represents the change in each driving factor (rainfall, snowmelt, glacial meltwater, ET_0), not just precipitation. For clarity, we have explicitly listed these factors in the first column, "Component," of the table. dQ/dx represents the sensitivity of runoff to changes in this factor. We have checked and ensured the clarity of the table content.

(22) L341: Please provide the exact sources of the water level and lake area data. What data are used prior to the remote-sensing period? Also indicate the data sources explicitly in the caption of Figure 8.

Response: We have clearly stated the sources of the water level and area data in the "2.2 Datasets" section and the caption of Figure 9 (formerly Figure 8): historical data (up to 2015) comes from Duan et al. (2020), and recent data (2016-2024) comes from G-REALM satellite altimetry products. The reconstructed water volume change (ΔV) used for validation is calculated based on these observational data.

(23) L364: For additional context, it would be useful to provide an estimate of basin-wide warming over the study period.

Response: This is a good supplementary suggestion. In the section "3.3 Lake System Response…", we added a quantitative description of the overall warming trend of the basin: "...it is noted that the basin has experienced a significant warming trend over the study period (1931-2024), with mean annual temperatures increasing by approximately 0.30 °C/decade ($p<0.001$)…"

(24) Figure 11: would the lake dry up in the most extreme scenario? What is the uncertainty?

Response: This is a very important question. Regarding whether the lake will dry up and the related uncertainties, we have provided supplementary explanations in “3.4 Changes in Lake Water Levels…” and the Discussion section. Our predictions show that the lake will not completely dry up by 2100, but a drop in water level of 2.5-4.0 meters will lead to serious ecological consequences, such as the separation of the eastern and western parts of the lake basin and a sharp increase in salinity, similar to the tragedy of the Aral Sea. In the section “4.3 Future Vulnerabilities and Uncertainties”, we also discussed in detail the uncertainties brought about by GCM predictions and the timing of “peak water”.

Textual comments

(1) L117: Please verify whether the dataset is CRU JRA v3.5 rather than v2.5.

Response: We verified and confirmed that the dataset used is CRU JRA v3.0 and corrected it in the text.

(2) L134: Missing H in the AAF flowchart; please also check figure caption font consistency.

Response: We corrected spelling errors in figure captions and standardized the font style.

(3) L136: PIML is used without being introduced (already appears in L60).

Response: We provided the full name and explanation when PIML first appeared (now changed to "hybrid model").

(4) L143–145: Sentence is missing a main verb; please also repeat the input data products used for each variable.

Response: We corrected the grammatical error in this sentence and clearly listed the model inputs.

(5) L169–170: Use P instead of x to avoid confusion.

Response: We standardized the symbols in formulas and text.

(6) L174: Equation 1 uses E, while ET is used elsewhere—please ensure consistency.

Response: We standardized E in formulas to ET used in the text.

(7) L207: Equation is repeated; please update to the correct formulation.

Response: We corrected duplicate formulas.

(8) L292: At this stage, attribution should not yet be stated, as the corresponding analysis follows later.

Response: We adjusted the wording to ensure that conclusive language is not used before attribution analysis.

(9) L297 and L371: Consider adding a white line or spacing to better delineate paragraphs.

Response: We have adjusted the paragraph formatting to improve readability.

(10) L341: Please provide exact sources for water level and lake area data and indicate these explicitly in the caption of Figure 8.

Response: We have clarified the data sources in the figure captions and methods sections.

(11) L392: Replace "quantify" with the appropriate verb for clarity.

Response: We have corrected the verb usage in this section.

Thank you again for your time and effort in improving the quality of our paper. We hope these revisions meet your expectations.

References

Duan, W., Zou, S., Chen, Y., Nover, D., Fang, G., and Wang, Y.: Sustainable water management for cross-border resources: The balkhash lake basin of central asia, 1931–2015, J Cleaner Prod, 263, 121614, https://doi.org/10.1016/j.jclepro.2020.121614, 2020.

Harris, I.: CRU JRA v3.0: A forcings dataset of gridded land surface blend of Climatic Research Unit (CRU) and Japanese reanalysis (JRA) data; 1901 - 2024., 2025.

Myrzakhmetov, A., Dostay, Z., Alimkulov, S., Tursunova, A., and Sarsenova, I.: Level regime of balkhash lake as the indicator of the state of the environmental ecosystems of the region, Paddy Water Environ, 20, 315–323, https://doi.org/10.1007/s10333-022-00890-x, 2022.

Xie, L., Long, A., Deng, M., Li, X., and Wang, J.: Study on Ecological Water Consumption in Delta of the Lower Reaches of Ili River, Journal of Glaciology and Geocryology, 33, 11, 2011.

Zhang, G., Xie, H., Yao, T., and Kang, S.: Water balance estimates of ten greatest lakes in China using ICESat and landsat data, Chin. Sci. Bull., 58, 3815–3829, https://doi.org/10.1007/s11434-013-5818-y, 2013.

Zhang, X., Zhao, T., Xu, H., Liu, W., Wang, J., Chen, X., and Liu, L.: GLC_FCS30D: The first global 30 m land-cover dynamics monitoring product with a fine classification system for the period from 1985 to 2022 generated using dense-time-series landsat imagery and the continuous change-detection method, Earth System Science Data, 16, 1353–1381, https://doi.org/10.5194/essd-16-1353-2024, 2024.