Modeling hydrological processes of the Lake Titicaca hydrosystem under changing climate and anthropogenic conditions

Funded by AFD under the CECC (Water cycle and climate change in the intertropical region) project

PhD student: Nilo Alberto LIMA QUISPE

PhD directors: Thomas CONDOM (IRD, IGE), Denis RUELLAND (CNRS, HSM)

Partners involved: IHH-UMSA, SEI-US, SENAMHI Peru, SENAMHI Bolivia, ALT

April 24, 2023

Context

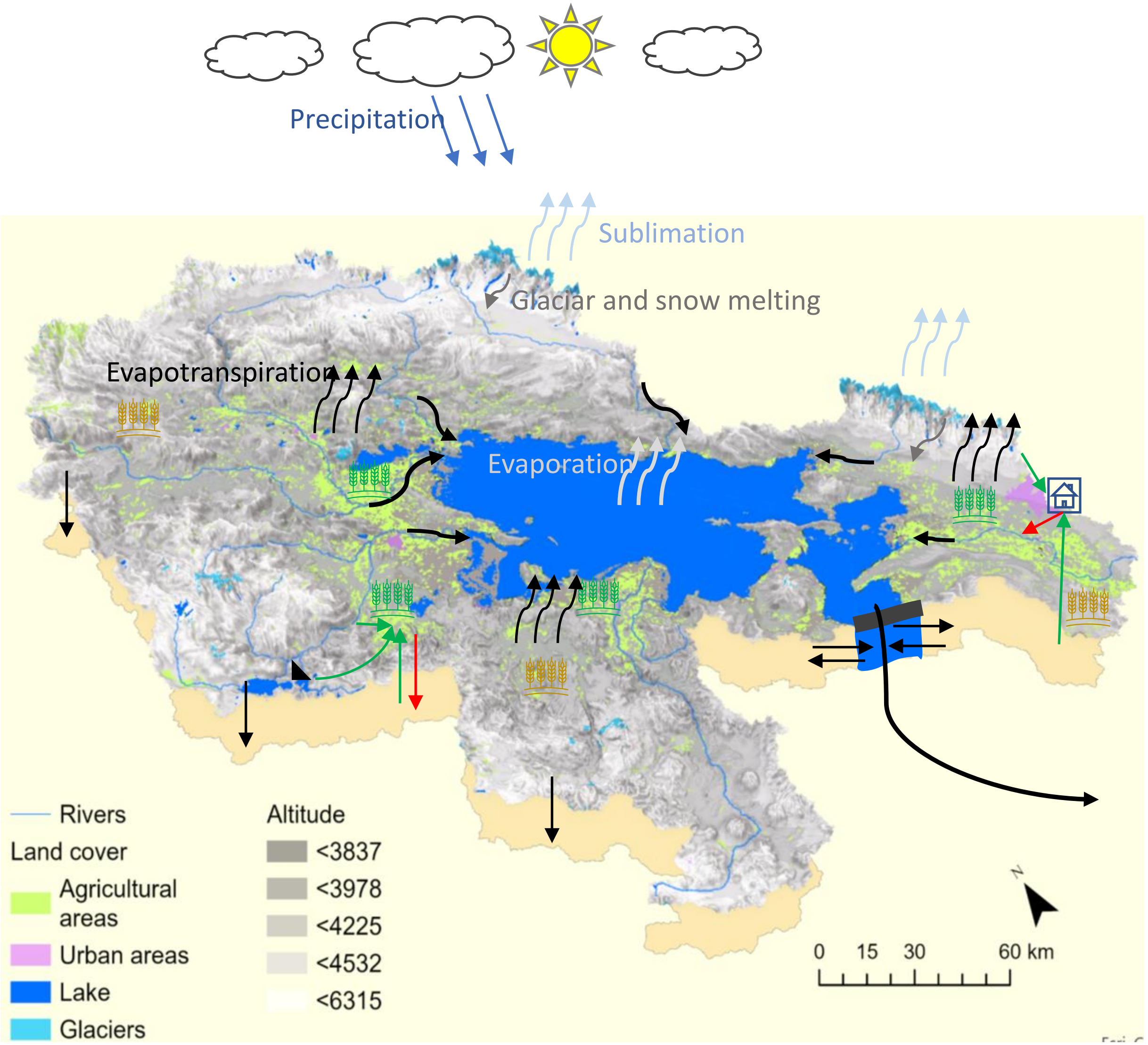
Lakes in the world:

- Many lakes around the world have experienced a reduction in their water levels (Wurtsbaugh et al., 2017).
- Lakes are sensitive to variations in inflows, precipitation, and evaporation (Setegn et al., 2011).

The Titicaca lake:

- Historical records of Lake Titicaca's water levels show a variation of 5 m, with the lowest levels in 1944 and the highest in 1986 (Ronchail et al., 2014).
- These fluctuations have primarily been attributed to climate variability (Lima et al. 2021).

Hydrological processes in lacustrine hydrosystems



What are the natural hydrological processes that occur in the upstream catchments?

Precipitation (rain and snow), sublimation, ice melt, snow melt, evapotranspiration, groundwater exchanges, runoff.

What are the anthropogenic activities that can impact the catchment functioning?

Water withdrawals (i.e. irrigation and domestic uses), reservoirs management.

What are the hydrological processes that impact the lake?

Upstream inflow, direct precipitation and evaporation, groundwater losses and gain, downstream outflow, . . .

PhD questions

Main scientific questions

- What are the hydrological processes that control interannual and seasonal water level variations of large lakes in semi-arid environments?
- How could these processes be altered by the potential effects of climate change?

Additional questions

- How can we represent or capture the hydrological processes in a complex and poorly gauged hydrosystem?
- Which processes are dominant on the interannual and seasonal hydrological response of lakes and which can be considered as local and negligible? To what extent is it convenient not to include some local or insignificant processes?
- Any question about future scenarios (lake drying when the water level is below of outlet)

Developing an integrated modeling chain

Two main goals

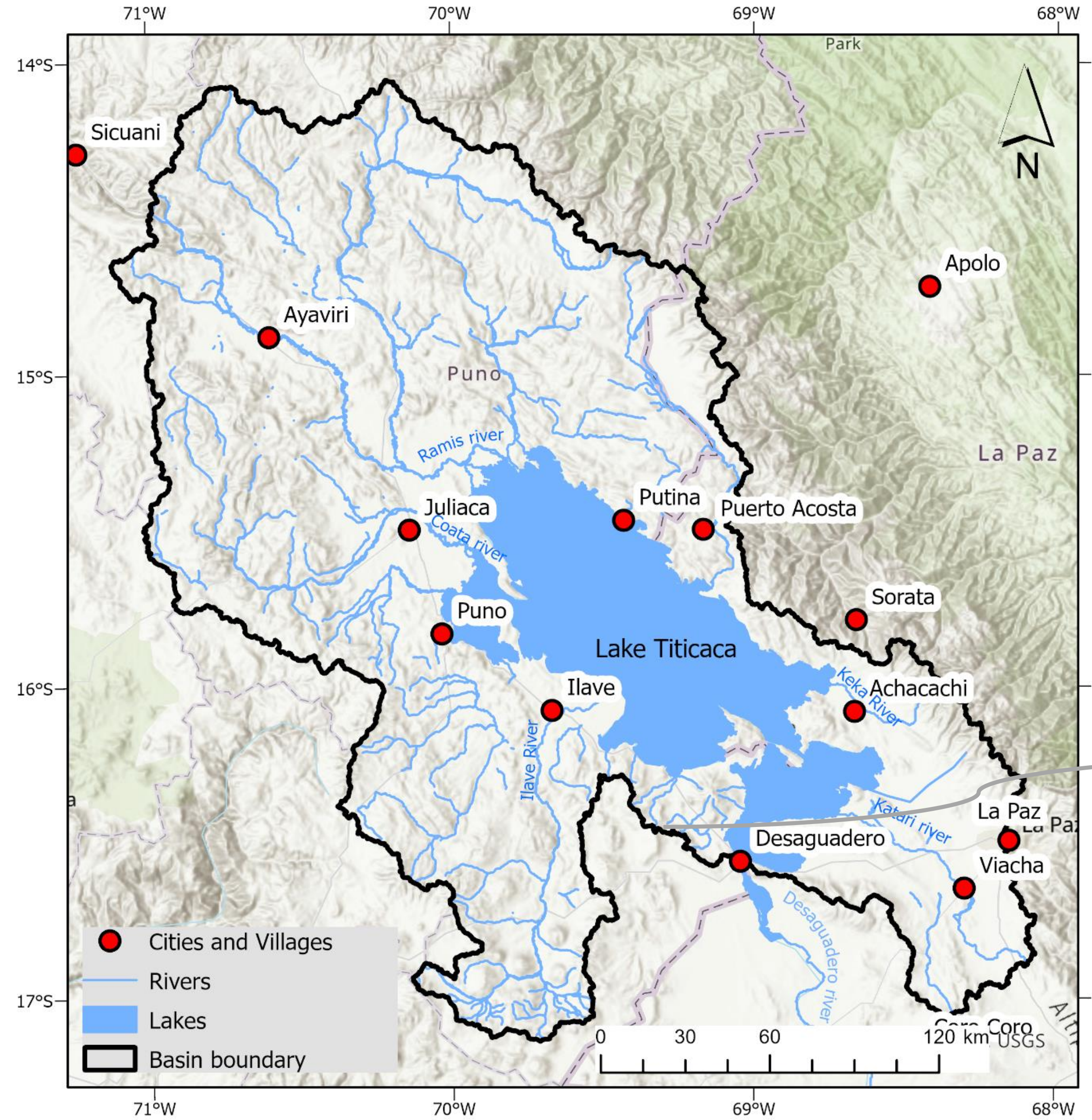
- Representing the hydrological processes that control interannual and seasonal variations in the water level of large lakes (daily time step over a multidecadal past and future period).
- Assessing the potential impacts of projected climate change on **water management**.

Technical challenges associated to the modeling chain

- Development and implementation of a model adapted to a poorly gauged region.
- Modeling chain that includes: snow accumulation, ice and snow melt, rainfall-runoff, basin-scale irrigation, water consumption, and the lake (inflows and outflows).
- Building of climate change and water management scenarios.

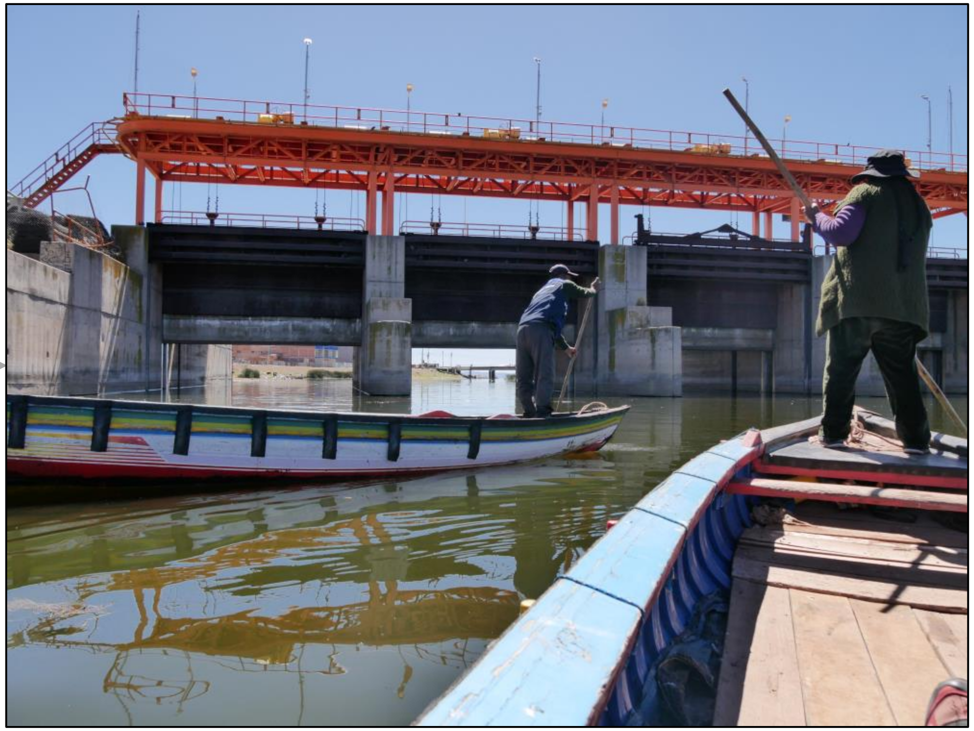
Study area

The Lake Titicaca hydrosystem



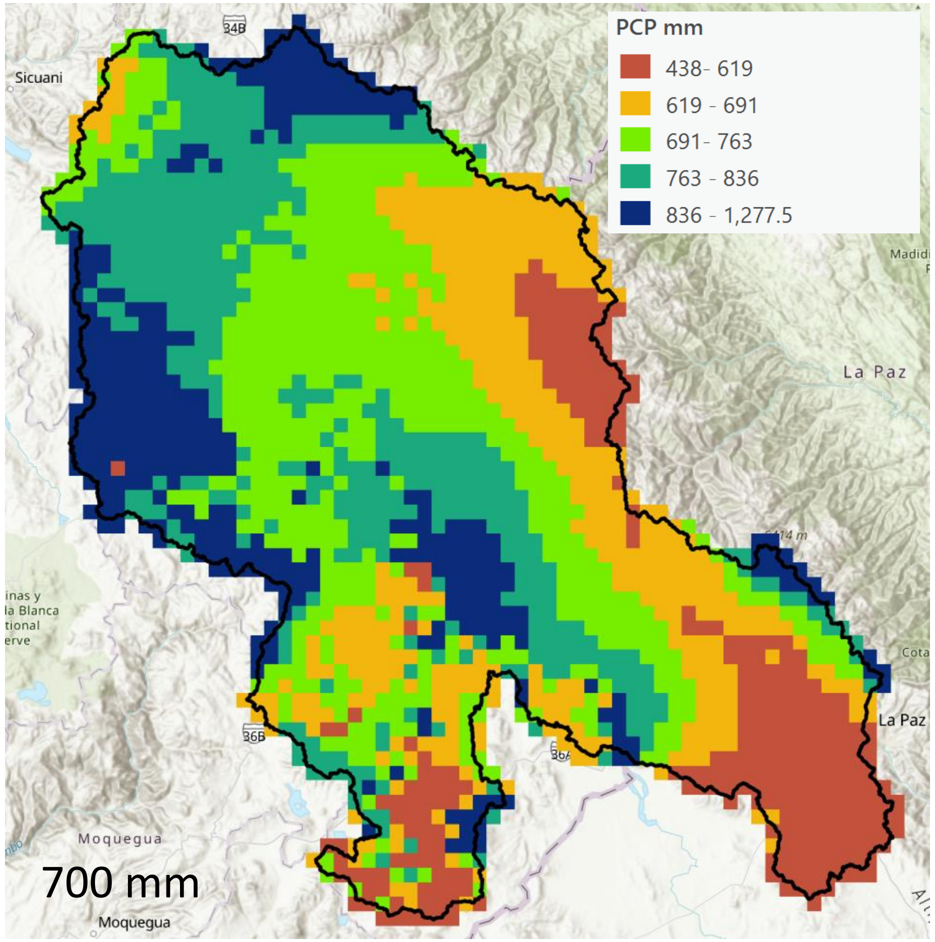
Hydrosystem area: 57,000 km^2
Lake altitude: 3,800 m asl
Lake area: 8,400 km^2
Lake maximum depth: 280 m
Lake volume: 932 km^3

Lake outlet – Compuerta Vagon

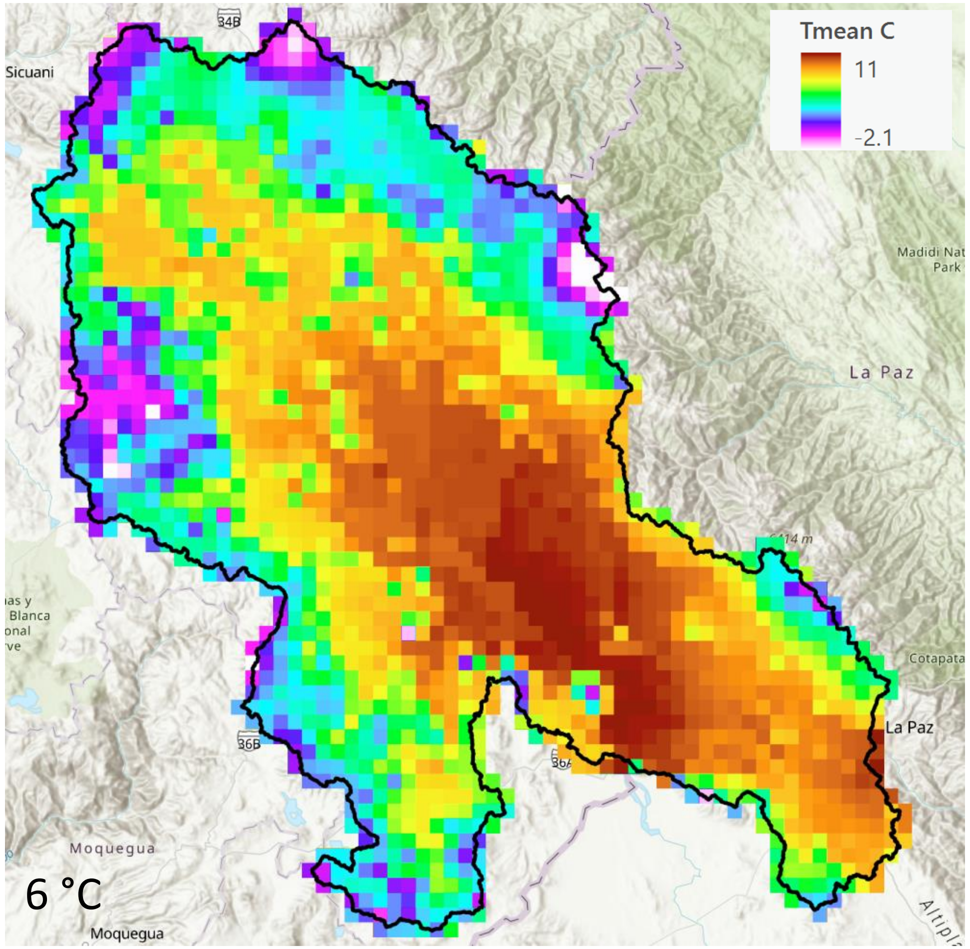


Precipitation and temperature (GMET dataset)

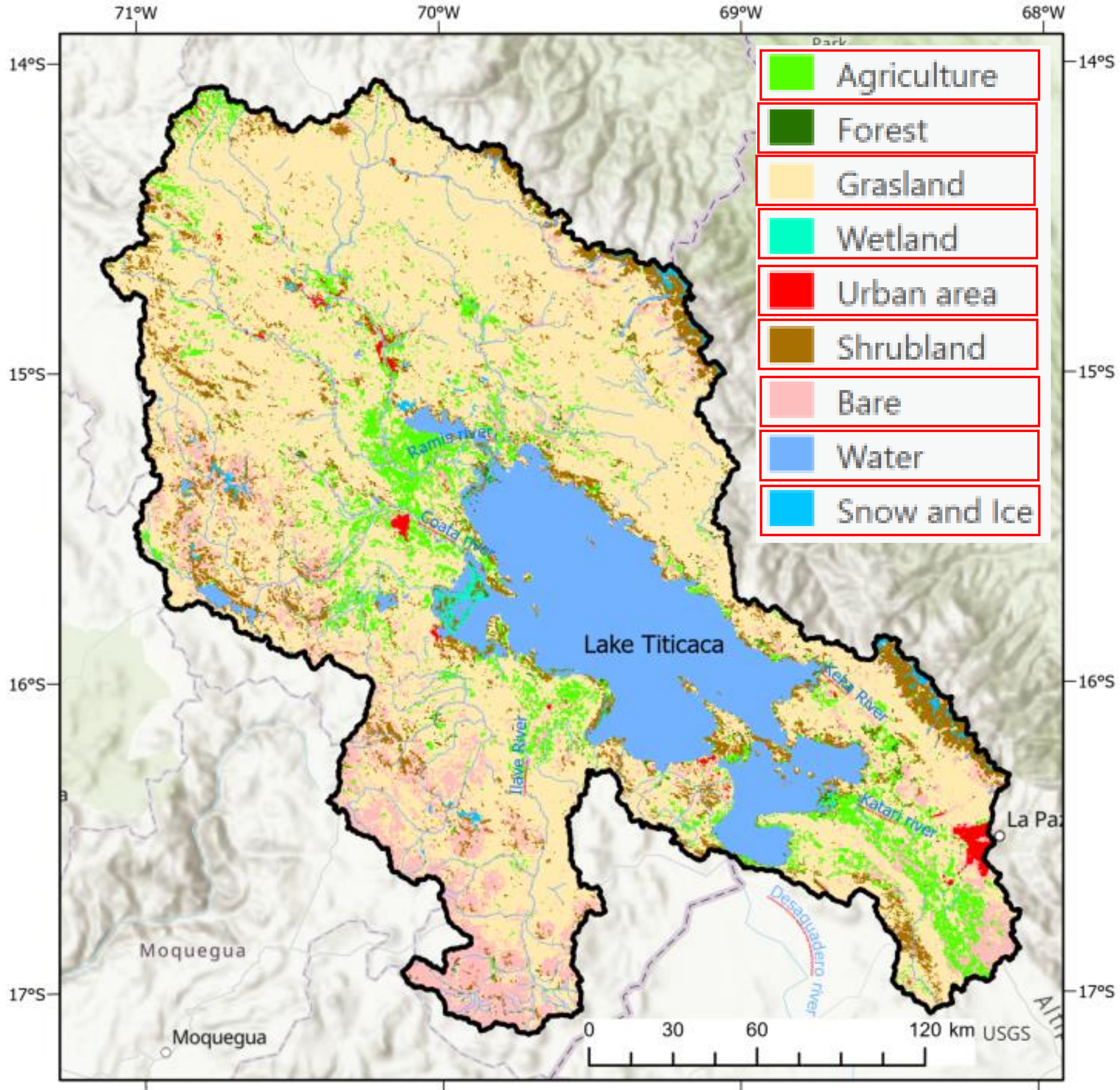
Annual precipitation (1980-2015)



Annual air temperature (1980-2015)



Land cover/use 2020



Source: C3S

Grassland (58%)

Water (15%)

Bare soils (10%)

Croplands (7%)

Shrublands (7%)

Forest (1%)

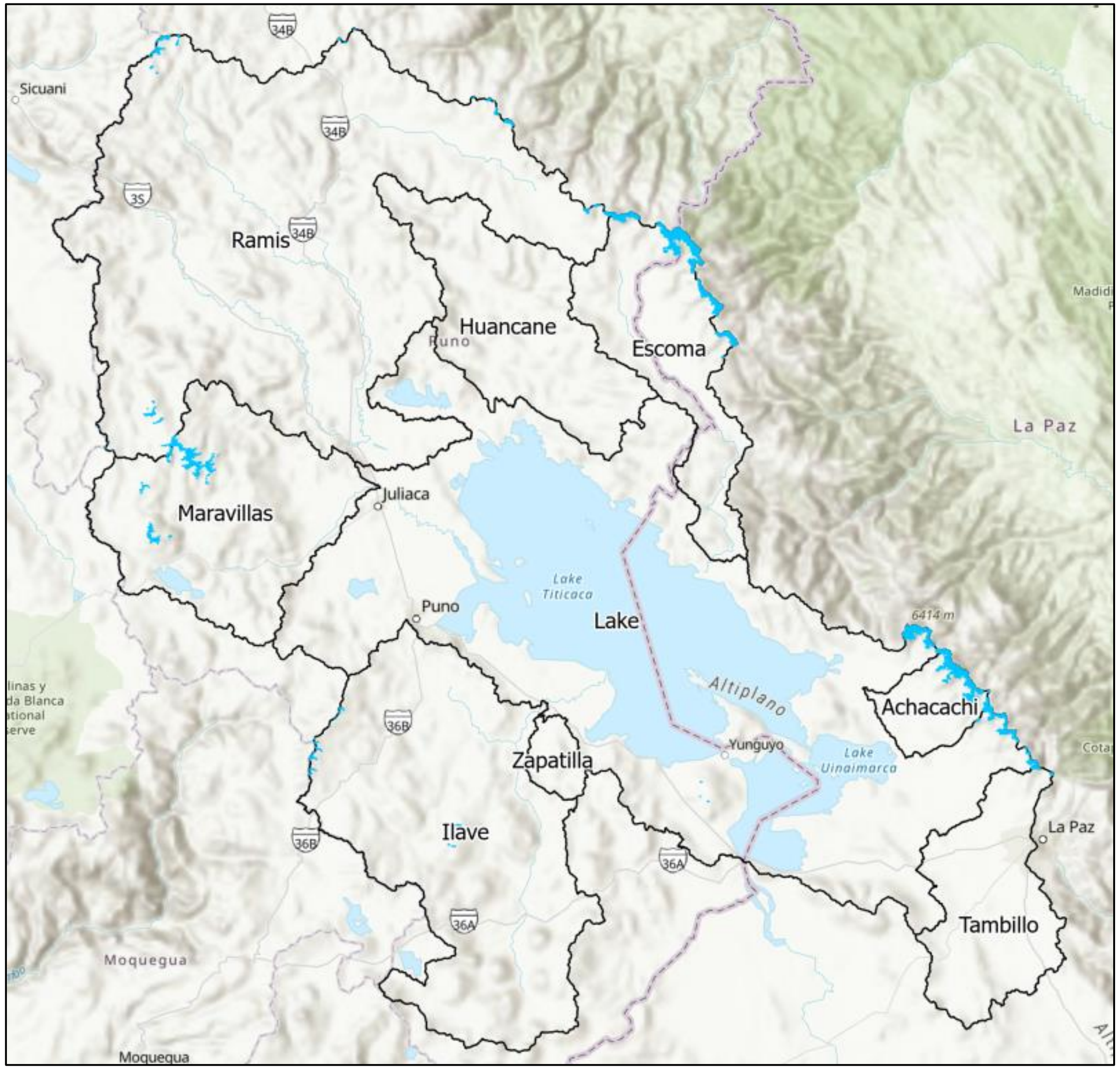
Urban area (1%)

Snow and ice (1%)

Wetlands (0%)

How much has it changed?

Glaciers



Glacier area

Randolf Glacier Inventory V6.0

- ~300 glaciers
- i.e. 270 km^2 (0.5% of the total area)

Glacier volume

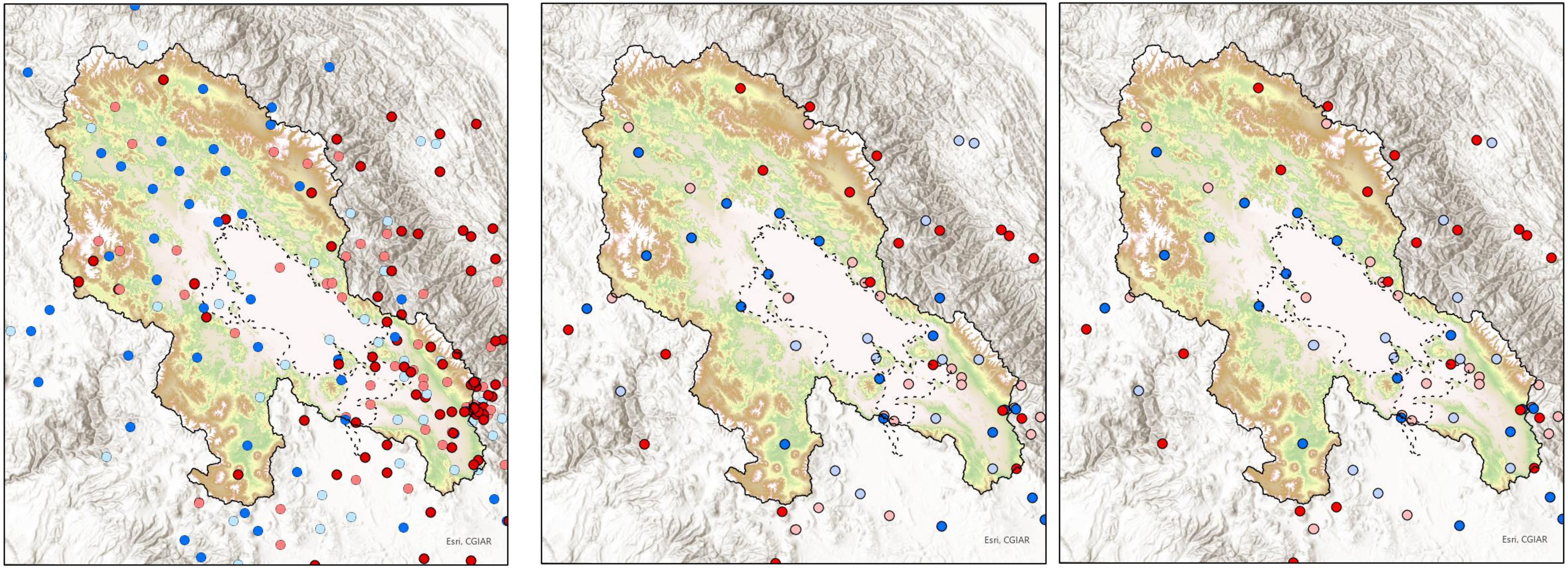
Based on Farinotti et al. (2019)

- Glacier volume (we): 12 km^3
- i.e. ~1% of the lake volume (930 km^3)

Available data

Availability of precipitation and temperature data in space and over time

Precipitation (110 stations) | **Minimum temperature (40 stations)** | **Maximum temperature (40 stations)**



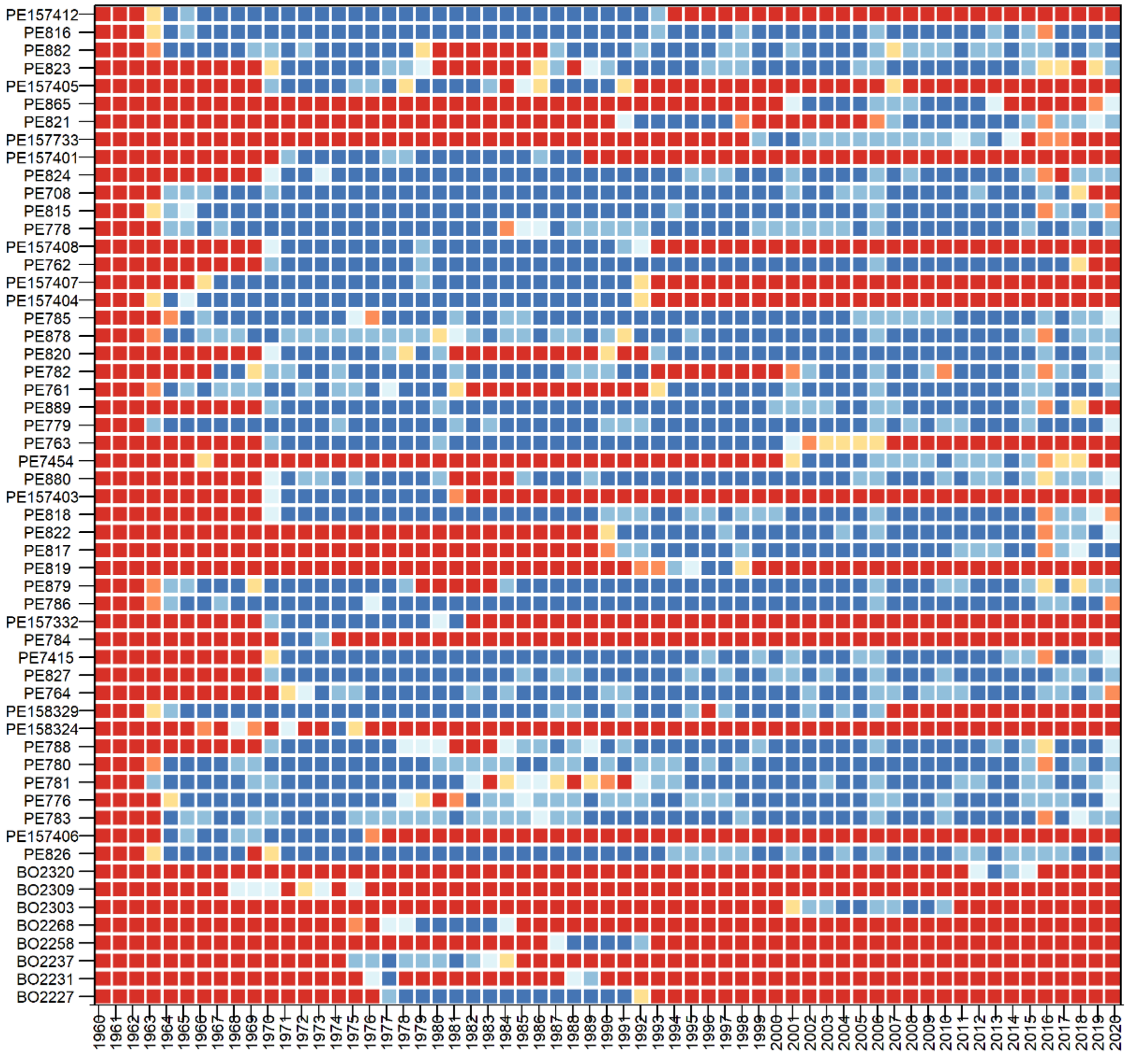
Available data 1960-2020 [%]:
- <25
- 25-50
- 50-75
- >75

Altitude [m]:
- 6315
- 3796

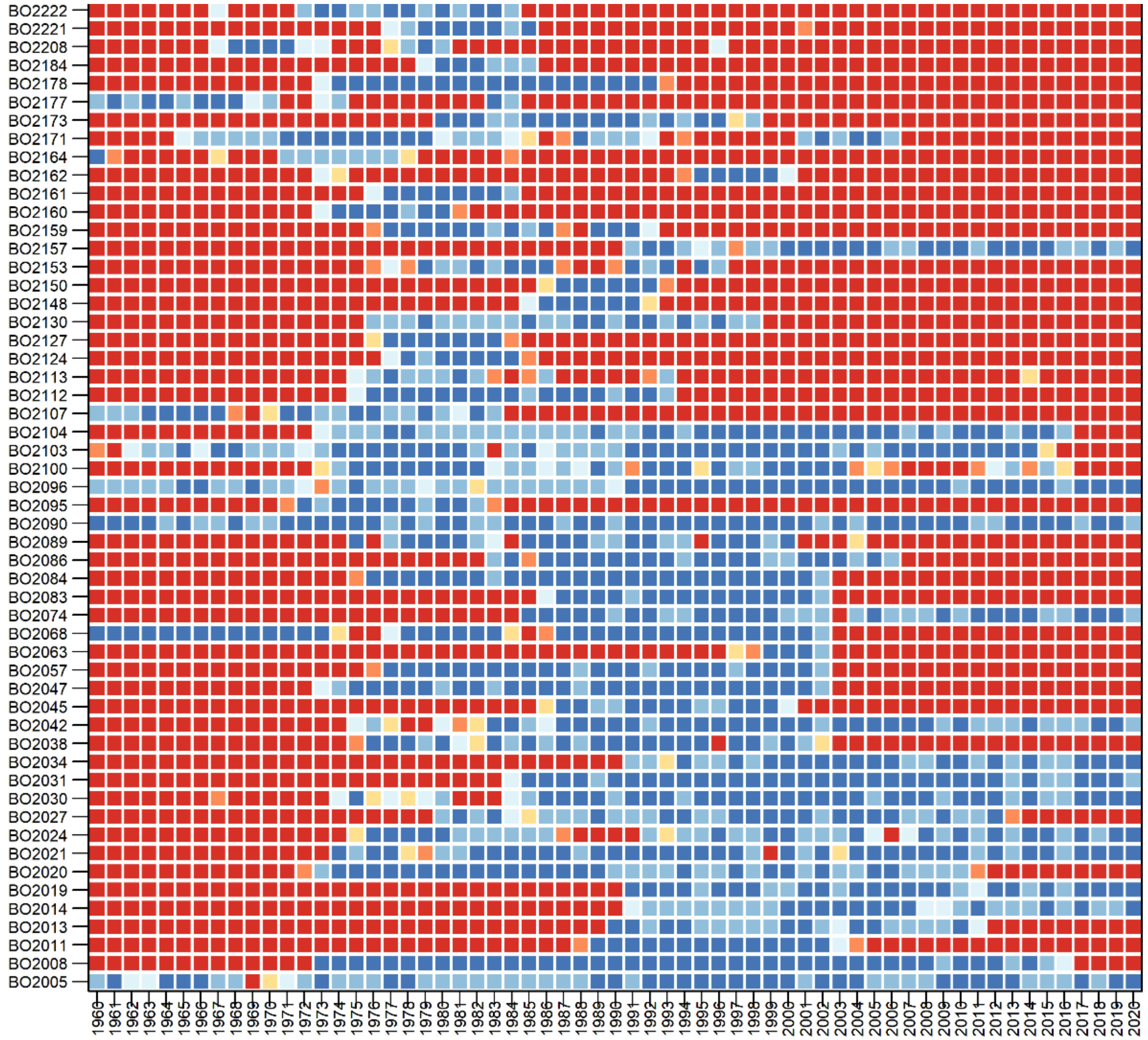
Source: Bolivian stations (SENAMHI)
Peruvian stations (SENANHI)

What precipitation data are available? (over time)

Peruvian stations



Bolivian stations

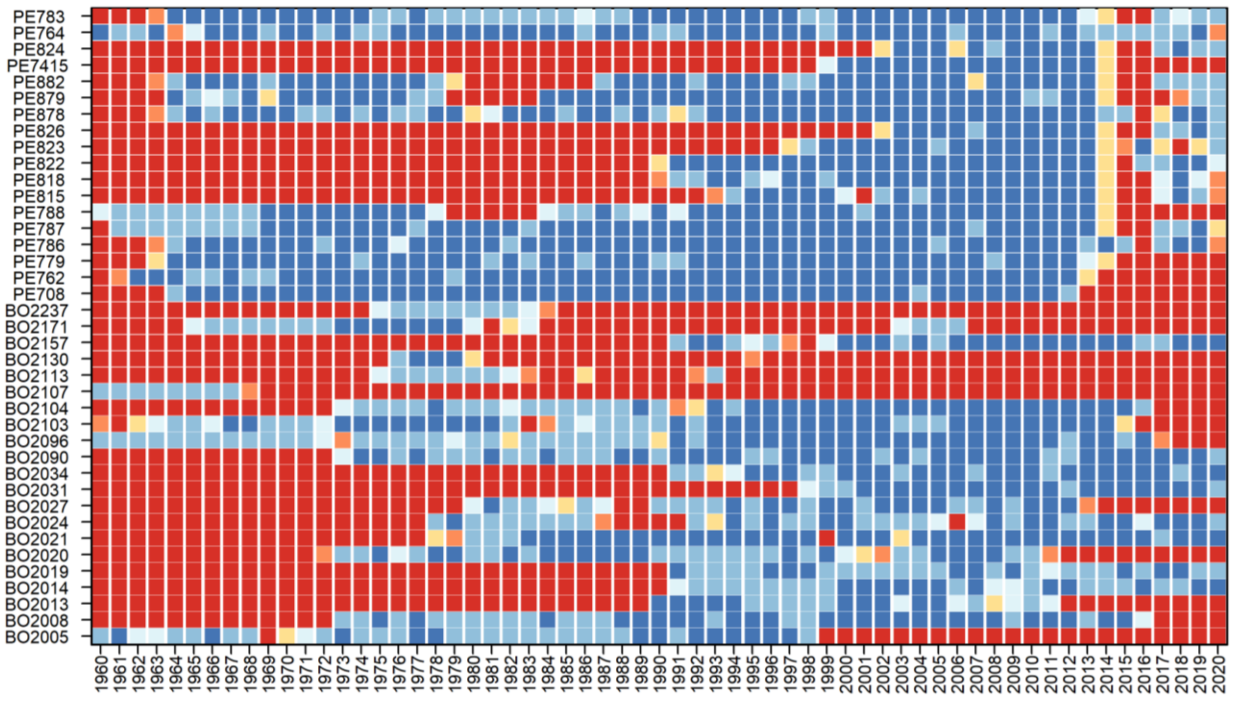


0% <25% <50% <75% <100% 100%

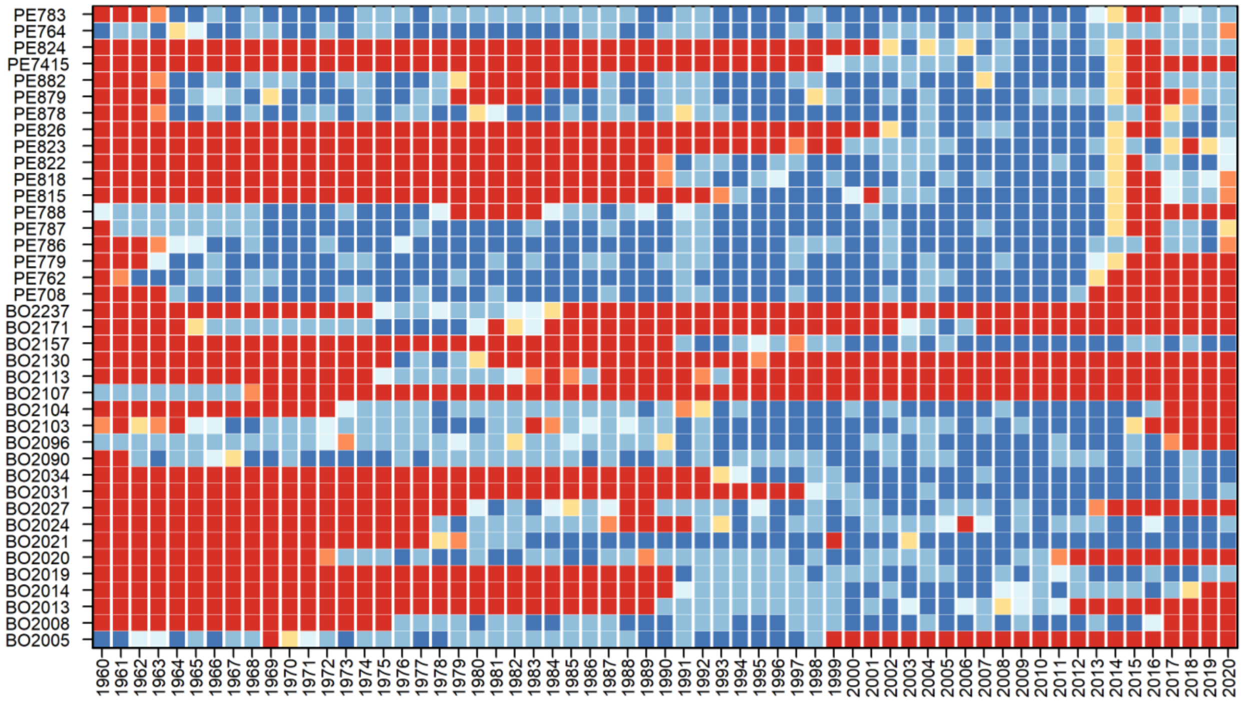
Source: Bolivian stations (SENAMHI)
Peruvian stations (SENANHI)

What temperature data are available? (over time)

Minimum temperature



Maximum temperature



0% <25% <50% <75% <100% 100%

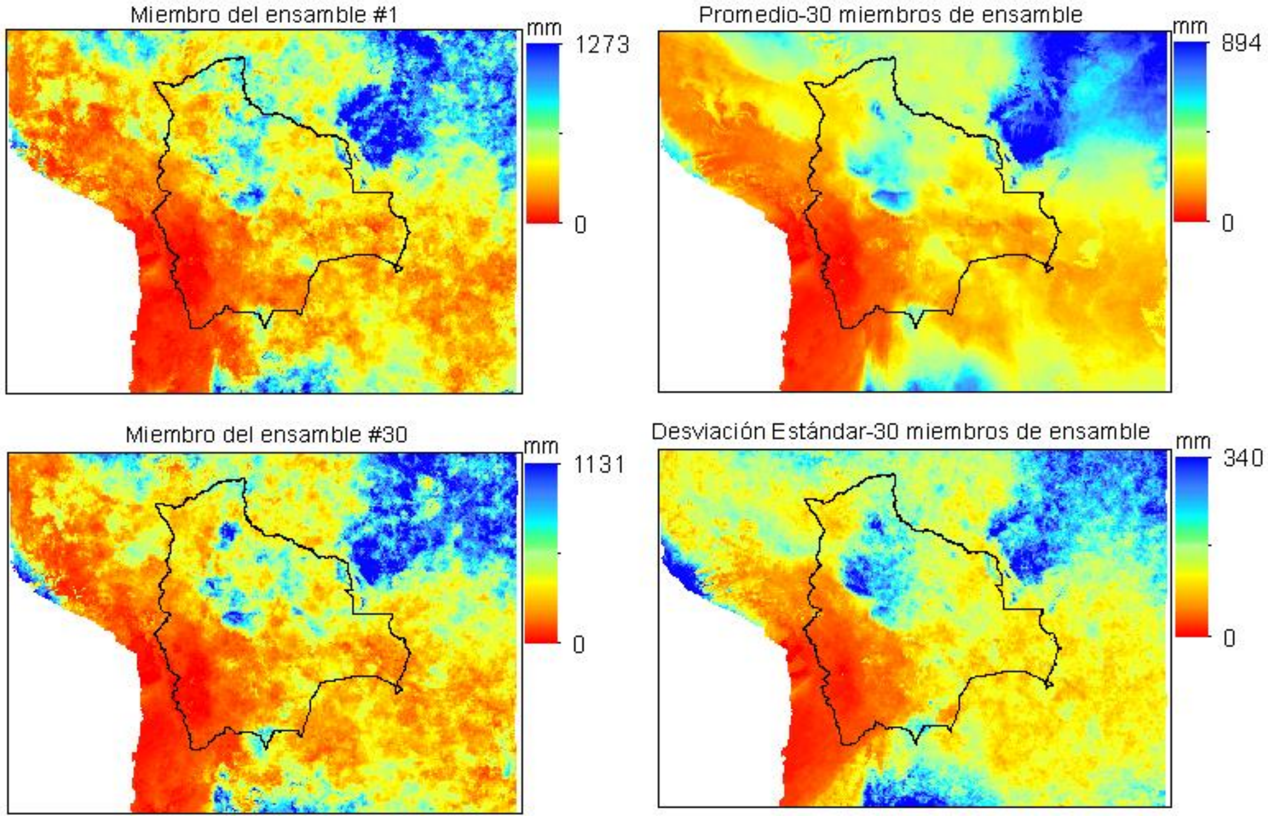
Source: Bolivian stations (SENAMHI)
Peruvian stations (SENANHI)

Data for other variables (HR, WS, SD) were also collected on a daily time step

Gridded Meteorological Ensemble Tool (GMET)

Tool

- GMET is an algorithm for the probabilistic interpolation of point data of precipitation and temperature (Clark and Slater, 2006; Newman et al., 2015).
- Based on this algorithm, a gridded product was generated for Bolivia and its transboundary basins in 2017.
- GMETv1.0 Bolivia has 30 ensemble members. The average of the ensembles was used.

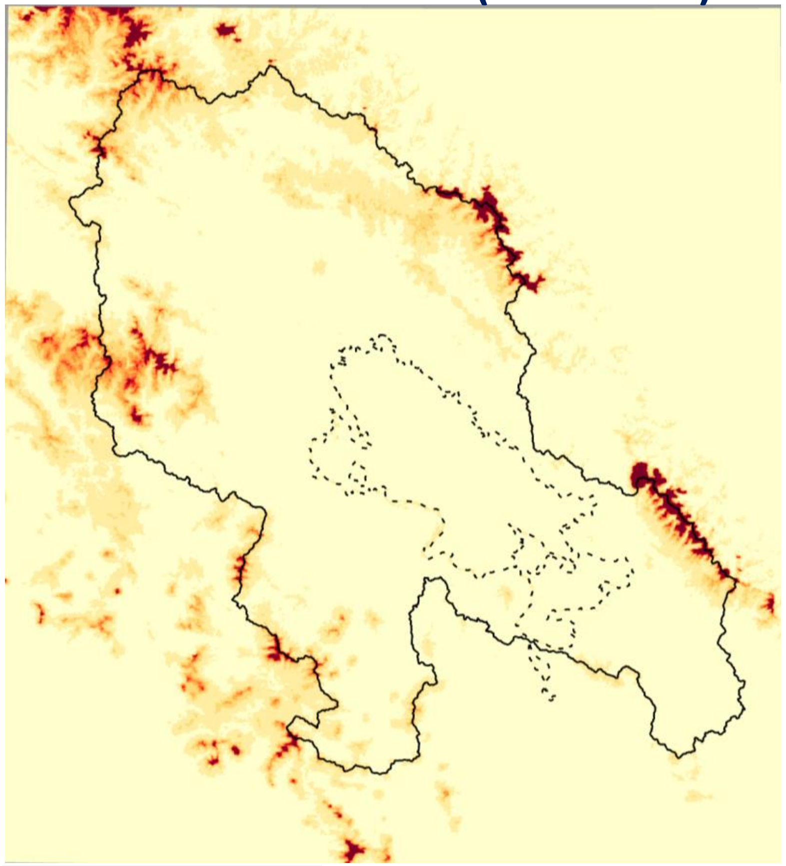


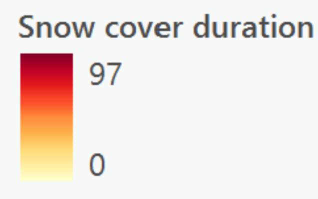
Main characteristic

- Variables: precipitation, mean temperature and diurnal range
- Spatial resolution: ~5 km
- Temporal resolution: daily
- Period: 1/01/1980-31/09/2016

Available control data (in space) – snow and hydrology

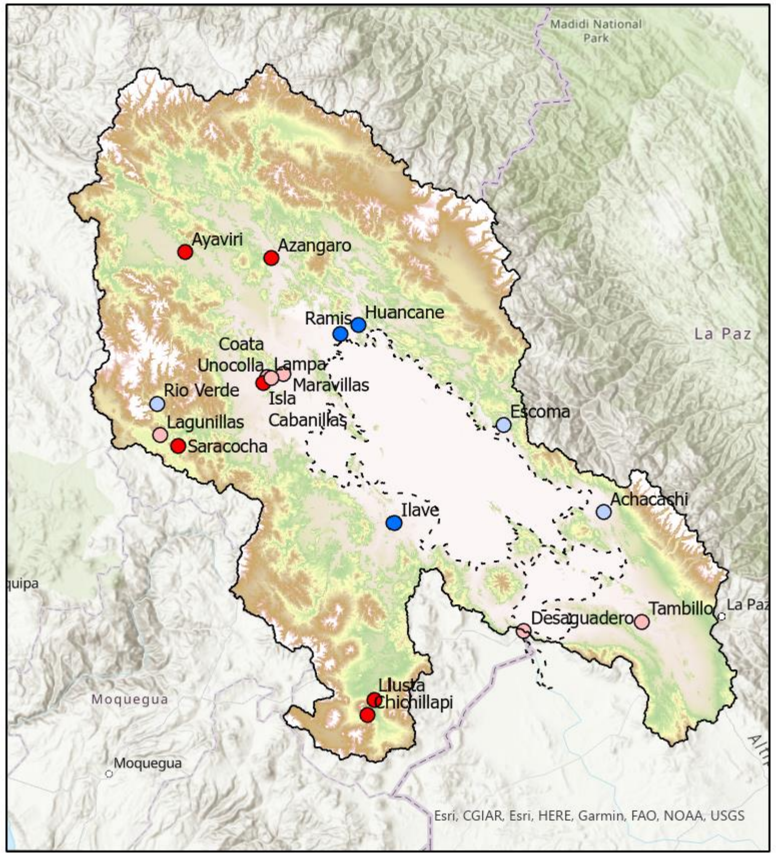
Remotely-sensed snow cover duration (2000-2016)



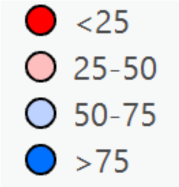


Source: MODIS snow products
Spatial resolution: 500 m
Gap filled method used (Ruelland 2020)

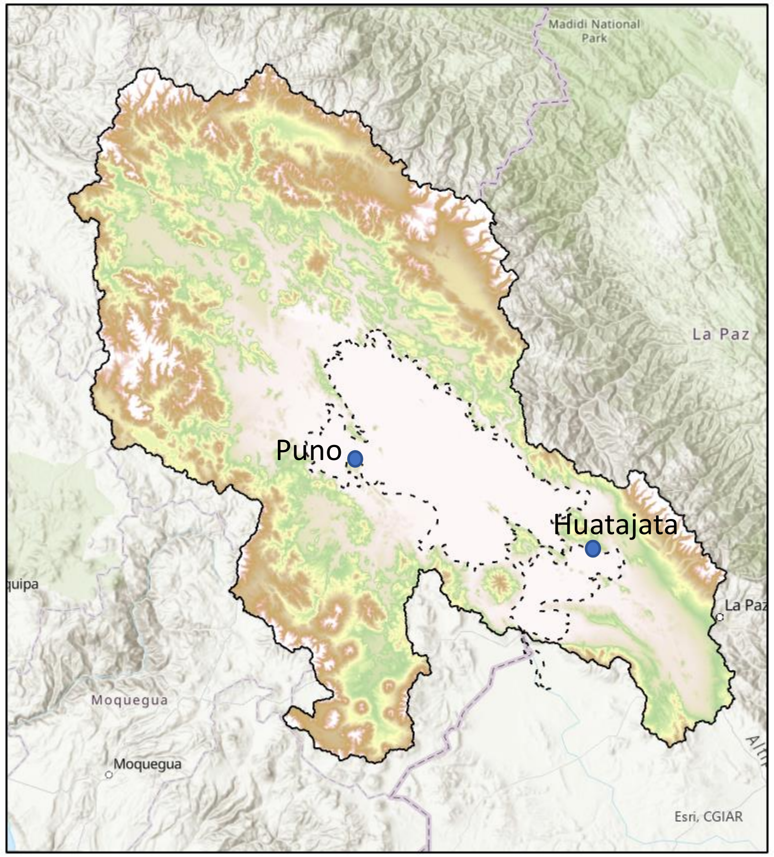
Streamflow gauges (18)



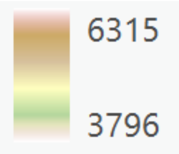
Available data 1960-2020 [%]:



Water level gauges (2)



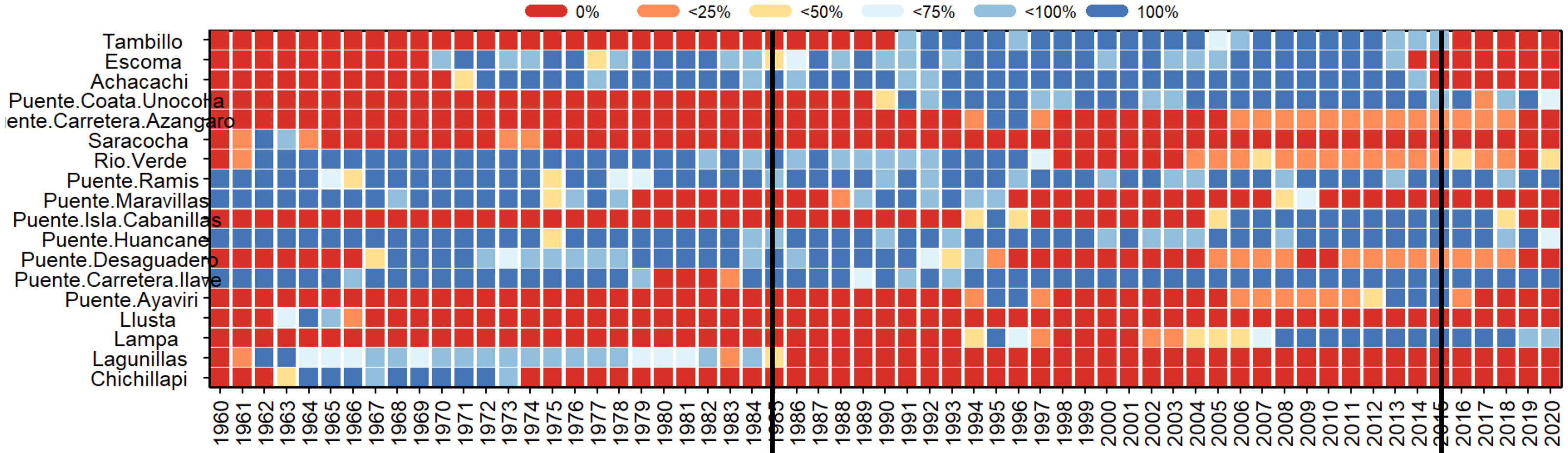
Altitude [m]:



Source: Bolivian stations (SENAMHI)
Peruvian stations (SENANHI)

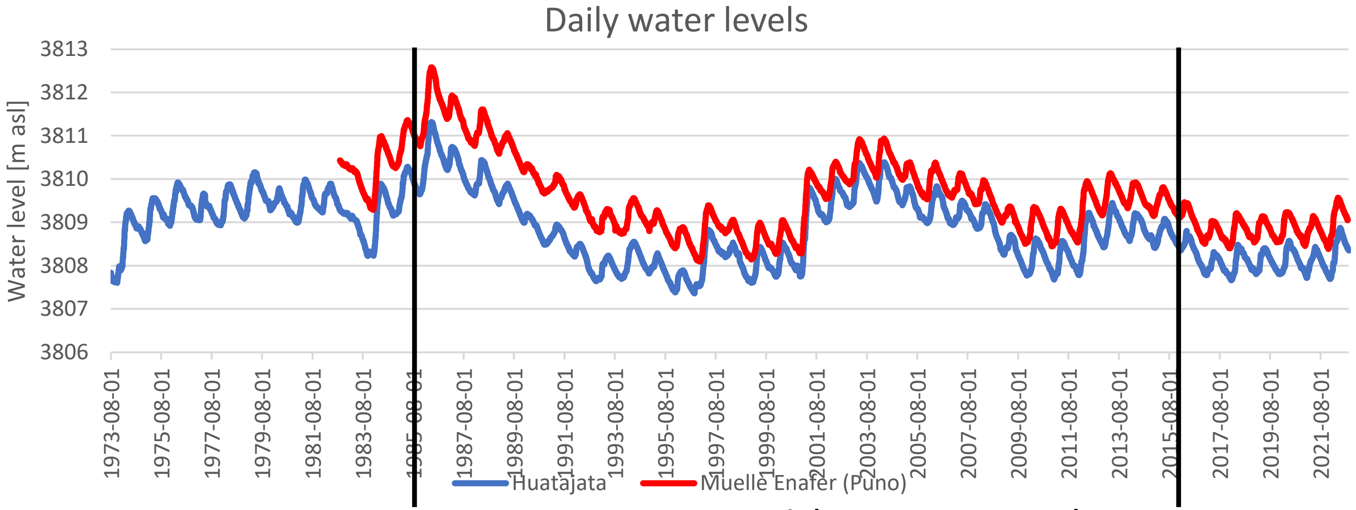
Available control data in streamflow and water levels (over time)

Streamflow data available (18)



30-year period (1985 – 2015)

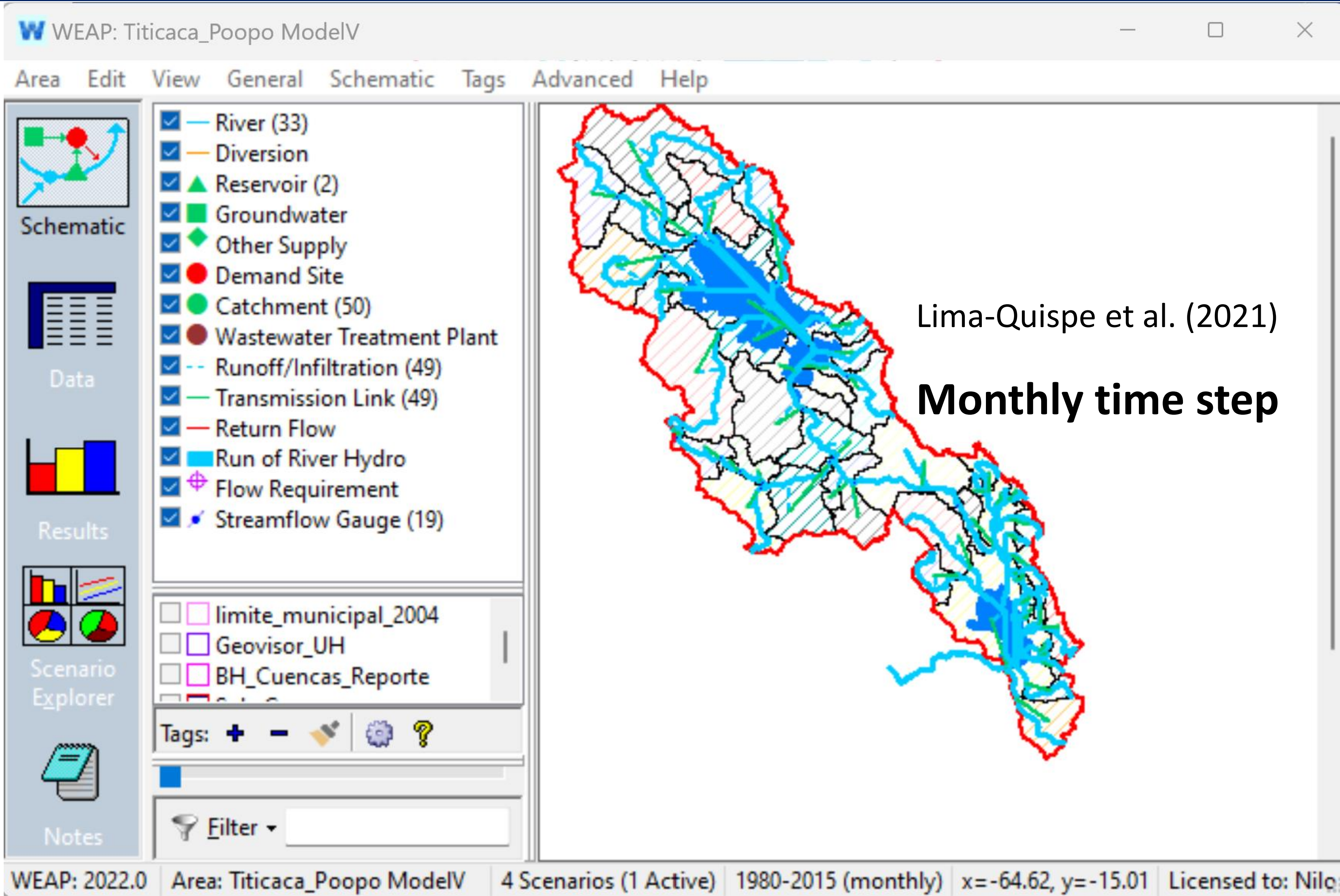
Water level-Lake Titicaca



Source: SENAMHI Bolivia and Peru

30-year period (1985 – 2015)

Models



Lima-Quispe et al. (2021)

Monthly time step

Integrated modeling chain at the daily time step

Hydrological model (catchment model)

- Snow and ice modeling
- Production (soil moisture) and routing

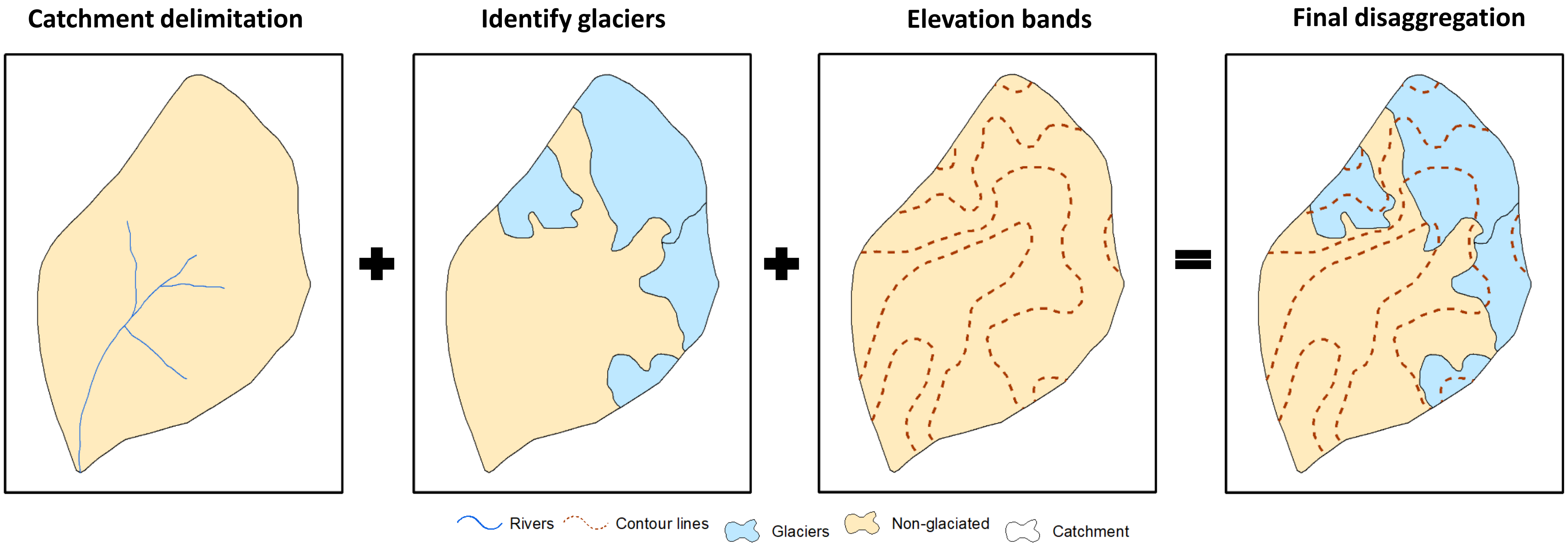
Irrigation model

- Phenological dynamics of crops (Kc)
- Land use dynamics
- Estimated net ET crop
- Return flows

Lake model

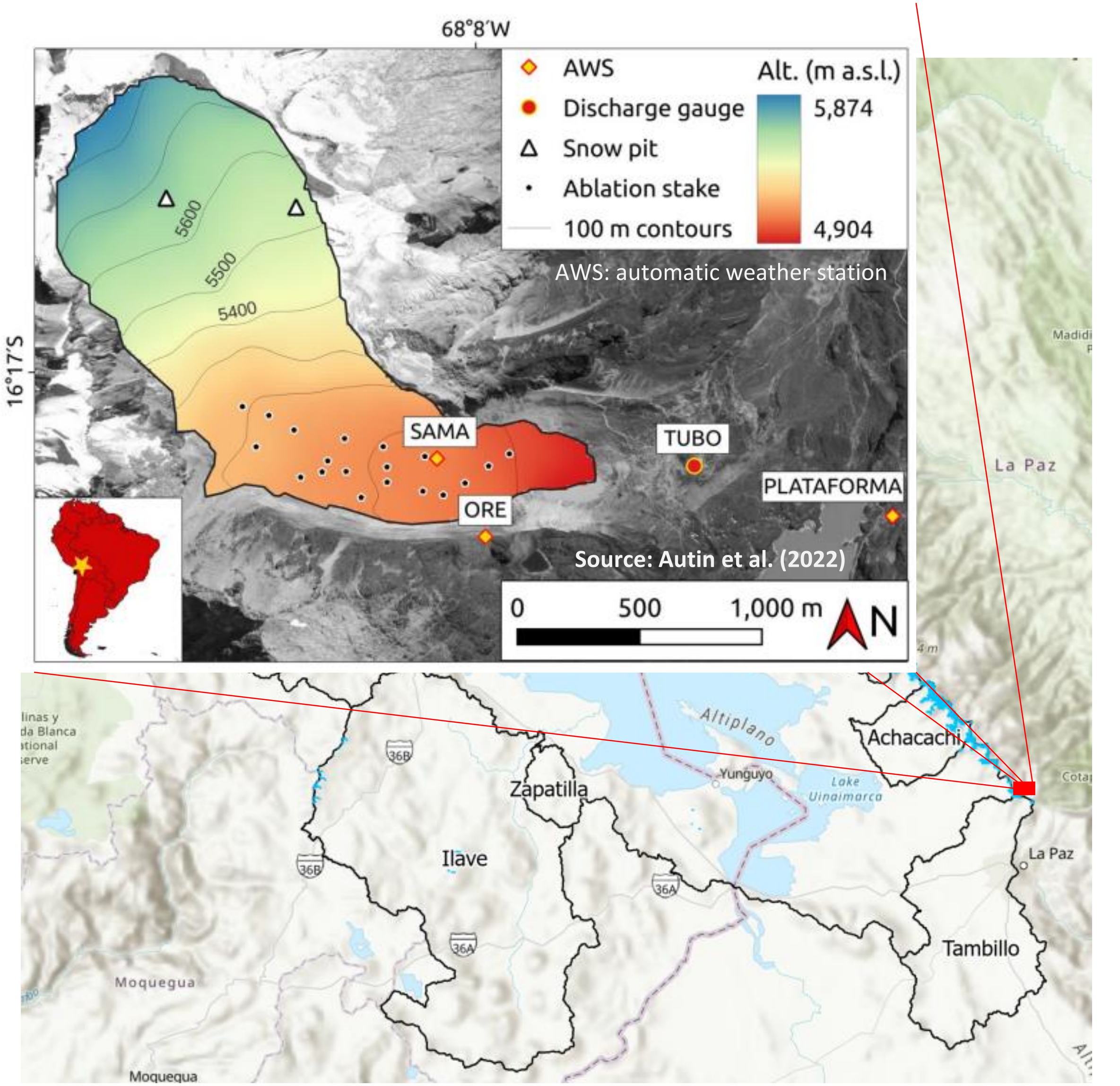
- Inflows (surface and groundwater)
- Direct precipitation and evaporation
- Bathymetry relationship between water volume and water levels
- Outflow (downstream, groundwater losses)

Snow and ice modeling: spatial disaggregation



Zongo site for calibration

- The Zongo glacier is the most studied glacier near the study area.
- It has data since the early 1990s.
- Some of the data collected are precipitation, temperature, humidity, wind, radiation, mass balances, ELA, etc.
- The area of the Catchment up to the Tubo station is 3.6 km^2.
- The glacierized area corresponds to 66%.



Snow and glacier model performance in Zongo

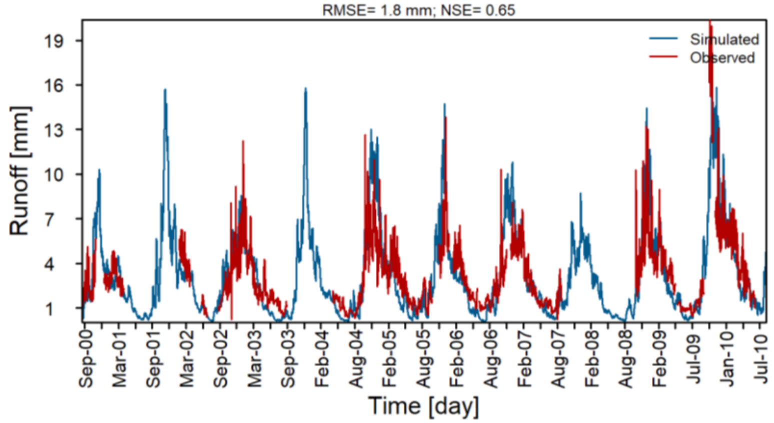
Model Parameters

N	Parameter	Unit	Comments
1	T_s	°C	Fixed
2	T_l	°C	Fixed
3	T_m	°C	Fixed
4	a_{snow}	mm/day/°C	Calibrated
5	a_{ice}	mm/day/°C	Calibrated
6	k_{snow}	day	Calibrated
7	k_{ice}	day	Calibrated

Input Data

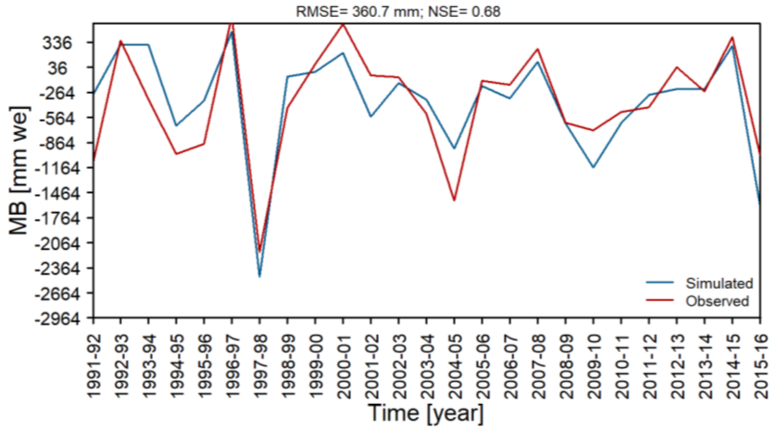
- Precipitation and air temperature: GMET
- Glacier thickness and area: RGI V6.0 and Farinotti et al. (2019)

Calibration

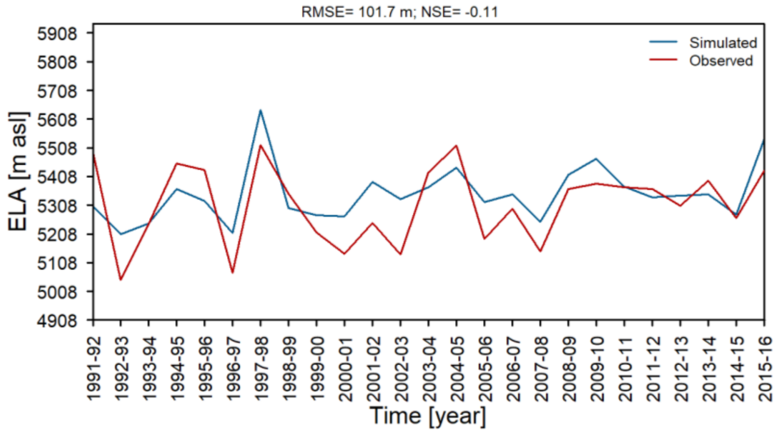


Does the model have internal consistency?

Mass balance

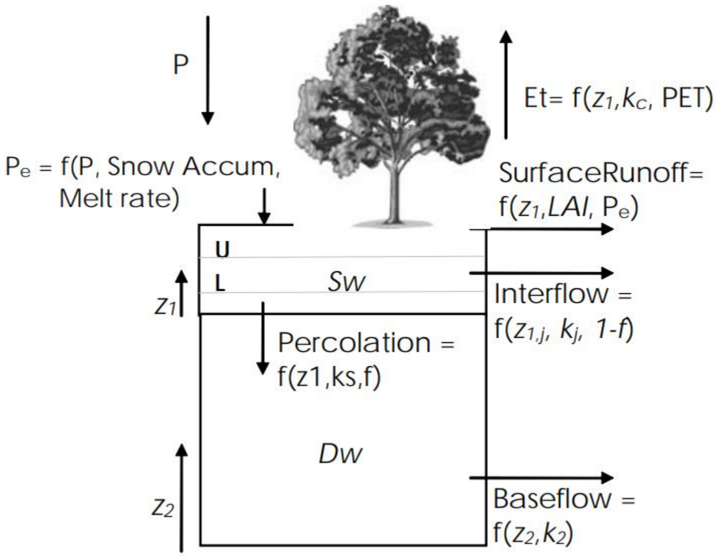


Equilibrium-line altitude



Hydrological models

Soil Moisture Model (SMM) part of WEAP



Source: Yates et al. (2005)

Model free parameters (7 could move to 9):

Rainfall-runoff (7):

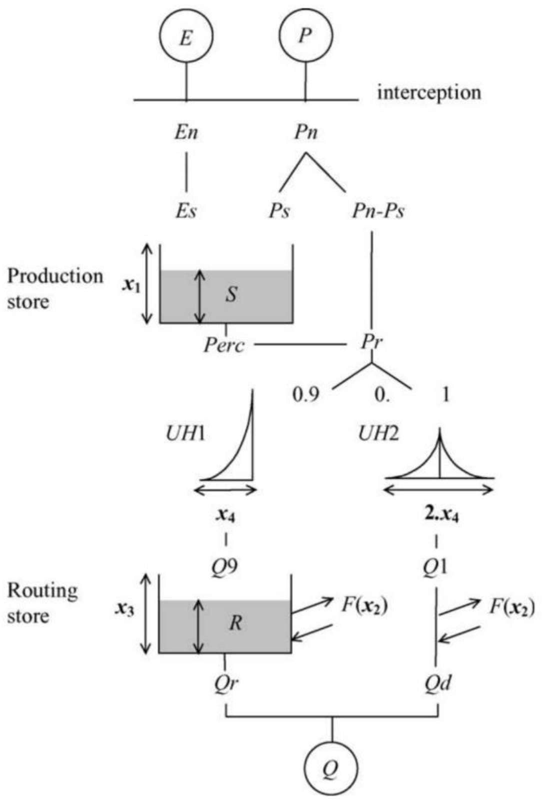
Kc: Crop coefficient
Sw: Soil water capacity (mm).
RRF: Runoff resistance factor.
Ks: Root zone conductivity.
f: Preferred flow direction.
Dw: Deep water capacity.
K_2: Deep conductivity

Irrigation (2):

Lt: Lower threshold in the soil moisture
Ut: Upper threshold in the soil moisture

This model was applied in previous study in lake Titicaca hydrosystem in monthly time step over 1980-2015 (Lima-Quispe et al., 2021)

Génie Rural à 4 paramètres en journalier (GR4J)



Source: Perrin et al. (2003)

Rainfall-Runoff (4):

x1: maximum capacity of the production store (mm).
x2: groundwater exchange coefficient (mm).
x3: one day ahead maximum capacity of the routing store (mm).
x4: time base of unit hydrograph UH1 (days).

Runs and model performance: SMM-WEAP

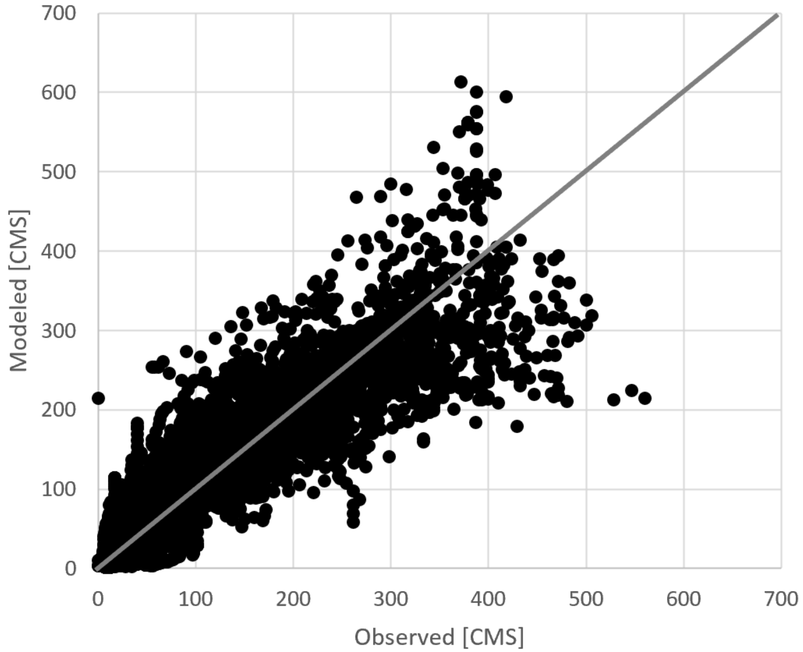
Defined ranges for Monte Carlo simulation

Parameters	Value	Unit
Crop coeficient (Kc)	[0.8 - 1.5]	-
Soil Water Capacity (Sw)	[50 - 400]	mm
Runoff Resistante Factor (RRF)	[1 - 20]	-
Root Zone Conductivity (Ks)	[0.5 - 10]	mm/d
Prefered Flow Direction (PFD)	[0.3 - 0.9]	-
Deep Water Capacity (Dw)	[50 - 500]	mm
Deep Conductivity (Dc)	[0.3 - 15]	mm/d
Solid threshold [Ts]	**-1**	**C**
Liquid threshold [Tl]	**3**	**C**

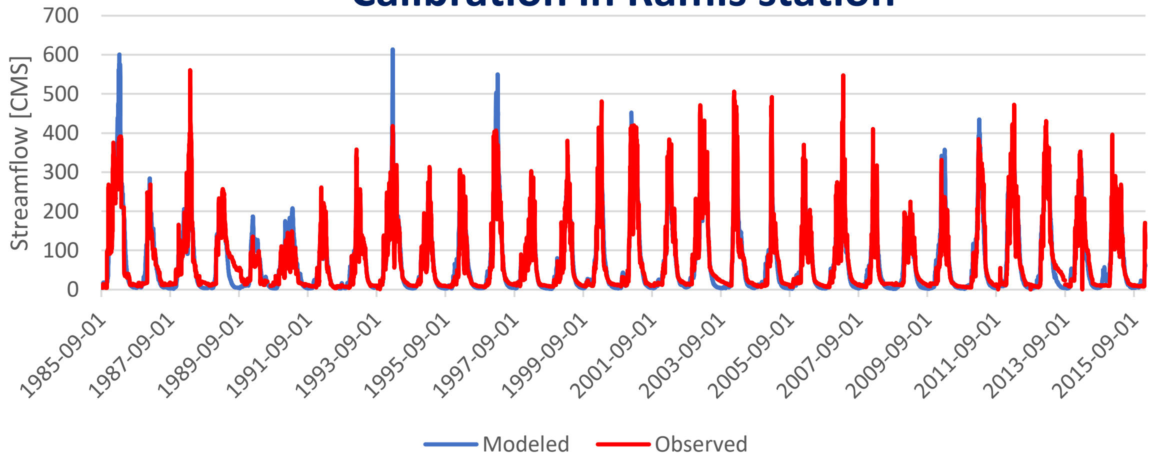
- 7 free parameters for calibration
- 2 fixed parameters of snow accumulation and melting

Runs setup

- **Calibration method:** random hypercube sampling
- **Number of runs:** 10 000
- **Calibration metrics:** NSE, KGE, NSElog (LNS)
- **Calibration period:** 1985-2015
- **Evaluation period:** Non
- **Precipitation input:** GMET
- **PET input:** Pisco (Huerta et al. 2022)



Calibration in Ramis station



PhD prospects

2022: O N D | 2023: J F M A M J J A S O N D | 2024: J F M A M J J A S O N D | 2025: J F M A M J J A S

	Activities/outputs
Hydrological modeling	Data collection and processing: PCP, Temp, and Q (Peru)
	Data collection and processing: HR, VV
	Data collection and processing: PE, SH
	Data collection and processing: Q (Bolivia)
	Review satellite data set
	Literature review (uncertainty, reg. of parameters, etc)
	Collect irrigation data
	Model implementation and calibration
	Analysis of outputs model
Future scenarios	Literature review (downscaling, uncertainty, etc)
	Download climate model dataset
	Assess the performance of the models
	Building climate scenarios
	Collection of management strategies
	Develop land use scenarios
	Runs of future scenarios and analysis
Papers	JP1 (Hydrological modeling) - submitted
	JP2 (Future scenarios) - submitted
Thesis	PhD questions and literature review
	Manuscript draft
	Review of the manuscript
	Manuscript final version
	Defense
Courses	Scientific and related to the thesis (40 hrs)
	Transversal (40 hrs)
	Professional (40 hrs)
Stays	France
	Peru
	Bolivia
Thesis committee	First thesis committee
	Second thesis committee

References

Huerta, Adrian, Vivien Bonnesoeur, José Cuadros-Adriazola, Leonardo Gutierrez, Boris F. Ochoa-Tocachi, Francisco Román-Dañobeytia, and Waldo Lavado-Casimiro., 2022. PISCOeo_pm, a Reference Evapotranspiration Gridded Database Based on FAO Penman-Monteith in Peru. Scientific Data 9(1):328. doi: 10.1038/s41597-022-01373-8

Lima-Quispe, Nilo, Marisa Escobar, Albertus J. Wickel, Manon von Kaenel, and David Purkey., 2021. Untangling the Effects of Climate Variability and Irrigation Management on Water Levels in Lakes Titicaca and Poopó. Journal of Hydrology: Regional Studies 37:100927. doi: 10.1016/j.ejrh.2021.100927.

Perrin, Charles, Claude Michel, and Vazken Andréassian., 2003. Improvement of a Parsimonious Model for Streamflow Simulation. Journal of Hydrology 279(1):275–89. doi: 10.1016/S0022-1694(03)00225-7.

Ronchail, J., Espinoza, J.C., Labat, D., Call`ede, J., Lavado, W., 2014. Evolucion del nivel del Lago Titicaca durante el siglo XX. Línea Base de Conocimientos Sobre Los Recursos Hidrologicos e Hidrobiologicos en el Sistema TDPS Con Enfoque En La Cuenca Del Lago Titicaca, p. 320. Quito, Ecuador.

Setegn, S.G., Rayner, D., Melesse, A.M., Dargahi, B., Srinivasan, R., 2011. Impact of climate change on the hydroclimatology of Lake Tana Basin, Ethiopia. Water Resour. Res. 47 https://doi.org/10.1029/2010WR009248.

Wurtsbaugh, W.A., Miller, C., Null, S.E., DeRose, R.J., Wilcock, P., Hahnenberger, M., Howe, F., Moore, J., 2017. Decline of the world’s saline lakes. Nat. Geosci. 10, 816–821. https://doi.org/10.1038/ngeo3052.

Yates, D., Sieber, J., Purkey, D., Huber-Lee, A., 2005. WEAP21—A demand-, priority-, and preference-driven water planning model: part 1: model characteristics. Water Int. 30, 487–500. 20