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WATER BALANCE OF GLACIERIZED CATCHMENTS IN TROPICS: A CASE STUDY IN BOLIVIAN ANDES

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On outer-tropical glaciers, mostly in Peru and Bolivia, ablation and accumulation occur all year round whereas maximum in wet seasons. This study investigated glacier mass balance and catchment scale water balance of Glacier Tuni and Huayna Potosi, which locate at the west side of Bolivian Andes. Remote sensing and hydrological methods have been applied to conduct glacier mass balances monthly and annually in recent years. With remote sensing method, glacier volume change has been derived based on glacier area change obtained utilizing cloud free Landsat Thematic Mapper (TM) scenes. Results of commonly negative glacier mass balance have revealed that glaciers in this region are retreating. Despite of interests on glaciological aspects, water balances of glacierized catchments have been carried out. Except for in a few months glaciers got positive mass balance, glaciers continuously contributed to discharge.

Key Words: *Glacier mass balance, water balance, tropical glacier, remote sensing*

1. OBJECTIVE

Approximately 99% of tropical glaciers are located in South America which store large volumes of precipitation during wet seasons and gradually release into rivers in dry seasons[1), 2)]. The dry Andes in South America, where glaciers feed rivers all year round, are the regions where most at risk from glaciers melting due to climate change. The selected glaciers in this study, Glacier Tuni and Huayna Potosi in Bolivian Andes are the major water resources for the two main cities nearby, La Paz and El Alto. The rapid glacier retreat may lead to water shortages for millions of local residents depending on glacier melting water in the way of drinking and hydroelectric power. Therefore, glacier mass balance and water balance of glacierized catchments in this region are essential to estimate water availability for the future. In addition, catchment-scale water balance will become significant after the glaciers retreat or complete disappearance. Therefore, water balance characteristics are also need to be clarified.

Previous studies in Bolivian Andes focused on Glacier Zongo which has been under a glaciological program by the Institut de Recherche pour le Développement (IRD), France since 1991[3), 4)]. Previous studies showed great interests in energy balance of glacier surface[5)], glacier mass balance[4)], or runoff directly from glacier[3)]. Three main methods have been applied to assess glacier mass balances using glaciological data[3)], hydrological data[4)] and geodetic data[6)]. Hydrological analysis has been performed to compare mass balance derived from glaciological and hydrological methods, concluded that hydrological method gives lower mass balance than glaciological method[7)]. Later studies utilized photogrammetric data to reconstruct the cumulative glacier mass balance and achieved satisfactory agreements[6)]. However, for Glacier Tuni and Huayna Potosi that this study concerns, there are either field measurements available for glaciological methods or high resolution aerial images with short time intervals for geodetic methods. Therefore, an independent method utilizing satellite images has been developed in this study to assess glacier mass balance comparing with hydrological method. Another purpose is to obtain water balance of the glacierized catchments. There are few studies working on the catchment-scale water balance in tropical glacierized regions.

2. STUDY AREA

Glacier Tuni and Huayna Potosi are located in the Southern part of Cordillera Real, Bolivia (16°S, 68°W), 30km north of La Paz, with dry Altiplano in the west and wet Amazon in the east. Tuni catchment is 9.78km^2 with about 7.50% covered by glaciers, while Huayna Potosi catchment is 7.99 km^2 with about 22.88% of its area glacierized. The catchments with altitudes ranging from 4400 m to 6000 m a.s.l have been covered by Landsat TM scenes available online since 1980s (**Fig. 1**).

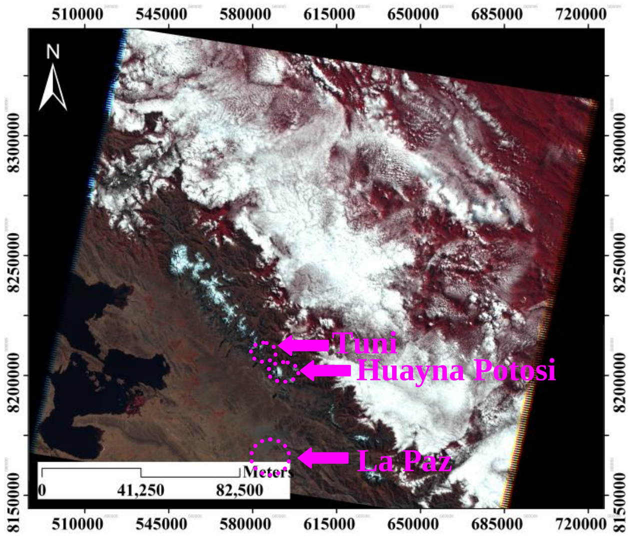

Fig. 1 Overview of the study region (Landsat TM with RGB=432, July 26th, 2008)

The meteorological conditions of the region are determined by seasonal oscillation in the intertropical convergence zone (ITCZ). During winter, the ITCZ is north of Bolivia and tropical anticyclones produce a cold and dry season, whereas in summer, from December to March, is the wet and warm, coinciding with the eastern intertropical flux that brings water vapour from the Atlantic[4]. The intertropical zone has been further distinguished into two regions: the inner tropics with almost no seasonality in precipitation and the outer tropics with strong seasonality in precipitation[2]. The meteorological differences have greatly influenced glacier mass balance. In the inner tropics, both accumulation and ablation occur throughout the year. In the outer tropics, accumulation and ice/snow melt occur mainly during wet seasons. During dry seasons, ice/snow melt reduces and ice/snow sublimation increases[8), 9]. Glaciar Tuni and Huayna Potosi focused in this study are located in the outer tropics[9]. Examples of precipitation, air temperature and discharge of Huayna Potosi catchment are shown in **Fig. 2**.

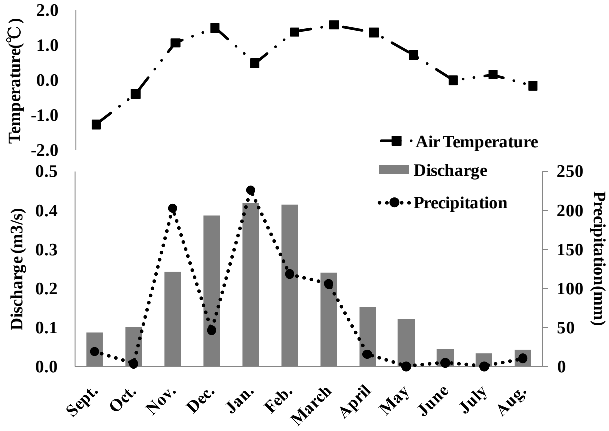

Fig.2 Precipitation, discharge and air temperature of Huayna Potosi from Sept. 2005 to Aug. 2006

3. METHODOLOGY

Glacier mass balances of Glacier Tuni and Huayna Potosi and water balances of each catchment have been constructed respectively in 2000s using remote sensing and hydrological data.

(1) Remote sensing method

Catchment boundaries have been identified and conducted using ASTER 30m Global Digital Elevation Model (DEM) data.

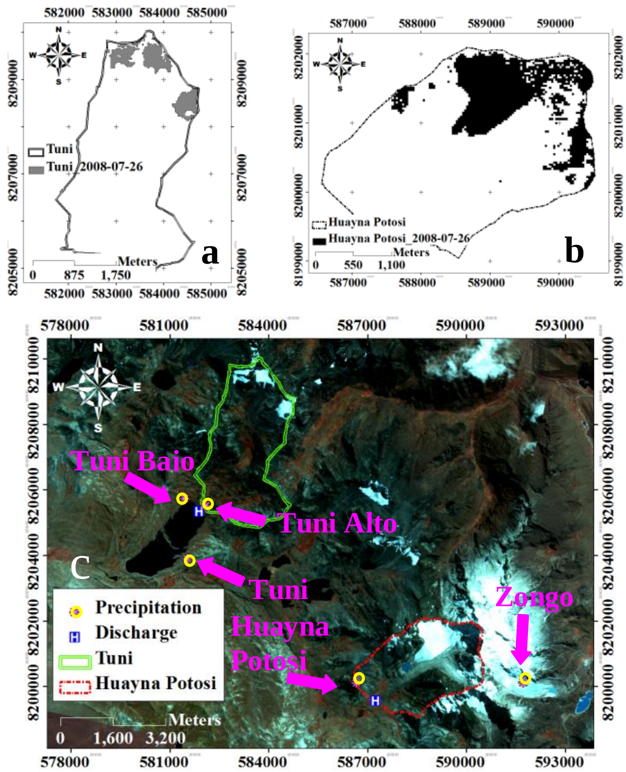

Fig. 3 Glacier outlining (a:Tuni,b:Huayna Potosi) by L4/L5>5 comparing to ALOS image (c)

Glaciers have been identified with scenes of Landsat TM. The individual bands TM4 (near - infrared: 0.76 – 0.90μm) and TM5 (mid - infrared: 1.55 – 1.75μm) of Landsat TM have been converted to at - sensor spectral radiance (L_λ) [10]. Band ratio L4/L5 when greater than 5 has been proved to be better suited threshold value in outlining glacier maps validated by comparing to ALOS AVNIR-2 images (**Fig. 3**)[11]. This method has well defined glacier under the shadow according to the false color composite by ALOS and field observation. The accuracy of remote sensing method depends on data process, which has been evaluated within 5% by comparing to true value.

Methods of converting glacier area to volume have been proved to have satisfactory agreement with field measurements[12] (**Fig. 4**). Glacier areas obtained in our study region ranging from 0.68 to 1.85 km^2, which lay within the scale of previous study observed; therefore the relationship shown in **Fig.4** were used in this study.

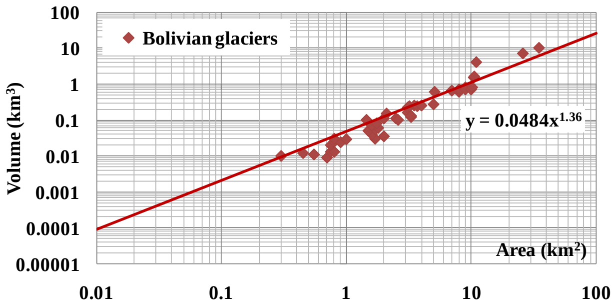

Fig. 4 Relationship between glacier area and volume in Bolivian Andes[12]

(2) Hydrological method

By neglecting the amount of ice and snow lost by sublimation, the glacier mass balance b_h can be calculated from the difference between precipitation and discharge out of basin[7]:

$$b_h = P - 1/S_g\,[Q - (S - S_g)c_e\,P] \quad (1)$$

Where S_g is the glacier area (m^2), S is the basin area (m^2), Q is the discharge out of the basin ($m^3 year^{-1}$) and c_e is the runoff coefficient (ratio of runoff to precipitation) of the non-glacierized surface. P is the average of the precipitation in the basin.

In this study, the value 0.8 has been used for runoff coefficient c_e of the area not covered by glaciers[4]. According to field observations, most of the regions are covered with almost impermeable rocks. Therefore, the value 0.8, which was roughly estimated in previous study[4], is reasonable though the uncertainty of which remains unknown. Large value of c_e decreases the fraction of discharge coming from glacier melting and increases the glacier mass balance b_h in equation (1).

Precipitation measurements directly affect glacier mass balance b_h .Therefore, precipitation data need to be calibrated or validated.

As shown in **Fig. 3**, there are three rain gauges in Tuni catchment and one in Huayna Potosi catchment. Besides, data from a rain gauge in Zongo is just on the other side of Huayna Potosi. Furthermore, among all the rain gauges in the study region, Tuni and Zongo have continuous measurements while others rarely have records after 2004. Consequently, in order to testify the data reliability and find out if there is any relationship between precipitation and elevation, data from other 13 stations have also been utilized.

Precipitation records from November 2003 to March 2004 have been plotted in **Fig. 5** for comparison. There are two main reasons of data selection. One is that data from all stations are available during this period of time. Another reason is that historical data showed that over 80% of annual precipitation occurred from November to March in this region.

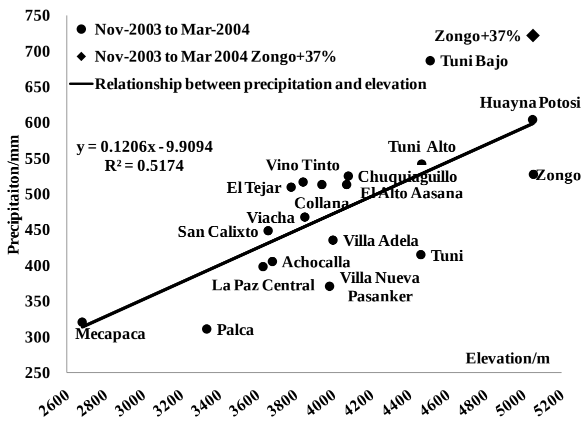

Fig. 5 Relationship between precipitation and elevation

There are three points worth noticing in **Fig. 5**.

(a) Tuni, Tuni Alto and Tuni Bajo are located beside each other at the same elevation, but Tuni Bajo had much more precipitation than any other rain gauges. Hence, data from Tuni Bajo have been considered unusual and been ignored in this study.

(b) Rain gauge Tuni has been measured and recorded monthly by Institut de Recherche pour le Développement (IRD) (GLACIOCLIM: http: //www-lgge.ujf-grenoble.fr/ServiceObs/index.htm) that may have missing readings.

(c) Previous study revealed that the rain gauge P4750 in Zongo basin have underestimated precipitation by 37% [6]. Zongo data with 37% increase has been added to **Fig. 5**, which appears to be larger than Huayna Potosi. This result is reasonable since Zongo locates in the east side of Andes with wet Amazon aside, while Huayna Potosi has dry Altiplano aside.

To sum up, data from Tuni has been raised 14.58% to Tuni Alto as precipitation for Tuni sub-catchment. While Zongo data has been adjusted 30.87% to Huayna Potosi as precipitation for analysis in Huayna Potosi catchment. Moreover, there has been an obvious increasing trend of precipitation as elevation goes up. The two catchments have been divided into 100m elevation zones afterwards in order to reflect dependency on elevation. Eventually, the P in the equation (1) is the area-averaged precipitation of the whole catchment derived from different elevation zones.

(3) Water balance of the catchments

By considering the water catchment as a basic hydrologic system, the total volume of water discharging from a catchment is equal to the volume of water entering the catchment plus a change in storage. In this study, discharge (Q) leaving the catchment were used, whereas the only input is precipitation (P). Losses from the system include evaporation/sublimation (E) and groundwater recharge (G_W). The change in storage is considered to be a gain or loss of glacier volume (Δg), where a loss of glacier volume contributes to Q. Thus the water balance is expressed as:

$$Q = P - E - G_W - \Delta g \qquad (2)$$

In this study, the catchments consist mainly impermeable bedrock, thus groundwater recharge (G_W) can be ignored. The water balance can be simplified and rearranged to consider the glacial meltwater contribution to stream discharge as the change in the storage Δg.

$$Q + E = P - \Delta g \qquad (3)$$

Measurement of Q (m^3s^{-1}) and precipitation (P) are concerted to a depth measure (mm) to compare with other variables. Likewise, Δg calculated by remote sensing or hydrological methods illustrated above is also converted to a depth covering the whole catchment.

3. RESULTS AND DISCUSSION

(1) Glacier mass balance by hydrological method

Hydrological year starts from September in Bolivia. In this study, precipitation and discharge of Glacier Tuni have been measured from September 2000 to August 2004, September 2004 to August 2005 and September 2006 to August 2007. While the measurements of Glacier Huayna Potosi covered from September 2004 to August 2006.

As shown in **Fig. 6**, both Glacier Tuni and Huayna Potosi have marked seasonal variations of glacier mass balance within each hydrological year, which have just agreed with the characteristics of glaciers in outer tropics, i.e. glacier melting occurs mainly during wet season from October to March, while during dry seasons melting decreases and sublimation increases. As the sublimation has not been considered in this study, we may only observe melting decreases during dry season. Moreover, both glaciers had negative mass balance most of the months, while only a few had positive value. These results have been supported by the fact that tropical glaciers has been retreating in decades[2].

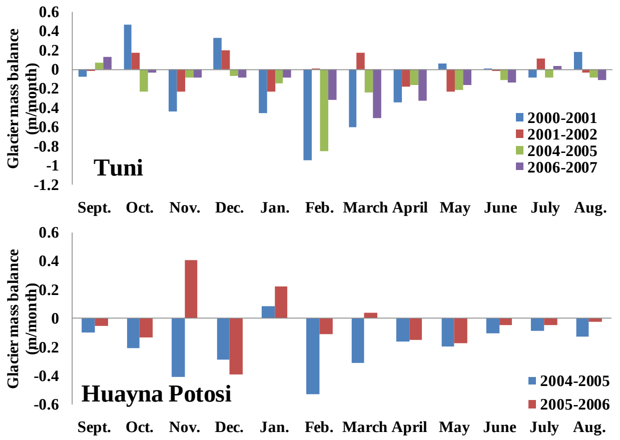

Fig. 6 Glacier mass balance by hydrological method

Glacier mass balances deduced from hydrological method are strongly related to precipitation so that precipitation has been plotted with glacier mass balance in **Fig. 7** as reference. Both graphs in **Fig. 7** indicate that during wet season, precipitation is maximum value while melting also achieves peak negative value through the year. Besides, as shown in **Fig. 2**, air temperature in high altitude Andes ranges from -2 to 5°C all year round that it contributes to glacier melting in less direct way.

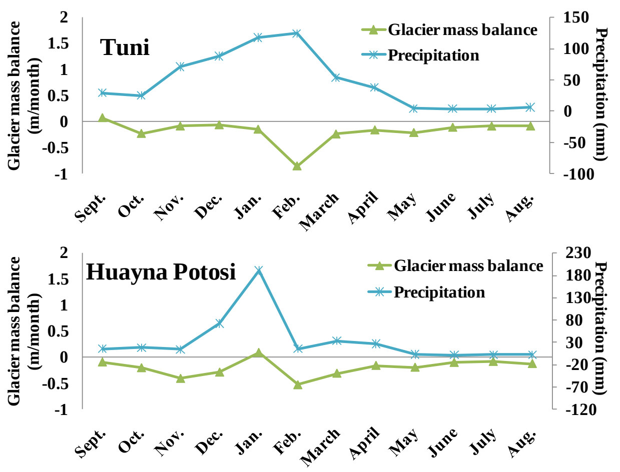

Fig. 7 Glacier mass balance by hydrological method in 2004-2005 comparing with precipitation

(2) Glacier mass balance by remote sensing method

Fig. 8 has shown annual glacier mass balances of Glacier Tuni and Huayna Potosi by comparing results from remote sensing and hydrological method. Results obtained from both methods showed no significant difference except for the values of Tuni from 2001 to 2002 and values of Huayna Potosi from 2004 to 2005. According to monthly glacier mass balance deduced from hydrological method (**Fig. 6**), during the hydrological year 2001 to 2002, Glacier Tuni had positive and negative mass balance fluctuated from month to month that the net mass balance over the year was small comparing to other years. In addition, tropical glaciers are highly sensitive to climate conditions, e.g. El Nino and La Nina events, variation of solar radiation, wind velocity, humidity etc., which may have impacts on glacier mass balance to some extent. Glacier Huayna Potosi had an unusual low precipitation in 2004 to 2005 (**Fig. 6**), which may due to data loss or catch deficiency of rain gauges especially for solid precipitation. In such condition, with the less precipitation and usual discharge, glacier melting has been regarded to increase as the source of discharge.

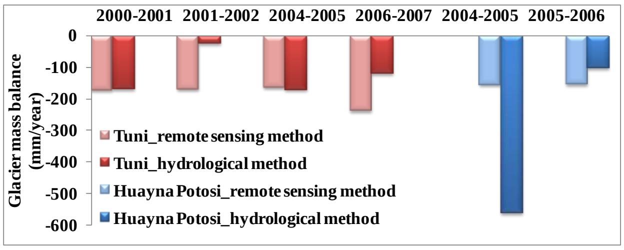

Fig. 8 Glacier mass balance by two methods

As discussed above, both methods have advantages and disadvantages. Remote sensing method is not precise enough to perform analysis within short intervals, but since it is not affected by precipitation and other meteorological data, as well as catchment parameters, it can be analyzed as an independent term. Although hydrological method is strongly affected by precipitation or runoff coefficient, field measurements can be used for frequent and intensive studies.

(3) Seasonality of water balance

Fig. 9 showed monthly water balance of the catchments as equation (3) illustrated. The left side terms are going out of the hydrological system while the right side terms are flowing into the system. In some months, glaciers got positive variations which indicated that accumulation was larger than ablation in that month although accumulation and ablation occur simultaneously in tropical glaciers. According to **Fig. 9**, glacier accumulated during such months when precipitation is large, discharge is small. Evaporation is also noticeable, which generally is considered to be small in wet seasons and large in dry seasons, while in both **Fig. 9** and **Fig. 10**, evaporation was large during wet seasons.

(4) Annual water balance of the sub-catchments

According to **Fig. 11**, there is no significant difference among years in the proportional of each component of annual water balances of Tuni catchment, which has 7.50% of its area occupied by glacier. Consequently, although glaciers account for water resource to some degree, taking long views, precipitation is the primary input to the catchment and dominates the long-term variation trend.

In the catchment of Huayna Potosi, the glaciers cover 22.88% of its area. Under such circumstances, glaciers may participate and influence water balance more. However, there are no enough data to sufficiently prove this hypothesis.

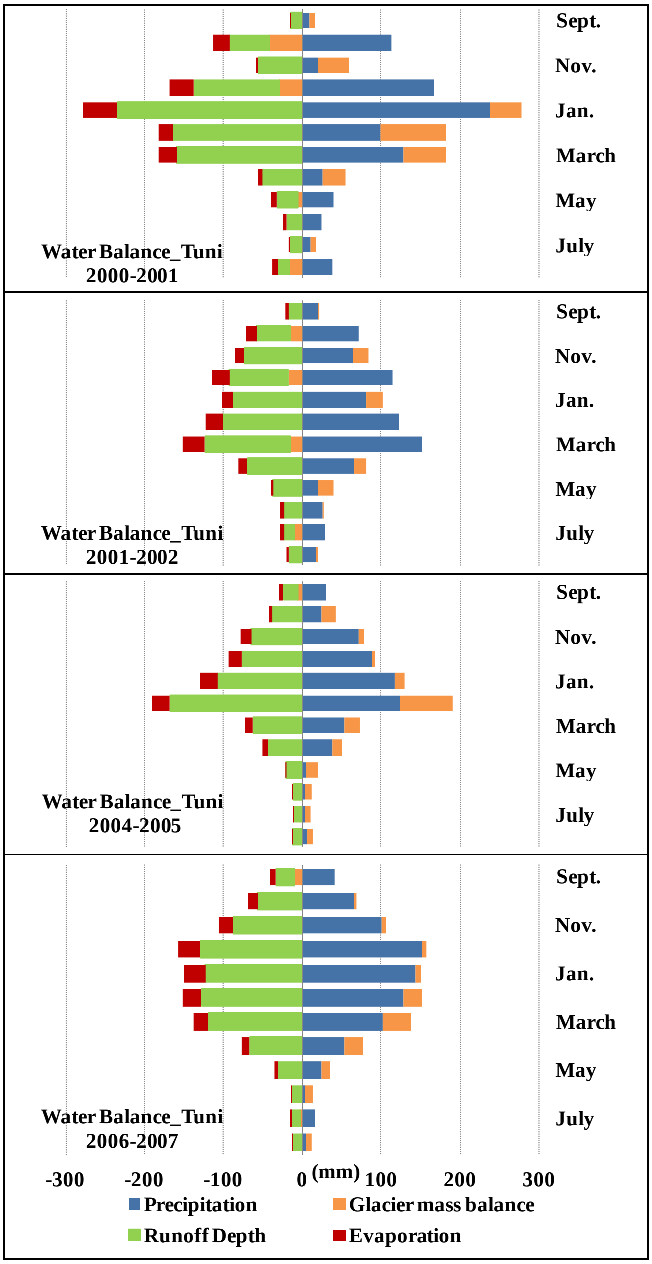

Fig. 9 Seasonal variations of water balance (Tuni)

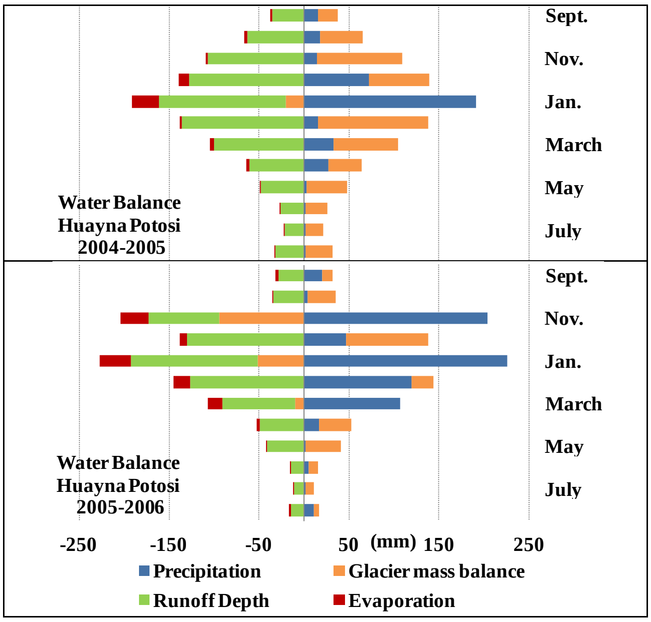

Fig. 10 Seasonal variations of water balance (Huayna Potosi)

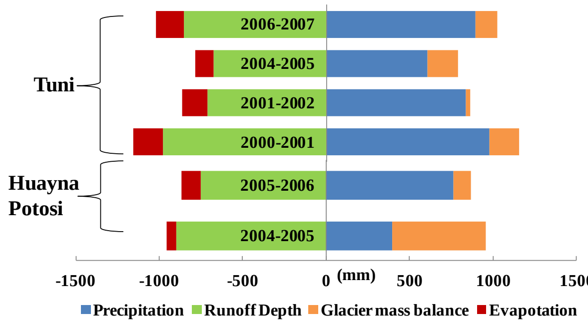

Fig. 11 Annual water balance in the two catchments

4. CONCLUSION

This study investigated glacier mass balance and water balance of Glacier Tuni and Huayna Potosi, which locate at the west side of Bolivian Andes. Remote sensing and hydrological methods have been applied to obtain glacier mass balance and catchment scale water balance. Results suggest that remote sensing method is less affected by meteorological factors but this method is suitable for long-term cumulative glacier mass balance study. On the contrary, hydrological method is sensitive to precipitation and discharge but reliable measurements enable it to carry out frequent and intensive analysis. Glacier mass balance in the study region behave as seasonal variations and had negative mass balance most time of the year. Meanwhile, water balances of the two glacierized catchments have been obtained monthly and annually. Except for in a few months glaciers got positive mass balance, glaciers continuously contributed to discharge. Tuni, with 7.50% of its area glacierized, has no significant difference in annual water balances among years. Consequently, although glaciers account for water resource to some degree, taking long views, precipitation is the primary input to the catchment and dominates the long-term variation trend. For the next step, runoff coefficient needs to be survey and verified.

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