Responses to comments from anonymous Reviewer #1

On "Assessing the different components of the water balance of Lake Titicaca" by Nilo Lima-Quispe Denis Ruelland, Antoine Rabatel, Waldo Lavado-Casimiro, and Thomas Condom.

General comments

The manuscript presents a water balance modeling chain for Lake Titicaca, simulating various water balance components, including precipitation, evaporation, inflow (considering irrigation water abstraction and glacial contributions), and outflow. The model effectively closes the water balance and quantifies the contributions of these components. Notably, the authors find that glaciers and irrigation water abstraction have a minimal impact on the overall results.

We would like to sincerely thank the referee for the time and effort she/he spent reading the initial manuscript and for making many clear, pertinent and constructive suggestions for improvement. This greatly helped to highlight the novelty and ensure clarity of the paper. Comments are shown in black text, while our responses appear in blue, with suggested modifications emphasized in *blue italics*.

The manuscript is interesting, well-written, detailed, and comprehensive and of interest for publication in HESS. However, the text is at times overly lengthy and repetitive, particularly in the methods and results sections. Condensing the content without sacrificing critical information and possibly moving some material to supplementary sections would enhance clarity and focus. In addition, the level to which the presented manuscript is build upon and novel to Lima-Quispe et al., 2021 in terms of methods applied can be made a bit more explicit. To aid the authors with this, detailed comments and suggestions are provided below.

We have carefully addressed the comments. Our responses can be found in the sections for general and specific comments.

Major Comments

- The manuscript concludes that glaciers and irrigation have a minor impact on the water balance. Given this finding, the detailed analysis of these components could be relocated to the appendix to streamline the manuscript.

  A specific objective is to evaluate the hydrologic sensitivity of upstream inflow predictions (including lake water level variations) to net irrigation withdrawals as well as snow and ice processes. The findings indicate that these factors have minimal impact. Nevertheless, this could be demonstrated precisely because these factors were considered in the modeling chain. However, we acknowledge that certain details related to data, methods, and results may affect the readability of the article. To address this, we propose the following changes:

  - **Materials:** Sentences referencing the Zongo glacier have been moved to the appendix. We have also shortened the sections on agricultural characteristics and irrigation management.
  - **Methods:** The procedure for obtaining snow and ice model parameters using the Zongo catchment has been moved to the appendix.
  - **Results:** We have shortened the paragraphs discussing the performance of the snow and glacier model compared to the geodetic mass balance.

- The manuscript builds on the model presented by Lima-Quispe et al., 2021. For example, the climatological data used (from the GMET tool) are very similar. This should be more clearly described in the manuscript, taking Lima-Quispe et al., 2021 as a starting point and not presenting already published methods as novel. The authors should more explicitly differentiate their work from the previous study, highlighting the findings of the former, and showcasing how the current study builds upon it. The novelty is already highlighted to some extent, for example by articulating the contribution of a detailed glacier method. However, the direct contributions from this have very little impact on the final results. Seen both studies are authored by the same first author, a direct comparison between the results of both studies, possibly through a figure, would further clarify the advancements made in the current study (for example, figure 6 of Lima-Quispe et al., 2021 is very similar to Fig 10 of the current paper).

We acknowledge that the current study utilizes some models from the WEAP platform previously presented by Lima-Quispe et al. (2021) at a monthly time step. There is also overlap in the precipitation and air temperature data (from the GMET tool), as well as in the irrigable area data on the Bolivian side. In terms of methods, there is overlap in the rainfall-runoff model (Soil Moisture Model), but in the current study, we simulate at a daily time step and employ a different approach to simulate irrigation water allocation as well as a snow and ice module which were not used in the first study, making it impossible to estimate the contribution from snow melt and ice melt to lake water level's variations. Additionally, to apply the model at the daily time step, it was necessary to collect new data updated to the required time scale. Furthermore, new data, such as lake bathymetry and irrigable area on the Peruvian side, became available.

We also acknowledge that, in the submitted version of the manuscript, we have not sufficiently highlighted the novelty of our study compared to the previous work by Lima-Quispe et al. (2021). A significant limitation of the previous study is that the authors applied a scaling factor to precipitation, in combination with calibrating the constant of a power function ($f(x) = ax^b$) to estimate the rating curve for lake outflows in an attempt to close the lake's water balance. For instance, Equation 1 in Lima-Quispe et al. (2021) does not account for the error or residual term in the water balance. We believe that applying scaling factors introduces additional uncertainty. A reliable water balance should close with a very small error or residual, without the need for scaling factors (Rientjes et al., 2011; Vanderkelen et al., 2018). Other limitations of the Lima-Quispe et al. (2021) study that we can highlight are:

1. The omission of snow and ice processes, which may play a crucial role in this high mountain region. To date, no study has assessed the impact of snow and ice melt on lake water level fluctuations. For instance, during periods of water level decline, some stakeholders often attribute this to glacier retreat and irrigation water withdrawals. Therefore, assessing the hydrologic sensitivity to these processes is essential.
2. Estimating evaporation using the Penman method, without accounting for changes in heat storage. Additionally, the authors estimated the lake surface water temperature (LSWT) by simply adding a delta value to the air temperature. Given that Lake Titicaca is located at an average altitude of 3810 m a.s.l., radiation plays a crucial role in the lake's physical and chemical processes. Therefore, it is essential to consider both LSWT and changes in heat storage. Since evaporation is the largest component of the water balance, special attention must be given to estimating it as accurately as possible, using available data, whether through in situ measurements, remote sensing, or reanalysis.
3. The use of historical monthly averages (humidity, wind speed, and incoming solar radiation) to estimate evapotranspiration and reference evaporation, without accounting for interannual variability. In light of ongoing climate change, it is crucial to consider temporal

variations in these variables. This could have significant implications for evaporation estimates and, consequently, the accuracy of the water balance. While data in the region are scarce, reanalysis data can now be used to improve these estimates.

One of the main novelties of our study is that the modeling approach allows us to close the water balance of Lake Titicaca with a very small error, without the need to apply scaling factors. The daily water levels simulated over the period 1982–2016 show acceptable performance. In the following figure, we present a comparison (at a monthly time step) of the water level simulations from our study and those of Lima-Quispe et al. (2021), without applying a scaling factor to the precipitation over the lake. As shown, the simulations by Lima-Quispe et al. (2021) without the scaling factor result in unrealistic water levels, mainly after 2000. For this reason, the authors increased the precipitation in an attempt to close the water balance.

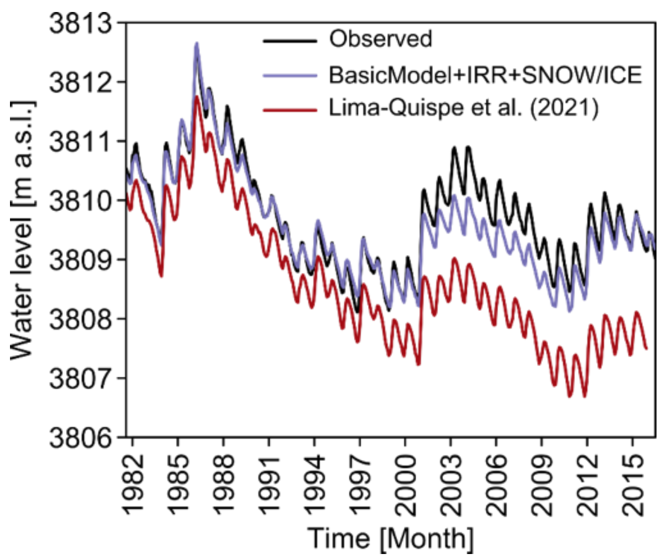


Figure 12. Comparison of simulated water levels by BasicModel+IRR+SNOW/ICE (aggregated to monthly time step) with those obtained by Lima-Quispe et al. (2021) without applying the scaling factor to the precipitation over the lake.

Our modeling framework benefits from the following: (i) a rigorous calibration and evaluation procedure to simulate upstream inflow (ii) the estimation of lake evaporation using the Penman method, which accounts for LSWT (estimated using a combination of a conceptual model and remotely sensed data) and heat storage; and (iii) estimates of reference evapotranspiration and lake evaporation that capture climate variability using the ERA5-land dataset for humidity, wind speed and solar radiation.

Another novelty is that we demonstrate that net irrigation withdrawals and snow and ice melt have minimal influence on water level variations. We also disentangle the role of changes in heat storage in estimating evaporation.

For the reasons stated above, our modeling approach is innovative, though it does share some overlaps in specific models (soil moisture model) and input data (GMET and irrigable area in the Bolivian side).

To address the reviewer's comment, we propose the following changes:

- In the Introduction section, before the objectives, we added a section introducing Lake Titicaca, where we mention the previous study and its limitations in order to better contextualize and highlight the novelty of our study.
- In the Methods section, we acknowledge the overlaps in methods and data with the previous study (Lima-Quispe et al. 2021).
- In the Discussion section, we clearly present the novel aspects of our study in comparison to the previous one.

The changes in the text are reflected in our responses to the specific comments.

- The manuscript would benefit from a more concise presentation. Repetitions, and lengthy wordings in the introduction, methods and results should be reduced.

  Agreed.

  We acknowledge that the initially submitted version was sometimes repetitive and lengthy. We have identified and removed the repetitions and shortened certain paragraphs to make it more concise. We propose the following changes:

  - **Introduction:** This section was originally about 2,400 words, now reduced to 1,900 words. Section 1.2 (Methods to estimate the individual components of a lake water balance) was too long and has been shortened. We also removed Section 1.3 (Integrated water balance in large lakes) and instead introduced Lake Titicaca by explaining why this study area was chosen and addressing the limitations of previous studies.
  - **Materials:** The original version had about 2,700 words, now reduced to 1,700 words. Some paragraphs related to the context of Lake Titicaca were moved to the Introduction section. We also shortened the sections related to irrigation. Details on the evaluation of the ERA5-Land and Zongo Glacier data were moved to the Appendix.
  - **Methods:** Initially 4,300 words, now reduced to 3,500 words. Sections related to the modeling of the Zongo catchment and LSWT have been moved to the Appendix.
  - **Results:** Originally 3,000 words, now reduced to 2,600 words. We shortened the glacier model performance section and removed repetitions.
  - **Discussions:** Originally 2,800 words, now reduced to 2,200 words. We removed sentences that were already mentioned earlier in the text.

- Abstract and Introduction: The introduction currently provides a broad overview of large, poorly gauged lakes, but since the focus is on Lake Titicaca, it should be emphasized from the outset. The introduction would benefit from a revision to prioritize the unique aspects of Lake Titicaca, with general information on lakes serving as background rather than the main focus. The description in the introduction of lakes in general terms could be condensed, with more specific examples of how different lakes' conditions can vary. This will help contextualize the study's focus on Lake Titicaca.

  We agree it is appropriate to introduce Lake Titicaca earlier in the Introduction section. We have thus reorganized the Introduction according to the following sections:

  - **1.1 On the need for an integrated water balance in large lakes:** We discuss variations in lake water levels and emphasize the need to estimate water balances that account for both natural flows and water management to better understand the drivers of these variations. We then introduce the concept of integrated modeling and highlight how it differs from traditional approaches.

- **1.2 Challenges in estimating the water balance of large lakes:** We outline the challenges involved in estimating the individual components of the water balance, which is essential for placing our research within a broader context.
- **1.3 Placing Lake Titicaca in the context of an integrated water balance:** We introduce Lake Titicaca, focusing on its unique characteristics and the challenges it faces. We also describe the lake's fluctuations and the need for a reliable water balance to support decision-making. Additionally, we present the previous study by Lima-Quispe et al. (2021) and highlight its limitations.
- **1.4 Scope and objectives:** We present the research questions and objectives.

We hope these changes address the reviewer's comment.

Specific comments:

L42: Specify which lakes are being referred to as "many lakes."

Agreed. The sentence has been modified to: *"…For example, it has been observed that direct precipitation over the African Great Lakes is more intense than in their surrounding areas…"*

L81: Replace "water uses" with "water management" to include aspects like dam management, which could lead to differences in flow magnitude and seasonality.

Agreed. The change was made.

L84-86: Clarify and reformulate the example given.

This sentence was removed in order to reduce the Introduction and focus more on integrated modeling and Lake Titicaca.

L124: Clarify whether "net water withdrawals" refer to the lake itself.

Agreed. In this case, it refers to the contributing catchments. The sentence has been modified to: *"…Several studies on large lakes (>500 km2) (e.g., Rientjes et al., 2011; Vanderkelen et al., 2018; Wale et al., 2009) have estimated the water balance under the assumption that net water withdrawals in the contributing catchments are negligible…"*

Section 1.4: Explain why Lake Titicaca was chosen for this study and what value the water balance study brings to lake managers.

Agreed. To address this comment, we have reorganized and condensed the content of the Introduction. We created a new Section 1.3 (before the objectives and scope) to introduce Lake Titicaca. In this section, we justify the selection of the study area by highlighting that it is a poorly gauged, transboundary lake with complex water management challenges that require a reliable water balance estimate. Information previously presented in the study area section was used to write this paragraph.

The proposed paragraph is presented here: *"Lake Titicaca, located on the Altiplano of the tropical Andes of South America, is one of the highest large lakes in the world and an interesting case study for an integrated water balance. This lake is part of a vast endoreic catchment, and is connected by the Desaguadero River to Lake Poopo in Bolivia (Lima-Quispe et al., 2021). As a transboundary lake shared by Peru and Bolivia and a poorly-gauged hydrosystem, it faces many of the aforementioned challenges. The region experiences significant interannual climate variability (Garreaud and Aceituno, 2001), which, coupled with complex water management issues (Revollo, 2001), intensifies the difficulties of managing Lake Titicaca. These* *challenges include extreme hydrological events (droughts and floods), lake releases, and water pollution (Revollo, 2001; Rieckermann et al., 2006). Water levels measured in Puno (Peru) have fluctuated by approximately six meters over the past century, with the lowest recorded in 1943–1944 and the highest in 1984–1986 (Sulca et al., 2024), causing US$125 million in flood damage (Revollo, 2001). In response to these challenges, a management plan was developed in the early 1990s for both Lake Titicaca and the Altiplano hydrosystem (Revollo, 2001). A key component of this plan was the construction of an outflow gate to regulate lake releases and the establishment of operating rules. Although the outflow gate was completed in 2001, lake releases remain nearly the same as under natural conditions because the operating rules have not yet been implemented. Addressing these water management challenges requires an accurate integrated water balance allowing a better knowledge on the drivers of the lake water level variations."*

L155: Introduce Lima-Quispe et al., 2021 earlier in the introduction, detailing its findings and limitations.

Agreed. To address this comment, we have reorganized the contents of the Introduction. This involved reducing the length of several paragraphs. Specifically, we have added a new paragraph before the objectives and scope, where we discuss the limitations of the study by Lima-Quispe et al. (2021). This revision helps better position our study in relation to previous research.

Here is the new paragraph: *"Unlike other large lakes, very few studies have been conducted on Lake Titicaca. The only study that modeled the water balance of Lakes Titicaca and Poopó was the one by Lima-Quispe et al. (2021) using the Water Evaluation and Planning System (WEAP) platform with a monthly time step for the period 1980–2015. The study aimed to distinguish the relative contributions of climate and irrigation management on water level fluctuations. However, the modeling approach proposed by the authors has a significant limitation because it is based on a scaling factor for precipitation over the lake to close the water balance, which clearly introduces additional uncertainty. Other methodological shortcomings include: (i) the omission of snow and ice processes, which can play a non-negligible role in this high-elevation region; (ii) the estimation of evaporation using the Penman method, without accounting for changes in heat storage; and (iii) the use of historical monthly averages (humidity, wind speed and incoming solar radiation) to calculate reference evapotranspiration and evaporation, without considering interannual variability."*

L161: why is this an "integrated" water balance approach and what is the difference with a normal water balance approach?

To address this comment, we have added a paragraph defining integrated water balance modeling:

"In large lakes, it is essential to adopt integrated water balance modeling, which represents the interactions and feedbacks between natural hydrological processes and water management within a single modeling framework (Niswonger et al., 2014). Unlike traditional decision support systems applied to large lakes (Hassanzadeh et al., 2012), which typically simulate natural flows and irrigation water requirements independently, integrated modeling enables these processes to be simulated in a coupled and dynamic manner."

L169: Include the lake's surface area.

Agreed. Although the lake area was mentioned at the beginning of the study, we believe it was not entirely clear. To clarify, we have revised it to: "*Lake Titicaca, located at 3,812 m a.s.l. on the Altiplano of the tropical Andes of South America, covers an area of approximately 8,340 km^2 and spans the borders of Peru and Bolivia."*

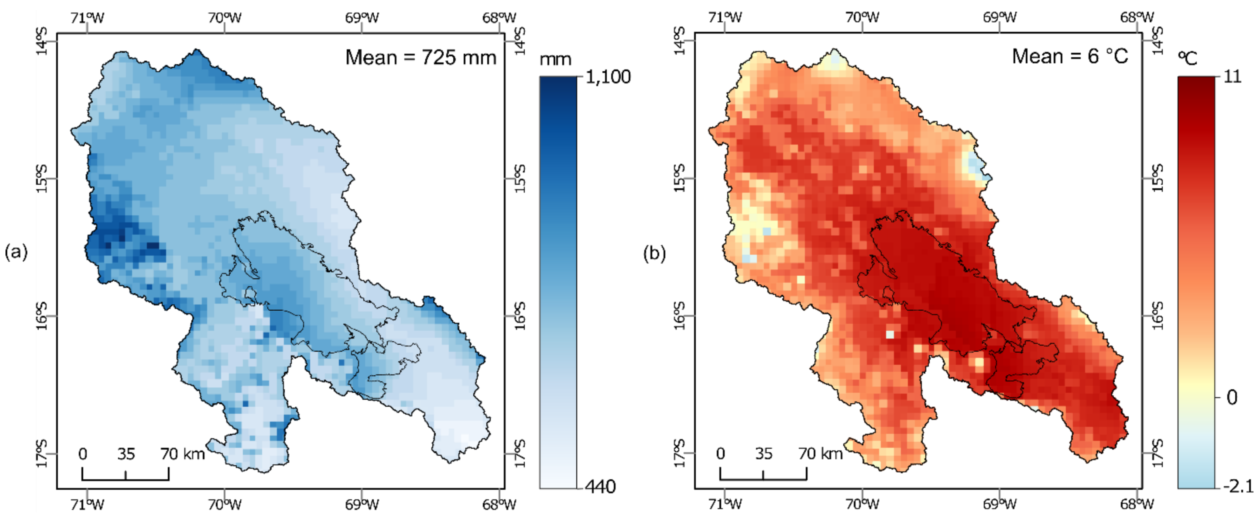
Section 2.2: Acknowledge the methodological overlap with Lima-Quispe et al., 2021.

Agreed. We did use the same set of precipitation and air temperature data. We have clarified this in the text with the following modification:

"...It is based on a probabilistic method using ground station data (for more details see Clark and Slater (2006), and Newman et al. (2015)). Lima-Quispe et al. (2021) used the same data."

Figure 2, panel b: Adjust the color bar to ensure white corresponds to zero or use a sequential color bar.

Agreed. To address the reviewer's comment, the figure has been modified using diverging colors, with yellow corresponding to zero Celsius degree. Here is the revised figure:



L252: Explain "Crop coefficient Kc" when first introduced; consider moving this to the methods section.

Agreed. We have moved the sentence related to "Crop coefficient Kc" to the Methods section, where the irrigation modeling approach is presented. The revised text is as follows:

"In SMM, water requirements (WR) for irrigation are determined by crop evapotranspiration (calculated from seasonal crop coefficients (Kc) and reference evapotranspiration) and the depletion of available water in the root zone store (see Fig. 4). Kc adjusts the reference evapotranspiration (ET0) to reflect crop-specific characteristics, such as phenology (Allen et al., 1998). It was derived using cropping calendar and crop type data (Autoridad Nacional del Agua, 2009, 2010; Instituto Nacional de Estadística, 2015)."

L347: Clarify what is meant by "production."

Agreed. Production (as well as routing) is a commonly used term in conceptual hydrological modelling. However, to address the reviewer's comment and make the purpose clearer, the sentence has been modified as follows: *"...the processes contributing to the generation and regulation of water storage and water flow in the catchments..."*

L445: Specify if LSWT time series availability is meant here.

Agreed. We have modified the text to include the following sentences: *"Since there are no long-term measurements of lake surface water temperature (LSWT) and the remotely sensed data sets do not cover the entire study period, the Air2Water model (Piccolroaz et al., 2013; Toffolon et al., 2014) was used to simulate LSWT."*

Additionally, details on the LSWT simulation have been moved to the appendix to improve conciseness.

L475: Replace "assessment" with "evaluation."

Agreed. The word was changed.

Models A, B, C: Consider renaming these to something more descriptive (e.g., IRR+GLAC) to avoid repetitive explanations and ease the figure interpretations.

Agreed. We have renamed the three modeling options as follows: *"…Three model structures were tested under the following configuration: (i) BasicModel+IRR+SNOW/ICE, which represents the full reference model structure (as shown in Fig. 4); (ii) BasicModel+IRR, where the processes associated with snow and ice (accumulation and ablation) are excluded, but irrigation is maintained; and (iii) BasicModel, where both snow and ice processes and irrigation consumption are excluded…"*

Changes reflecting these revisions have been made throughout the text, as well as in the figures and tables.

L568-573: Rewrite these sentences to be more concise.

Agreed. We have refined the writing to make it more concise. The modified sentences are:

"… The scatter plots reveal significant variability in model performance, with some glaciers (represented by each point) close to the identity line and others deviating significantly. The model simulates a more negative mass balance compared to the geodetic mass balance. Figure 7a displays glaciers according to their surface area, while Figure 7b shows them based on their mean elevation…".

Note that the numbering of the figures has been adjusted because some were moved to the appendix.

L595: Indicate in the figure caption that it deals with "glacier" mass balance; same for Table 4.

Agreed. Both the figure caption and the table have been clarified regarding glacier mass balance. For example:

"Figure 7. Scatter plots comparing simulated and geodetic glacier mass balance for 2000–2009, based on the remotely-sensed observations from Hugonnet et al. (2021). Dot size represents (a) glacier area and (b) mean elevation. The dashed line indicates the identity line, while the gray line represents the error in geodetic glacier mass balance".

Figure 8: Highlight in the text that variability between glaciers for simulated mass balance is greater than for geodetic mass balance. What would be a possible explanation?

Agreed. We have highlighted the following in the text:

"… The scatter plots show significant variability in model performance, with some glaciers (represented by each point) distributed close to the identity line and others deviating significantly. The model simulates a more negative glacier mass balance compared to the geodetic glacier mass balance…"

Regarding possible explanations, we have added:

"…The notable variability in model performance (Fig. 7b) could be attributed to inaccuracies in precipitation data for some catchments, as estimating precipitation in high-elevation remote areas remains a complex challenge (Ruelland, 2020)".

Please note that the numbering of the figures has been adjusted because some were moved to the appendix.

L614-615: Remove or shorten this sentence, as it is likely repeated later. There is no need to refer to the next section in the last sentence of the current section.

Agreed. Sentences were removed.

Fig. 12: add the "mm/year and mm/month" to the numbers in the legend, or alternatively, put the numbers in a separate table would allow to compare them more clearly.

Agreed. We believe that both suggestions help to clarify and better highlight our results. We have added the units to the figure and included a table with the values of the water balance components.

The modified figure is shown here:

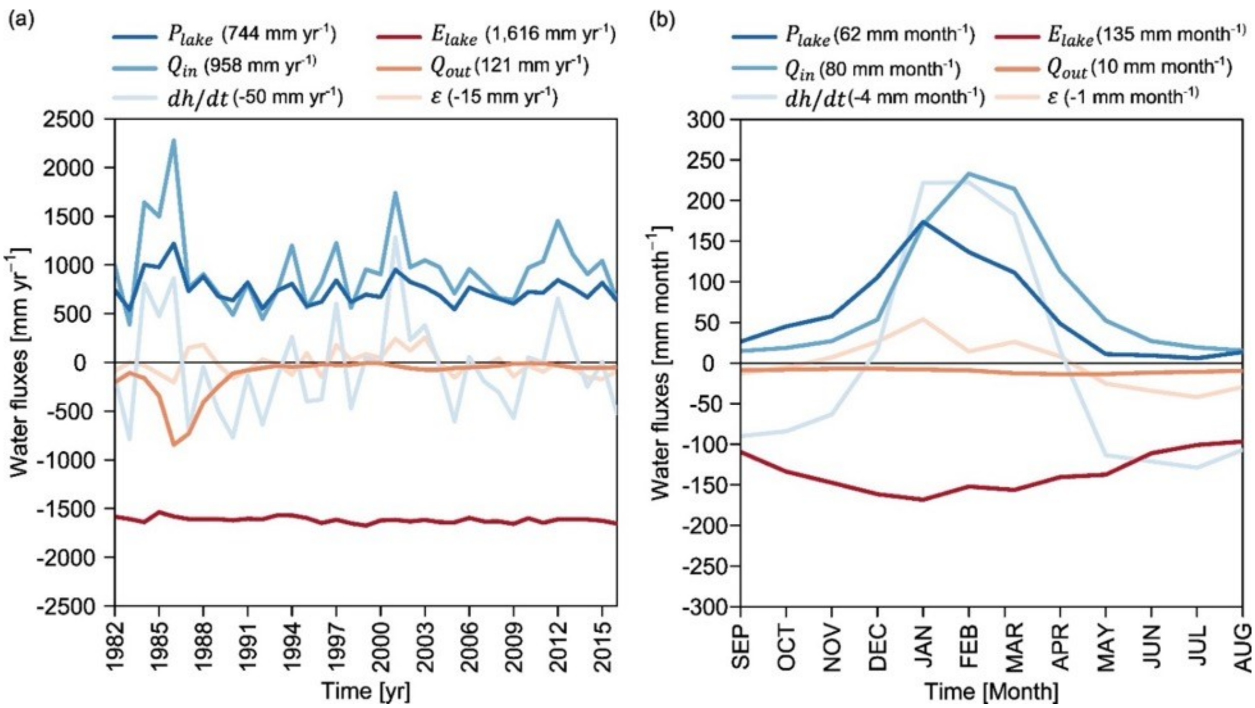


Figure 11. Water balance of Lake Titicaca for the period 1982–2016 in terms of (a) interannual variability and (b) seasonal cycle. The values in parentheses correspond to the mean annual or monthly values for the period 1982–2016. The lake water balance follows the equation $\boldsymbol{P_{lake} + Q_{in} - E_{lake} - Q_{out} - dh/dt + \varepsilon = 0}$.

The new table added is as follows:

Table 5. Lake Titicaca water balance components simulated for the period 1994–2003. The lake water balance follows the equation $\boldsymbol{P_{lake} + Q_{in} - E_{lake} - Q_{out} - dh/dt + \varepsilon = 0}$.

Components	mm yr-1	mm month-1
P_{lake}	744	62
Q_{in}	958	80
E_{lake}	1,616	135
Q_{out}	121	10
dh/dt	-50	-4
ε	-15	-1

Section 4.2.2: It would be useful to include the relative contributions of different water balance terms in the main text, as referred to in the abstract.

Agreed. Previously, we only provided relative water balance values for a few components. We have now included values for both inputs and outputs. Below are the updated details:

"This means that 44% of the inflows come from direct precipitation over the lake, while the remaining portion (56%) comes from the upstream catchments. Regarding outflows, annual evaporation from the lake is 1,616 mm (σ = 28 mm), and the downstream outflow is 121 mm (σ = 191 mm). Thus 93% of the losses are due to evaporation and 7% are due to downstream outflow."

Section 5.1: This section contains significant repetition and should be condensed.

We recognize that this section contained many repetitions and that the new findings need to be clearly differentiated from the study of Lima-Quispe et al. (2021). The first paragraph of this section has been rewritten as follows:

"5.1 Main findings

This study presents three main novelties. First, our integrated modeling framework accurately simulates the daily water balance of Lake Titicaca without requiring scaling factors. Consequently, the propagation of uncertainty in estimating components of the water balance is significantly reduced. For instance, Figure 12 illustrates how omitting the calibrated precipitation scaling factor used by Lima-Quispe et al. (2021) leads to unrealistic simulations of lake water levels. Our modeling approach also benefits from: (i) a rigorous calibration and evaluation procedure for simulating upstream inflows; (ii) the estimation of evaporation from the lake using the Penman method, while accounting for lake surface water temperature (LSWT) and heat storage; and (iii) estimates of reference evapotranspiration and lake evaporation that accounts for climate variability, using ERA5-land dataset for humidity, wind speed, and solar radiation. This study provides a realistic water balance that estimates most hydrologic processes (see Table 4 and Table 5), although the role of groundwater remains a major unknown. Its magnitude is expected to be a small component of the total water balance.

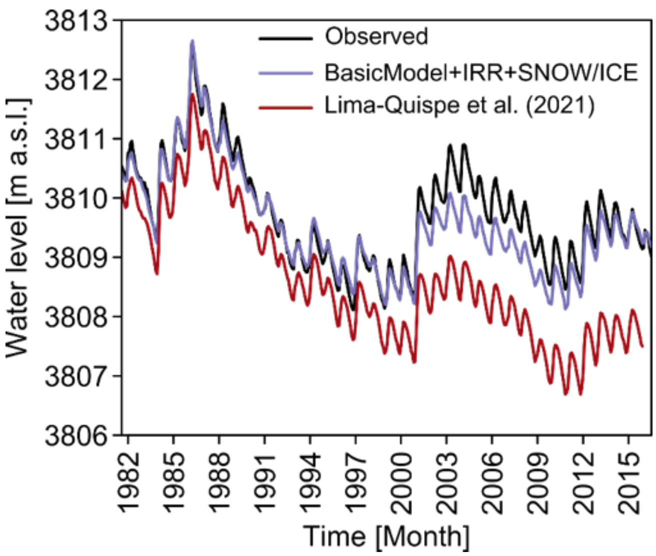


Figure 12. Comparison of simulated water levels by BasicModel+IRR+SNOW/ICE (aggregated to monthly time step) with those obtained by Lima-Quispe et al. (2021) without applying the scaling factor on precipitation over the lake.

Second, through the hydrologic sensitivity analysis, we demonstrate that net irrigation withdrawals and snow and ice melt have minimal impact on lake level fluctuations, indicating that it is primarily driven by rainfall and evaporation variability. However, this does not diminish the importance of glaciers. In fact, glaciers are significant at the scale of the headwater catchments, particularly for supplying water to large cities such as El Alto and La Paz (Buytaert et al., 2017; Soruco et al., 2015), maintaining wetlands like the bofedales (Herrera et al., 2015), and supporting irrigation (Buytaert et al., 2017). In most gauged catchments, incorporating irrigation resulted in only slight improvements in modeling performance. Nonetheless, this approach made it possible to estimate the net consumption due to irrigation at the scale of the catchments that contribute to the lake. Although this consumption is currently low, it is expected to increase significantly due the climatic and anthropogenic changes in the study area. It should also be noted that this process was based not only on soil water deficit but also on local knowledge of farmers' water allocation practices.

Third, we disentangle the role of the change in heat storage in estimating E_{lake}. Annual evaporation (1,616 mm yr^{-1}) is comparable to the evaporation (~1,600) of other low-latitudes lakes (Wang et al., 2018) and aligns with previous studies of Lake Titicaca (~1,600) (Delclaux et al., 2007; Pillco Zolá et al., 2019). Despite the low air temperature over Lake Titicaca due to its high altitude, the evaporation rate is quite high. This is largely due to net radiation, although humidity, wind speed, and changes in heat storage also play a significant role in the seasonal variation. Regarding heat storage changes, the lake reaches maximum heat gain in October and the maximum heat loss in May (Fig. 13a). Neglecting changes in heat storage leads to overestimating evaporation during the lake's heating period and underestimating it during the cooling period (Fig. 13b). A similar finding was reported by Bai and Wang (2023) for Lake Taihu in China. Although several studies have investigated evaporation from Lake Titicaca using various methods (Carmouze, 1992; Delclaux et al., 2007; Pillco Zolá et al., 2019), our estimates are innovative because they are based on long-term data, including recent periods. Additionally, the accuracy of our estimates was underpinned by a water balance with a small error term, which enhances the reliability of our findings.

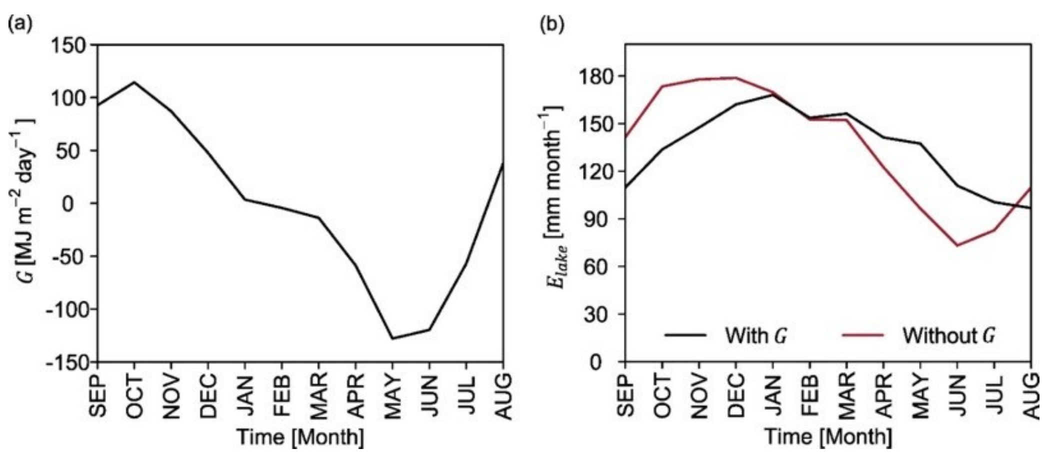


Figure 13. Seasonal variations in (a) heat storage and (b) the role of heat storage in seasonal variation of evaporation. Figures are based on long-term (1982–2016) average values.

The periods of rising and falling water levels are closely linked to direct precipitation over the lake and upstream inflows (see Fig. 11a), which is mostly influenced by interannual precipitation variability. Understanding the effects of climate oscillations on precipitation variability is therefore crucial for understanding water level changes. Some authors (e.g,. Garreaud and Aceituno, 2001; Jonaitis et al., 2021) noted that the interannual variability of precipitation in the region is mainly driven by the El Niño Southern Oscillation (ENSO). During its warm phase, conditions are typically dry, while during the cold phase, *conditions are usually wet, although this relationship is not always consistent (Garreaud et al., 2003). For instance, Jonaitis et al. (2021) observed negative precipitation anomalies during La Niña phase and positive anomalies during El Niño phases in the Lake Titicaca region, though these anomalies were not statistically significant. Segura et al. (2016) argue that El Niño plays an important role in interannual precipitation variability, and that decadal and interdecadal variations are influenced by sea surface temperature (SST) anomalies in the central-western Pacific. Therefore, variations in water level cannot be attributed to ENSO alone. Sulca et al. (2024) found that interannual variations in water levels are related to SST anomalies in the southern South Atlantic, and that interdecadal and multidecadal variability can be explained by Pacific and Atlantic SST anomalies. Additionally, they noted that multidecadal variations are linked to North Atlantic SST anomalies and southern South Atlantic SST anomalies."*

L736-740: the direct comparison and description of the added value of the present study with Hosseini-Moghari et al., 2020 is a repetition from the intro, and possibly redundant as they treat very different lake system (Urmia), moreover, there are more water balance studies of large lakes, such as Vanderkelen et al., 2020 and other studies included in the introduction.

Agreed. To avoid repetition, we have removed sentences referencing other lake references from different contexts. Instead we have focused on highlighting findings related to Lake Titicaca. The proposed changes are reflected in the previous responses.

L744-750: These lines contrast the following paragraph: here, the point is made the current study includes more detailed representation of snow and ice, and irrigation in the upstream catchments. In the next paragraph there is discussed that these components are of little importance to the water balance of the lake. While the manuscript proves its value of uncovering this, it should not be highlighted this clear in the text that it is an added value.

Agreed. To emphasize the inclusion of these processes, we have formulated a clear research question in the Scope and Objectives section, specifically to understand the sensitivity of water level fluctuations to natural and anthropogenic processes. It is precisely because processes related to snow and ice as well as irrigation were considered that it was possible to show that they had a minimal impact on the variations in the lake's water levels, which are primarily driven by rainfall and evaporation variability. It is worth noting also that, in the face of greater anthropogenic pressures, future irrigation could increase and net irrigation withdrawals may have a greater impact on lake fluctuations. As far as snow and ice processes are concerned, for the Achacachi catchment, the contribution of the total annual inflow (rainfall+snowmelt+ice melt) is 19% for the snowmelt and 7% for the ice melt. This means that snow and ice processes are not negligible in some catchments and at a more local scale even though their impact is limited on lake variations. Finally, we intend to use our integrated model to evaluate irrigation management and climate change scenarios to understand the potential impacts on water level fluctuations. The inclusion of these processes in the development of a water management tool is therefore justified.

Some of the issues were addressed in the Discussion section, highlighting as one of the novelties of the study:

"Second, through the hydrologic sensitivity analysis, we demonstrate that net irrigation withdrawals and snow and ice melt have minimal impact on lake level fluctuations, indicating that it is primarily driven by rainfall and evaporation variability."

L878-880: Is it really necessary to refine the glacier simulations as they are not important in the water level simulations?

This not necessary to consider this aspect at present, as its impact on lake fluctuations is minimal. However, it could become more important if we aim to evaluate future changes in glaciers and their potential impacts on specific catchments (e.g. Achacachi and Escoma). To address this, we have modified the sentence to: *"If it is intended to simulate future changes in glaciers, it may be beneficial to include morphometric changes in the model, drawing inspiration from simple approaches in the literature (e.g., Seibert et al., 2018). To initialize the model, global glacier thickness datasets could be used (e.g., Farinotti et al., 2019; Millan et al., 2022)."*

Section 5.3: how feasible is it to translate this modelling chain to another large lake? Also, what are the implications for Lake Titicaca of the presented results? This would be interesting to include in the papers abstract.

Agreed. To address these questions, we have added relevant sentences to Section 5.3 and the Abstract.

For the first question, the following sentence has been included in Section 5.3:

"…The conceptual models within the modeling framework are easy to apply, require minimal data, and are computationally inexpensive. Several of these models are part of the WEAP platform, which is openly accessible for developing countries (for academic purposes and public institutions). Additionally, we provide in the current article detailed equations for models that are not included in this platform…"

Regarding the second question, the following sentence was included in Section 5.3:

"…Contrary to the perceptions of some stakeholders, who often attribute the lake's water level variations to water withdrawals for irrigation or glacier retreat, this study demonstrates that Lake Titicaca's variations are primarily driven by rainfall and evaporation variability…"

Appendix: Ensure all figures in the appendix are referenced in the main manuscript.

Agreed. We have checked that all the figures in the appendix were referenced in the main text.

New references

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M.: Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56, FAO Rome, 300, D05109, 1998.

Hassanzadeh, E., Zarghami, M., and Hassanzadeh, Y.: Determining the Main Factors in Declining the Urmia Lake Level by Using System Dynamics Modeling, Water Resour. Manag., 26, 129–145, https://doi.org/10.1007/s11269-011-9909-8, 2012.