

## Mass balance estimation on the Zongo glacier, Bolivia, using a semi-distributed conceptual model (SCM)

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### Resumen

En el caso de un glaciar, el balance de masa sirve para cuantificar los procesos de acumulación y de derretimiento que experimenta un glaciar. Con esta información se puede inferir la variación de la cantidad de agua que se encuentra en reserva y así tomar decisiones con base en la oferta y demanda hídrica. El objetivo de este trabajo es mostrar los resultados de una modelación del balance de masa aplicada al Glaciar Zongo en Bolivia. El modelo utilizado es un modelo conceptual semidistribuido (Schaepli et al., 2005). Se evaluó la sensibilidad mensual de predicción del balance de masa y de la descarga para los años hidrológicos 2004-2006.

Nuestros resultados muestran que el modelo presenta valores de descarga y balance de masa con un error de MAE de 2.4 y un BIAS de 1.3 con respecto a los datos observados en el glaciar. Los modelos conceptuales simples pueden ser una herramienta valiosa para proyectar el comportamiento de una cuenca glaciar, pero si solo se cuenta con suficiente información para la calibración y validación de los parámetros del modelo.

### Abstract

The mass balance of a glacier is used to quantify the accumulation and melting processes, which affect its mass. With this information, it is possible to infer the variation in water reserves, which will support decision-making based on the supply and demand of water. The objective of this work is to show the results of a mass balance model applied to the Zongo Glacier in Bolivia. The model used is a semi-distributed conceptual model (Schaepli et al., 2005). The monthly sensitivity of the mass balance and discharge predictions was evaluated for the hydrological years 2004-2006.

Our results show that the model presents discharge and mass balance values with an MAE error of 2.4 and a BIAS of 1.3 concerning the data observed in the glacier. Simple conceptual models can be a valuable tool to project the behavior of a glacial basin, but only if it has sufficient information for the calibration and validation of the model parameters.

## 1. Introduction

The estimation of discharge over a basin is a key aspect of hydrological studies, especially in the context of climate change, where the melting regime shows significant variations, particularly in highland regions with tropical glaciers (Hoffmann, 2006). High-mountain hydrology is commonly modeled using conceptual approaches that simulate accumulation and ablation using time series of temperature and precipitation as input data (Schaeffli et al., 2005). These empirical models, which are easy to implement, allow complex processes to be represented by time- and location-based parameterizations.

However, the growing need to simulate melt rates with high temporal and spatial resolution has motivated the development of hybrid approaches that integrate the accuracy of physically based models in energy balance with the simplicity of temperature index models (Hock, 2003; Pellicciotti et al., 2005). In this context, the climatic variables such as temperature and precipitation are essential for estimating discharge in regions where snow and ice storage control the hydrological regime (Braun et al., 2000). Several studies have proposed methodologies to address this problem in basins difficult-to-access, including semi-distributed models with calibration of hydrometeorological parameters (Braun & Renner, 1992; Willis & Bonvin, 1995; Schaeffli et al., 2005).

When the meteorological data come from distant stations, the careful variable selection and appropriate extrapolation methods allow for the improvement of the reliability of simulations (Magnusson et al., 2011). In the tropical Andes, glacier retreat has been particularly marked in recent decades (Rabatel et al., 2013; Masiokas et al., 2020), with the Zongo glacier being a reference case due to its continuous monitoring since 1991 (Francou et al., 1995).

In this study, we propose a modification to the semi-distributed conceptual model developed by Schaeffli et al. (2005), adapted to high-altitude conditions. The model operates with a monthly time step during the melt season to analyze its impact on glacier mass balance and discharge simulations.

## 2. Study Area

The study was conducted on the tropical Zongo glacier located in the Huayna Potosí massif in the Cordillera Real, Bolivia (16°15'S, 68°10'W), Figure 1, 30 km north of La Paz, between the dry Altiplano plateau in the west and the humid Amazon basin in the east. It extends from 4900 to 6000 m a.s.l., covering an area of 1.90 km<sup>2</sup> (Francou et al., 1995; Soruco et al., 2009).

## 3. Methodology

### 3.1. Glacio-Hydrological melting model

In this study, the degree-day model proposed by Schaeffli et al. (2005) was used. This conceptual and semi-distributed GSM-SOCONT model was designed to estimate melt rates (discharges) and glacial mass balance at daily time steps and in projects to evaluate the impacts of climate change. The basin is represented as a set of spatial units, each assumed to have homogeneous hydrological behavior. For each unit, meteorological data series are calculated from observed data from weather stations in the glacial basin. Based on these series, the

snow accumulation and snow and ice melting are simulated. A reservoir-based modeling approach is used to simulate the hydrological response, i.e., precipitation and the transformation of meltwater into runoff, for each unit. Runoff contributions from all units are summed to provide the total discharge at the outlet for the entire basin (Schaeffli et al., 2005).

In the present model, this simplification is justified by the fact that the studied basin is relatively small and has a steep slope, with a runoff coefficient of 0.8 (Wagnon et al., 1999) and (Sicart et al., 2007). Simulations are performed for each elevation band of the basin separately. In this work, the model structure was modified for a monthly temporal resolution, thus generating a degree-month model whose formulation is presented below.

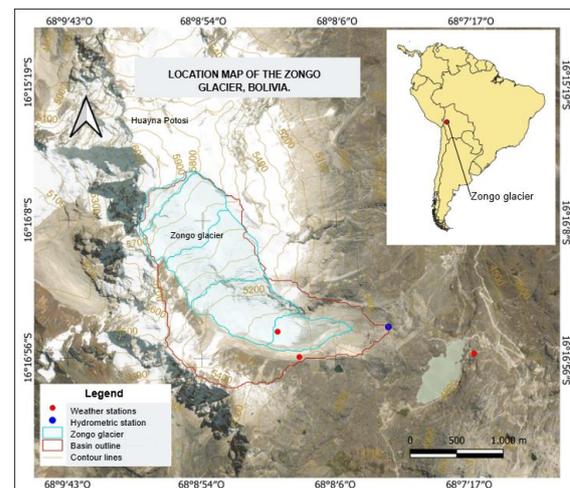


Figure 1: Zongo Glacier location and Huayna Potosí Oeste in the Cordillera Real; (b) The Huayna Potosí Massif.

### 3.1.1. Basin discretization

The model has two discretization levels: The first level corresponds to the separation between ice-covered and ice-uncovered areas within the basin based on digital land cover data. Each of these areas is characterized by its surface and hypsometric curve, derived from the ASTER GDEM digital elevation model, which provides global coverage between latitudes 83° N and 83° S with a vertical accuracy of 20 m and a horizontal accuracy of 30 m (Tachikawa et al., 2011). Although the glacier surface area is assumed to remain constant during the simulation period (short-term), this approximation does not always represent the actual dynamics of glacier retreat (Schaeffli et al., 2005). The second level of discretization consists of dividing each basin area into elevation bands (Figure 2), determined from the ASTER GDEM digital elevation model. Time series of precipitation, temperature, and runoff were calculated independently for each band. Runoff generation varies depending on whether the band corresponds to an area covered by ice or not.

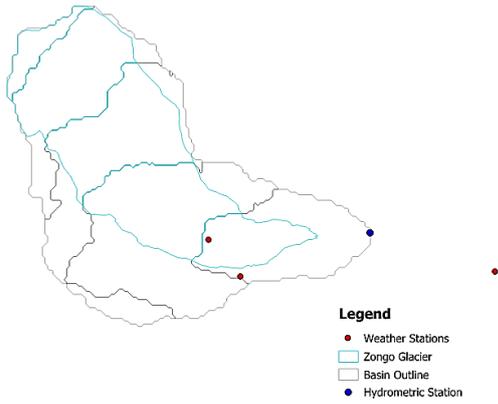


Figure 2: Discretization of the Zongo basin into a set of four elevation bands with 310 m intervals.

The model was applied to the Zongo Glacier basin for two consecutive hydrological years (September 2004–August 2005 and September 2005–August 2006), using data from weather stations, hydrometric stations, satellite images, and elevation models. In particular, air temperature and precipitation records from the automatic weather station located at 5050 m a.s.l. (ORE Zongo) were used to feed a semi-distributed conceptual model. The discharge estimate was based on the calibration of three key parameters: the degree-month factor for snow ( $a_{snow}$ ) and the degree-month factor for ice ( $a_{ice}$ ), and the threshold temperature ( $T_o$ ). Ranges adopted from Condom et al. (2012) are presented in Table 1:

Table 1: Parameter ranges  $a_{snow}$ ,  $a_{ice}$ , and  $T_o$ , (from literature).

Parameter	Unit	(Condom et al., 2012)
Monthly degree snow factor ( $a_{snow}$ )	mm/°C/month	(40 to 400)
Monthly degree ice factor ( $a_{ice}$ )	mm/°C/month	(165 to 600)
Temperature threshold ( $T_o$ )	°C	(-2 to 2)

### 3.1.2. Spatialization of temperature data

In mountain basins, one of the most complex challenges relates to the availability of input meteorological information, especially at high altitudes. This complicates model calibration and validation, generating uncertainty due to high spatial and altitudinal variability (Schaeffli et al., 2005). The following equation, based on a thermal gradient, is used to estimate monthly temperature in different elevation zones:

$$T_j = T_{ref} + \gamma \cdot (h_{ref} - h_j) \quad (1)$$

Where  $T_j$  is the temperature (°C) at elevation zone  $j$ ,  $T_{ref}$  is the temperature (°C) measured at a reference station,  $\gamma$  is the thermal gradient (°C/100m), and  $h_{ref}$  and  $h_j$  are the elevation (m a.s.l.) of the reference station and the elevation zone  $j$ , respectively.

Similarly, precipitation was expressed with:

$$P_j = P_{ref} \cdot [1 + \gamma_p \cdot (h_j - h_{ref})] \quad (2)$$

Where  $\gamma_p$  is the precipitation gradient as a function of height (%/100m). They were taken  $\gamma$  and  $\gamma_p$  equal to 0.65°C/100 m and 0%/100 m, respectively.

Elevation zones are divided into bands, where temperature, precipitation, and runoff series are calculated separately.

### 3.1.3. Accumulation and melting of snow and ice

The evolution of snow cover in each elevation band is estimated using an accumulation and melting index (Schaeffli et al., 2005). The precipitation phase (snow or rain) is determined based on the air temperature estimated for the mean elevation of each band. Since these bands cover significant altitudinal ranges, temperature differences within each band can generate different precipitation phases simultaneously. Therefore, the fraction of solid or liquid precipitation is distinguished using a critical temperature  $T_c$  equal to 0 °C, then:

$$P_{snow} = P_{tot}, P_{liq} = 0, T \leq T_c \quad (3)$$

$$P_{snow} = 0, P_{liq} = P_{tot}, T > T_c \quad (4)$$

Where  $P_{tot}$  is the total monthly (mm),  $P_{snow}$  is the solid precipitation in (mm),  $P_{liq}$  is the liquid precipitation (mm), and  $T$  is the temperature at (°C).

Determining the phase of precipitation is critical for modeling hydrological processes, as errors in this estimate can underestimate the amount of water stored as snow or generated runoff (Schaeffli et al., 2005b). Furthermore, temperature and relative humidity also influence the phase of precipitation. (Froidurot et al., 2013).

### 3.1.4. Evolution of the snow cover.

The correct estimation of initial snow cover is key to adequately simulating flows in hydrological models. Given that observational data on snow are scarce and difficult to spatialize, one alternative is to initialize the model with a warm-up period, which simulates the previous evolution of water storage. This period, compared to a year, is especially relevant in mountain basins with seasonal snowfall (Musy et al., 2014). In the case of tropical glaciers, this condition is more flexible due to their distinct seasonality.

The evolution of the snow cover,  $H_{snow}$  (mm) it is calculated as:

$$H_{snow,n} = H_{snow,n-1} + P_{snow,n} - M_{snow,n} \quad (5)$$

Where  $H_{snow,n-1}$  is the height of the snow (mm w.e.),  $P_{snow,t}$  is the snow precipitation in (mm/month w.e.),  $M_{snow}$  (mm/month w.e.) is the calculated melting, and  $n$  is the monthly value in which the calculation is made.

The Snow melting is estimated as:

$$M_{snow,n} = \begin{cases} a_{snow} * (T_n - T_o) & \text{if } T_n > T_o, H_{snow,n-1} > 0 \\ 0 & \text{otherwise} \end{cases} \quad (6)$$

Where  $a_{snow}$  (mm/°C/month) is the degree month factor for snow,  $T_o$  the threshold temperature (°C) and  $H_{snow,n-1}$  (mm/month w.e.), the snow Depth at the beginning of the time step  $t$ .

For ice melting over glacier-covered areas, a similar expression applies:

$$M_{ice,n} = \begin{cases} a_{ice} * (T_n - T_o) & \forall j \in G \text{ if } H_{snow,n} = 0 \\ 0 & \text{if otherwise} \end{cases} \quad (7)$$

Where  $a_{ice}$  (mm/°C/month) is the ice degree-month factor and  $G$  is the glacier. In the absence of precise estimates of ice volume in each band, infinite availability is assumed for long periods, and glacier extent is updated annually (Schaeffli & Huss, 2011).

The parameters  $a_{snow}$ ,  $a_{ice}$ , and  $T_0$  are calibrated based on previous literature. For the monthly model, the values would vary between 40 to 400 mm month<sup>-1</sup> °C<sup>-1</sup> for snow and 165 to 600 mm month<sup>-1</sup> °C<sup>-1</sup> for ice (Condom et al., 2012). The threshold temperature is set between -2°C to 2 °C.

The total discharge generated is estimated as:

$$Q = \sum_{j=1}^n (M_{snow,j} + M_{ice,j} + P_{liq,j}) \cdot A_j \quad (8)$$

Where  $Q$  is the caudal in m<sup>3</sup> s<sup>-1</sup> and  $A_j$  is the area covered by glaciers in elevation band  $j$ .

The model also allows for the estimation of the annual mass balance, a key variable for assessing mass exchanges between the glacier and the atmosphere (Paterson, 1994). For each elevation band, this is calculated as:

$$b_{a,j} = \int_{t_0}^{t_1} [P_{snow}(t) - M_{snow}(t) - M_{ice}(t)] dt \quad (9)$$

Where  $b_{a,j}$  is the annual mass balance (mm) for elevation band  $j$ ,  $t_0$  is the start date of the hydrological year (September 1), and  $t_1$  is the end date of the hydrological year (August 31 of the following year). The annual mass balance of the entire glacier is estimated as the area-weighted average of the mass balance determined for all elevation zones:

$$B = \frac{1}{A} \sum_{j=1}^n (b_{a,j} \cdot A_j) \quad (10)$$

### 3.1.5. Parameter Calibration

Parameter calibration was carried out using a manual adjustment procedure, in which the values of the degree-month factor parameters for snow ( $a_{snow}$ ) and ice ( $a_{ice}$ ), as well as the threshold temperature ( $T_0$ ), were iteratively varied, without exceeding the ranges reported in the literature (Condom et al., 2012). In each iteration, the simulated flows were compared with the observed flows, prioritizing configurations that produced time series and flow curves with a shape and magnitude similar to the observed measurements. This strategy allowed for the identification of the set of parameters that best reproduced the mass balance and hydrological dynamics of the basin.

## 4. RESULTS

Figure 3 and Figure 4 show the monthly precipitation and temperature time series used as input data for the semi-distributed conceptual model, corresponding to the period September 2004 – August 2006.

During this time, a constant glacier area of 1.9 km<sup>2</sup> was assumed. At the same time, monthly hydrometric records of the basin were collected, which were essential for calibrating the melt model.

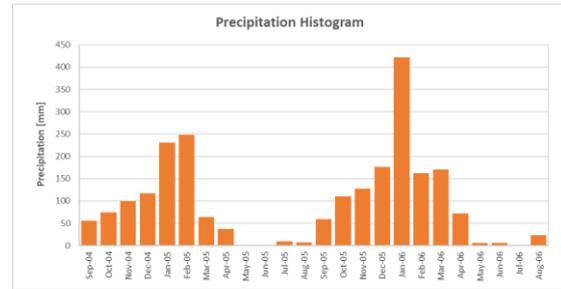


Figure 3. Monthly precipitation time series used in the model

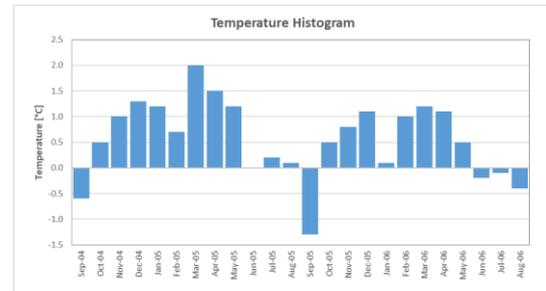


Figure 4. Monthly temperature time series used in the model

The calibration process was based on combinations of the parameters  $a_{snow}$ ,  $a_{ice}$ , and melting threshold temperature ( $T_0$ ) reported in the literature. Among the different combinations tested, two representative simulations stood out:  $Q_{sim2}$ , which showed better performance in estimating the annual mass balance, and  $Q_{sim4}$ , which presented the best fit between the simulated and observed flows (see Table 2).

In particular,  $Q_{sim4}$  achieved an MAE of 1.48 and an RMS of 1.87, demonstrating its greater predictive capacity for monthly flow dynamics. For its part,  $Q_{sim2}$  more accurately approximated the annual mass balance values, especially in 2005–2006, where the simulated value coincided with the observed value (-197 mm w.e.). Table 2 summarizes the calibrated parameters and performance metrics for the different simulations.

Table 2: The values of the melting threshold temperature ( $T_0$ ), the degree-month factor for snow ( $a_{snow}$ ) and for ice ( $a_{ice}$ ) are shown, together with the hydrological adjustment indicators: mean absolute error (MAE), root mean square error (RMS), Nash–Sutcliffe efficiency coefficient (NSE) and coefficient of determination ( $R^2$ ).

	$Q_{sim 1}$	$Q_{sim 2}$	$Q_{sim 3}$	$Q_{sim 4}$
$T_0$ [°C]	-0.1	-0.5	-0.7	-0.6
$a_{snow}$ [mm/mes °C]	350	314	100	179
$a_{ice}$ [mm/mes °C]	400	400	400	400
MAE [l/s]	1.85	2.48	1.64	1.48
RMS [l/s]	2.45	3.27	2.26	1.87
NSE	0.19	-0.45	0.31	0.53
$R^2$	0.73	0.77	0.80	0.78

The hydrographs in Figures 5 and 6 illustrate the monthly behavior of observed versus simulated flow. Although the

overall model trend is satisfactory, an overestimation is observed in March and April, with differences of up to twofold, possibly due to an overestimation of melting.

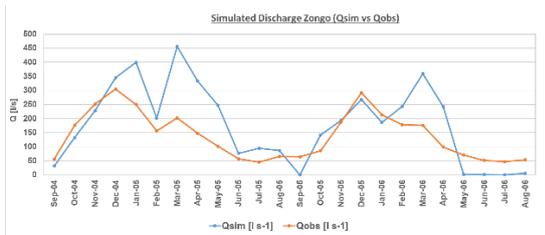


Figure 5. Hydrograph of discharge flow observed at the monthly level (orange line) and simulated by the model (blue line) simulated flow  $Q_{sim2}$  during the period 2004-2006.

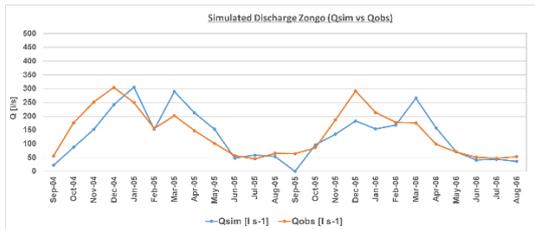
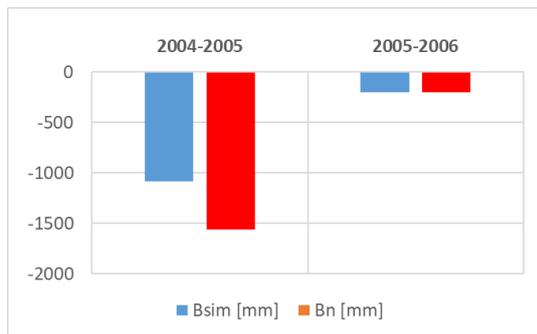


Figure 6. Hydrograph of discharge flow observed at the monthly level (orange line) and simulated by the model (blue line) simulated flow  $Q_{sim4}$  during the period 2004-2006.

Finally, to assess the glaciological representation of the model, the annual mass balance was calculated from the results of  $Q_{sim2}$  (Figure 7). The model reproduces the negative trend in mass balance, although with important differences in 2004 to 2005 (-1083 mm w.e. simulated vs. -1559 mm w.e. observed). However, for 2005 to 2006, the simulated value coincided with the observed value (-197 mm w.e.).



Date	Simulated	Observed
	$B_{sim}$ [mm w.e.]	$B_n$ [mm w.e.]
2004-2005	-1083	-1559
2005-2006	-197	-197

Figure 7. Annual mass balance for the period 2004-2006.

## 5. DISCUSSION

The results show that the conceptual semi-distributed model (SCM) adequately reproduces the monthly flow dynamics and mass balance of the Zongo Glacier. The

performance metrics for the  $Q_{sim4}$  simulation (MAE = 1.48 l/s; RMS = 1.87 l/s; NSE = 0.53;  $R^2 = 0.78$ ) indicate a satisfactory fit between observed and simulated flows, although the seasonal analysis shows a slight overestimation during the wet season and an underestimation during the dry season. This behavior highlights the model's sensitivity to precipitation seasonality and the monthly temporal resolution, which tends to smooth out flow peaks and hinders the representation of rapid melting events.

Manual calibration of key parameters ( $a_{snow}$ ,  $a_{ice}$ , and  $T_0$ ) allowed the simulated flows to be adjusted against observed flows, considering parameters from the literature (Condom et al., 2012), achieving a consistent representation of accumulation and melting processes. The choice of  $Q_{sim4}$  as the most representative simulation is due to the fact that, while other simulations showed comparable statistical performance,  $Q_{sim4}$  achieves a better balance between hydrograph shape and flow magnitude, prioritizing comprehensive hydrological coherence over minimal local deviation.

However, it is important to recognize the inherent limitations of this approach. The resolution of the ASTER GDEM digital elevation model (20 m), the extrapolation of meteorological data, and the conceptual simplification of the reservoir can introduce uncertainty, particularly during periods of intense thawing. By not considering processes such as groundwater flow, deep percolation, or the influence of permafrost, the model tends to underestimate the true complexity of the hydrological system. A preliminary sensitivity analysis showed that variations of  $\pm 10\%$  in degree-month factors can modify the annual mass balance by up to  $\pm 15\%$ , demonstrating the importance of these parameters in the simulation.

Despite these limitations, the results are consistent with previous studies on tropical Andean glaciers, where conceptual models such as GSM-SOCONT have shown comparable performance to more complex models such as HBV or SRM (Pellicciotti et al., 2005; Condom et al., 2012). This supports the usefulness of simple conceptual models for estimating water resources under data-limited conditions. Future integration of additional observations, remote sensing, and climate models could improve the representation of spatial and temporal variability, especially during periods of high melting and extreme events.

## 6. CONCLUSIONS

This study demonstrates that simple conceptual models can be useful tools for estimating flow dynamics and mass balance in tropical glaciers, provided careful calibration of the key parameters is performed. Among the simulations performed,  $Q_{sim4}$  showed the best hydrological fit (MAE = 1.48 l/s; RMS = 1.87 l/s; NSE = 0.53;  $R^2 = 0.78$ ), adequately reproducing monthly flow dynamics compared to the others.  $Q_{sim2}$ , on the other hand, showed the best glaciological performance, more accurately approximating the annual mass balance, particularly for the 2005–2006 period, where the simulated value coincided with the observed value (-197 mm w.e.).

These results reflect the compromise between faithfully representing the annual glaciological signal ( $Q_{sim2}$ ) and reproducing monthly hydrological dynamics ( $Q_{sim4}$ ), reinforcing the importance of considering multiple validation metrics when evaluating model performance.

The quality of simulations depends largely on the accuracy of the available meteorological, hydrometric, and topographic data, as well as on the model's ability to represent the high spatial and temporal variability of tropical glaciers. In this sense, the results underscore the need to adjust parameters according to the particular characteristics of each glacier and its environment.

In summary, simple conceptual models like the one used in this study can be useful tools for predicting the hydrological behavior of glacial catchments in contexts with limited in situ data, provided careful calibration is performed. The integration of satellite observations, remote sensing products, and climate models tailored to local conditions represents a promising avenue for improving the representation of spatial and temporal variability, thus strengthening hydrological projections and the sustainable management of glacial water resources.

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