Responses to Reviews of Egusphere-2025-2984: "Questioning the Endorheic Paradigm: Water Balance dynamics in the Salar del Huasco basin, Chile" By Francisca Aguirre-Correa et al.

We thank the Reviewer for spending time revising our work and for the constructive comments. For clarity, we have grouped some related comments by theme and provided joint responses where appropriate. We answered the comments in blue font.

This manuscript presents an investigation of the spatiotemporal variability of groundwater recharge and upwelling in the Salar del Huasco basin, focusing on its interactions with precipitation, evaporation, and overall water balance dynamics in this arid endorheic system located in the Chilean Altiplano. The study addresses an important and timely topic with relevance to hydrological processes in data-scarce, high-altitude regions and provides valuable insights into the interactions among precipitation, evaporation, and groundwater recharge under conditions of extreme water scarcity. The manuscript is well structured, and the results are presented clearly. The work has the potential to make a contribution to the understanding of water balance processes in arid endorheic systems. However, certain aspects would benefit from clarification and further elaboration.

Some specific comments are provided below for consideration:

Lines 9-10: The message of this sentence is not entirely clear and would benefit from rephrasing to improve coherence and accuracy. Groundwater itself cannot "lead to recharge," since recharge is the process that feeds or replenishes groundwater storage. The intended meaning seems to be that groundwater storage decreases, or that recharge reaches a minimum following the dry period.

We agree and we will rephrase the sentence for accuracy. The intended meaning is that following the dry period, groundwater sustains high evaporation rates, while recharge declines to a minimum: *"Our findings highlight that when summer rainfall ceases, groundwater becomes the main water source supporting high evaporation rates, and recharge reaches a minimum by the end of autumn that persists until the end of the year."*

Line 11: The term *"competition"* is not ideal in this hydrological context. Please replace *"trade-off" or similar words* to describe the contrasting relationship between groundwater recharge and evaporation.

We agree and we will now use the term "trade-off" throughout the manuscript, which better reflects the contrasting relationship between recharge and evaporation.

Lines 84-87 It would be helpful to express the total annual discharge in units of mm yr^{-1}, in addition to the volumetric flow rates (m^3 s^{-1}), to facilitate direct comparison with precipitation and evaporation values reported elsewhere in mm yr^{-1} in the manuscript.

While we report spring flows in $m^3 s^{-1}$, conversion to mm yr^{-1} requires knowledge of the contributing recharge area, which is not available for these springs. To at least provide an order of magnitude, we will use the salt-flat nucleus sub-basin area (48.22 km^2) as a reference. Under this assumption, the total spring discharge of ~0.2 m^3 s^{-1} corresponds to roughly 130 mm yr^{-1} (order of magnitude of ~10^2 mm yr^{-1}).

We will now report this order-of-magnitude estimate in the manuscript, while we will continue to present the observed values in m^3s^{-1} that can be directly compared to precipitation and evaporation fluxes also expressed in m^3/s in Figs. 6 and 7.

Lines 131-132: The authors state that the Uribe et al. (2015) rainfall-runoff model is driven solely by precipitation, and in the model setup, evaporation occurs only in response to rainfall events. Please clarify the rationale for selecting this model despite this limitation, and discuss how this assumption may affect the results and the interpretation of the water balance.

We thank the reviewer for this comment. We used the Uribe et al. (2015) rainfall-runoff model because it was originally developed for the Salar de Huasco and is based on hydrological response units (HRUs) already defined for this basin and widely used in Altiplano studies (e.g., Acosta, 2004; Blin et al., 2022; Yañez-Morroni et al., 2024a,b). This ensures consistency with earlier work and takes advantage of a model structure already adapted to the physical, geological, and climatic conditions of the catchment.

While the original model formulation represents evaporation mainly as an event-driven process tied to rainfall, we adapted the setup to better capture off-season evaporation by introducing an evaporation component that operates independently of rainfall inputs. This allows the model to account for evaporation during the long dry season, which is particularly important in high-altitude basins such as the Salar de Huasco. In our study, the model is therefore used primarily to represent the partitioning and timing of surface runoff and groundwater recharge, while basin-scale closure is derived independently from bias corrected satellite-based evaporation and precipitation considering that no changes in groundwater levels have been observed in the basin (see Blin et al., 2022). However, we acknowledge that the modified model may misrepresent water losses, particularly during the dry season, due to uncertainties in satellite-derived evaporation data, which could in turn impact the accuracy of groundwater recharge estimates.

We will now explain in the manuscript the rationale for selecting this model and we will highlight that the same model structure has been successfully used in the Salar del Huasco and other basins. We will also discuss the limitation that it may affect recharge estimates, and we will emphasize that the model is primarily used to represent the partitioning and timing of surface runoff and recharge.

Figure 3: It is unclear how "monthly mean variability" can be represented in *mm* yr^{-1}, since those units denote annual totals or rates. It appears that Figure 3 presents monthly mean values on the x-axis; therefore, the corresponding y-axis units should likely be expressed in *mm* (or *mm* $month^{-1}$), rather than *mm* yr^{-1}. Please clarify the unit definition. If the intention is to show monthly distributions, the values should be expressed in *mm* $month^{-1}$ (or simply *mm*), or the caption should explicitly state that the data have been annualized (e.g., monthly averages scaled to their annual equivalents). Please clarify the units and calculation method to ensure the figure is interpreted correctly. Otherwise, the comparison between rainfall and evaporation may be misleading, as expressing monthly values in *mm* yr^{-1} artificially inflates their magnitude by a factor of 12.

The results described between lines 207–225 also seem to be based on monthly values presented in Figure 3. If this is the case, the current labeling in *mm* yr^{-1} is inconsistent and may cause confusion. Conversely, if the data were converted to annual equivalents, it would be preferable to present Figure 3 using an annual scale rather than monthly intervals, to maintain conceptual consistency.

A similar applies to Figure 4, particularly the right panels (a–c). The values are presented as a function of months, suggesting that the data represent *monthly means*. If the intention is to illustrate the mean variation across available months (e.g., showing typical January, February, etc., values), then the units should correspond to the monthly time step. Alternatively, if the values have been annualized, please clarify this in the caption and consider adjusting the x-axis to represent annual rather than monthly time intervals for conceptual consistency.

The reviewer is correct that Figures 3 and 4, and also Figure 5, show monthly means. All water balance components in the manuscript (precipitation, evaporation, and recharge) are presented as monthly averages but expressed in annual-equivalent units (mm yr^{-1}). This rescaling was applied to keep a consistent vertical scale across fluxes and to avoid very small values in mm $month^{-1}$, particularly for recharge, which is our main focus. The x-axis remains monthly to highlight seasonal variability, while the y-axis in mm yr^{-1} ensures comparability across figures. The captions will now make this explicit:

For Fig. 3: *"Values are presented for the 1980 - 2019 period and represent monthly means, rescaled to annual equivalents (mm year-1) for consistency across all water balance components."*

For Figs. 4 and 5: *"Values represent monthly means, rescaled to annual equivalents (mm year-1) for consistency across all water balance components."*

We will also clarify this in the text when necessary*: "Groundwater recharge is displayed as monthly averages scaled to their annual equivalents in mm $year^{-1}$".*

Line 196 -206: In this section, the results are presented without a corresponding reference to any figure or table. Please specify which figure (or sub-figure) illustrates these findings so that readers can easily locate and interpret the results. Clear cross-referencing between text and figures would greatly improve readability and traceability of the analysis for the Results and Discussion section

We will add explicit cross-references to Fig. 3 where the results are discussed, and we will also carefully review the manuscript to ensure that all figure references are consistent.

Line 244: The text refers to "S1-type HRUs with an annual mean of ∼600 mm yr^{-1} (see Fig. 2)," but Figure 2 does not display any numerical values or spatial distribution of annual means; it only shows the HRU classification. Please clarify whether these mean values are derived from another figure, dataset, or analysis step, and adjust the figure reference accordingly.

We thank the reviewer for this correction. We will update this reference to Fig. 4b.

The Discussion section would benefit from a more detailed consideration of the limitations associated with the satellite-derived datasets and the assumptions of the applied model. Currently, these aspects are only briefly mentioned in lines 383–386. Given that the presented data are derived rather than directly measured, it is important to discuss the potential uncertainties arising from data correction methods, model parameterization, and structural assumptions.

We thank Reviewer #2 for this comment, which overlaps with a point raised by Reviewer #1. Accordingly, we have provided a consistent response to ensure clarity and alignment. Overall, we agree that the validity of our conclusions depends on the reliability of the satellite-derived datasets and the underlying model assumptions. We acknowledge that the manuscript will benefit from a more thorough and transparent discussion of these limitations, which we will now expand accordingly.

To better explain the corrections of the satellite-derived data and quantify their uncertainty on the basin-scale water balance conclusions, we will make the following revisions in the manuscript:

1. Expand description of local data and corrections: We will provide detailed metadata for the DGA precipitation and temperature stations used for bias correction, including their locations, elevations, record lengths, and error metrics of the corrected satellite-derived timeseries (PBIAS, RMSE, R^2). These will be presented in Tables B1 and B2 to complement Fig. B2 in Appendix B (see below), which will be referenced in the main text when introducing the satellite-derived datasets. In light of this comment, we would like to note that we identified a minor error in Fig. B2, specifically in the color legend. This will be corrected and updated in the revised manuscript (see Fig. R1).

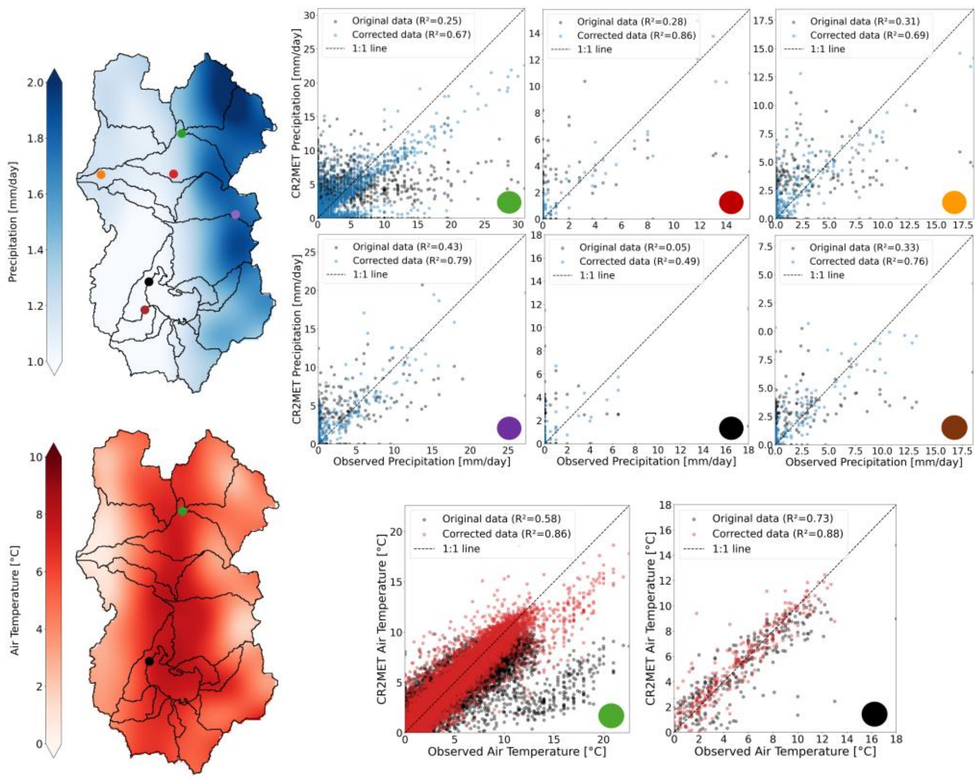

Figure R1: Original (black dots) and corrected CR2MET data (blue dots for precipitation and red dots for air temperature) for the Salar del Huasco basin. A machine learning bias correction approach was implemented (Fig. B1).

Table B1. Summary of validation metrics for daily precipitation at DGA meteorological stations used for CR2MET bias correction. The colors in parentheses correspond to station markers in Fig. B2. PBIAS represents the percent bias computed for all days with recorded precipitation > 1 mm, RMSE is the root mean square error, and R^2 is the coefficient of determination. The basin median signed bias is derived from aggregating all station records into a single time series.

Station	Lat/Lon	Elevation (m asl)	Record length	PBIAS (%)	RMSE (mm day^{-1})	R^2
Coyacagua (green)	-20.04°/-68.83°	4013	14326	22.4	1.05	0.67
Río Collacagua (red)	-20.10°/-68.84°	3853	612	11.4	0.56	0.86
Diablo Marca (orange)	-20.10°/-68.97°	4585	1397	0.7	0.93	0.69
Sillillica (purple)	-20.17°/-68.74°	3840	1427	-0.3	1.03	0.79
Salar Huasco (black)	-20.28°/-68.89°	3800	457	26.1	0.81	0.49
Altos del Huasco (brown)	-20.32°/-68.89°	4044	1449	2.6	0.62	0.76
Basin median signed bias (%)		-9.1				

Table B2. Summary of validation metrics for daily air temperature at DGA meteorological stations used for CR2MET bias correction. The colors in parentheses correspond to station markers in Fig. B2. PBIAS represents the percent bias, RMSE is the root mean square error, and R^2 is the coefficient of determination. The basin median signed bias is derived from aggregating all station records into a single time series.

Station	Lat/Lon	Elevation (m asl)	Record length	PBIAS (%)	RMSE (°C)	R^2
Coyacagua (green)	-20.04°/-68.83°	4013	11383	-0.2	1.52	0.86
Salar Huasco (black)	-20.28°/-68.89°	3800	300	3.9	1.24	0.88
Basin median signed bias (%)		-0.9				

2. Quantification of error ranges: We will quantify the uncertainties in the satellite-derived data and incorporate this analysis into the discussion, highlighting how these errors may influence our conclusions.
   - Precipitation (P): Nearly all individual DGA stations show positive percent bias (PBIAS) values, indicating that bias-corrected CR2MET precipitation mainly overestimates the measurements at the station level, with magnitudes ranging from -0.3% to +26% (Table B1). The largest errors occur at lower-elevation stations, where total precipitation is low and satellite products tend to overestimate the few convective events that do occur. To evaluate the implications for the water balance at the basin scale, we aggregated all station records into a combined time series. This yielded a basin median signed bias of ~-10%, which we adopt as a representative error bound for precipitation (±10%). We chose the basin-wide median rather than the mean of station biases because the median provides a more robust estimate of central tendency, less influenced by extreme local values, and more consistent with the scale at which the water balance is assessed. However, note that our water balance results indicate evaporation exceeds precipitation, and since the precipitation product is more likely to be overestimated, as evidenced by the positive PBIAS (Table B1), the imbalance we report can be considered as conservative in terms of precipitation (true precipitation deficit is likely larger than our estimates suggest).

   - Temperature (T): For air temperature, the available stations showed very small biases (<4%), with a basin-wide median signed bias of -0.9%. This indicates that after correction CR2MET temperature fields are in close agreement with in-situ observations, supporting their reliability as inputs to the rainfall-runoff model. This outcome is also consistent with the general expectation that satellite and reanalysis products reproduce temperature more accurately than precipitation.

- Evaporation (E): Direct local validation of evaporation was limited due to the absence of flux towers or lysimeter measurements in the basin. However, we will now compare EEFLUX-derived actual evaporation against daily evaporation estimated from pan measurements, adjusted using a pan coefficient of 0.7 as recommended by DGA (2009). These observations were collected at a representative site within the salt flat nucleus sub-basin (GP Consultores, 2008), the area with the highest evaporative fluxes in the study site. EEFLUX-derived actual evaporation underestimates the observed evaporation by approximately -18%, with a root mean square error (RMSE) of 1.41 mm day^{-1} (Fig. R2). EEFLUX effectively reproduces the temporal variability captured by the tank observations, and its magnitude remains within a plausible range (Fig. R2). Furthermore, since EEFLUX/METRIC retrievals are strongly constrained by temperature, and satellite-derived temperature fields closely align with ground observations, confidence in the accuracy of the evaporation estimates is further supported. Nonetheless, because this comparison is limited to a single site and relies on pan measurements rather than actual evaporation, and considering that published evaluations of METRIC/EEFLUX in arid and mountainous regions have reported uncertainties of ~5-20% (Nisa et al., 2021; Wasti, 2020; Lima et al., 2020; Madugundu et al., 2017), we will adopt a conservative ±20% error bound for evaporation in our basin-scale water balance analysis. It is important to note, however, that the reported imbalance may be also conservative with respect to evaporation, which could be underestimated in this high-evaporation environment, as observed in Fig. R1.

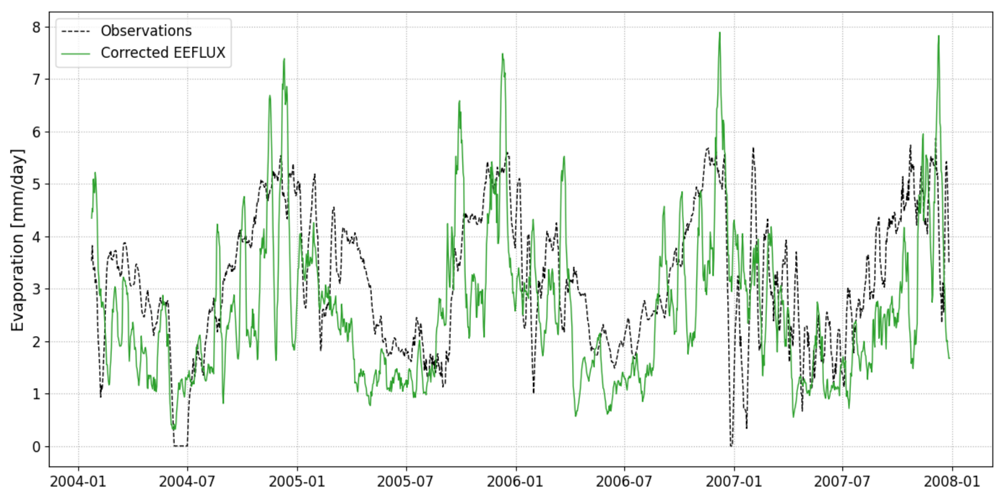

Figure R2: Comparison of EEFLUX-derived daily evaporation at the salt nucleus sub-basin (green) with ground-based observations of potential evaporation (black) at a representative location in the salt flat nucleus sub-basin (GP Consultores, 2008). Both time series have been smoothed using a 10-day rolling average to highlight temporal variability.

3. Analysis of implication of these errors into the basin water balance: Our baseline results indicate that basin-wide evaporation exceeds precipitation by a factor of ~1.5. To test whether plausible uncertainties could account for the imbalance, we will apply representative error bounds of ±10% for precipitation and ±20% for evaporation. Even under the most favorable scenario (increasing precipitation by 10% and decreasing evaporation by 20%), evaporation still exceeds precipitation and the imbalance persists. Based on our discussion, we hypothesize that the observed imbalance may reflect the influence of transboundary or interbasin groundwater flows not represented in the

current hydrological model. We will now stress that future efforts should incorporate hydrogeological mapping and assessments of geological connectivity, particularly toward neighboring Bolivian basins, to evaluate whether Salar del Huasco receives groundwater inflows from adjacent regions. This could help reconcile the apparent precipitation-evaporation deficit. Nevertheless, we will also emphasize in the revised manuscript the need for further validation of satellite-derived inputs against additional local observations across the basin, particularly for evaporation and air temperature for which only limited ground data are available, to strengthen the robustness of the water balance assessment.

Despite these limitations, we would like to highlight that the use of satellite-derived data represents a significant improvement in capturing the spatiotemporal variability of precipitation and evaporation in the basin. In the Altiplano region, convective storms and strong spatial heterogeneity limit the reliability of traditional approaches based on topographic gradients, as originally used in the rainfall-runoff model. While uncertainties in satellite products remain, our approach therefore provides a more realistic representation of hydrological dynamics in the Salar del Huasco, particularly of the interplay between precipitation, evaporation, and recharge. With this uncertainty analysis we will add transparency and robustness to our analysis, and we believe it will strengthen the overall contribution of the manuscript by providing a valuable first-order assessment of basin-scale water availability under the current climatic and data constraints.

We will also acknowledge that our rainfall-runoff modeling framework provides a first-order approximation of groundwater recharge and is subject to sources of uncertainty. To improve transparency, we will expand the discussion in both Appendix A and the main text to clarify the key assumptions and their potential impact on model results:

1. Satellite-derived input limitations: Despite bias corrections based on ground observations, residual errors remain in satellite-derived precipitation, temperature, and evaporation fields, particularly in sparsely monitored areas. These uncertainties propagate through the model and can lead to misrepresentation of water inputs and outputs, thereby influencing the estimated recharge and balance outcomes.

2. Dry-season evaporation parameterization: Evaporation during the dry season is not dynamically simulated but instead prescribed using satellite-derived input. This may lead to under- or overestimation of seasonal water losses, which can directly affect recharge estimates, especially during the dry season.

3. Omission of cryospheric and freeze-thaw processes: The model does not account for snow accumulation, snowmelt, or soil freeze-thaw processes which, although not dominant, have been observed in the Salar del Huasco basin. Excluding these processes may lead to inaccurate timing and magnitude of infiltration and recharge, especially during transitional seasons (e.g., spring melt), potentially biasing recharge estimates.

4. Streamflow data limitations: The discharge data used for model calibration are subject to observational uncertainty, especially during low or ephemeral flow conditions. These limitations can reduce the reliability of the calibration and impact the model’s ability to correctly represent water partitioning processes, including infiltration and runoff.

5. Model parameter uncertainty: The model includes 15 calibrated parameters, increasing the risk of equifinality, where multiple parameter sets yield similar performance but differ in internal process representation. This compromises the uniqueness and robustness of the estimated recharge. Following recent recommendations (e.g., Yáñez-Morroni et al., 2024a,b), we will recommend that future work simplify the model by reducing the number of parameters and using less complex formulations, to improve the clarity and reliability of parameter estimates.

We would like to emphasize that, despite the limitations in the rainfall-runoff model, it offers a spatially distributed and process-oriented framework for analyzing groundwater recharge, and it enables exploration of the dominant hydrological controls in the Salar del Huasco basin. Nevertheless, we will emphasize that the results should be interpreted as indicative, and future refinement will benefit from improved data coverage and model structure.

References

Acosta, O. (2004). Impacto de las extracciones de agua subterránea en el salar del huasco. Master's thesis, Tesis de Máster, Universidad Politécnica de Cataluña. Barcelona, España.

Blin, N., Hausner, M., Leray, S., Lowry, C., Suárez, F. (2022). Potential impacts of climate change on an aquifer in the arid altiplano, northern chile: The case of the protected wetlands of the salar del huasco basin. Journal of Hydrology: Regional Studies 39, 100996. https://doi.org/10.1016/j.ejrh.2022.100996

Blin, N., & Suárez, F.. (2023). Evaluating the contribution of satellite-derived evapotranspiration in the calibration of numerical groundwater models in remote zones using the EEFlux tool, Science of The Total Environment, Volume 858, Part 1, 159764, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2022.159764.

Collahuasi - GP Consultores. (2008). Información sobre evaporación provista por Compañía Minera Doña Inés de Collahuasi. Informes inéditos.

DGA. (2009). Sistema Piloto I Región: Salar del Huasco. In Levantamieno hidrogeológico para el desarrollo de nuevas fuentes de agua en áreas prioritarias de la zona norte de Chile, Regiones XV, I, II y III.

Madugundu, R., Al-Gaadi, K. A., Tola, E., Hassaballa, A. A., and Patil, V. C. (2017). Performance of the METRIC model in estimating evapotranspiration fluxes over an irrigated field in Saudi Arabia using Landsat-8 images, Hydrol. Earth Syst. Sci., 21, 6135–6151, https://doi.org/10.5194/hess-21-6135-2017.

Nisa, Z., Khan, M. S., Govind, A., Marchetti, M., Lasserre, B., Magliulo, E., & Manco, A. (2021). Evaluation of SEBS, METRIC-EEFlux, and QWaterModel Actual Evapotranspiration for a Mediterranean Cropping System in Southern Italy. *Agronomy*, *11*(2), 345. https://doi.org/10.3390/agronomy11020345

Lima, João & Sánchez-Tomás, Juan & G. Piqueras, José & Sobrinho, José & C. Viana, Paula & S. Alves, Aline. (2020). Evapotranspiration of sorghum from the energy balance by METRIC and STSEB. Revista Brasileira de Engenharia Agrícola e Ambiental. 24. 24-30. 10.1590/1807-1929/agriambi.v24n1p24-30.

Wasti, Shailaja. (2020). Estimation of land surface Evapotranspiration in Nepal using Landsat based METRIC model. 10.48550/arXiv.2007.13922.

Yáñez-Morroni, G., Suárez, F., Muñoz, J.F., Lagos, M.S. (2024a). Hydrological modeling of the silala river basin. 1. model development and long-term groundwater recharge assessment. WIREs Water 11(1), 1690 https://doi.org/10.1002/wat2.1690

Yáñez-Morroni, G., Suárez, F., Muñoz, J.F., Lagos, M.S. (2024b). Hydrological modeling of the silala river basin. 2. validation of hydrological fluxes with contemporary data. WIREs Water 11(1), 1696 https://doi.org/10.1002/wat2.1696