12th International Conference on Hydroinformatics, HIC 2016

Long-term change in ablation area of tropical glaciers
by Landsat data

Shota Funakia,*, Yoshihiro Asaoka

* Corresponding author. Tel.: +81-24-956-8732; fax: +81-24-956-8732.
E-mail address: funakishota.0304@gmail.com

Abstract

Glacier meltwater is one of the main water resources in the capital of Bolivia. To understand current situation of glacier decline is crucial for better water resources management. This study investigated temporal and spatial glacial area during the past three decades between 1984 and 2014. Object glaciers were Tuni, Condoriri, and Huayna Potosi West Glacier with Landsat images. Glacier-covered area by Tuni, Condoriri, and Huayna Potosi West Glacier diminished by 70%, 52%, and 50%, individually from 1984 to 2014. Second, we estimated a front altitude and an equilibrium line altitude for each glacier. Front altitudes for three glaciers rise rapidly after 2000. Finally, we evaluated long-term change in ablation area for selected glaciers. Results showed that accumulation area ratio (AAR) increased with decrease in ablation area and this led to decrease in water resources.

1. Introduction
Due to worldwide global warming since 1850s, mountain glaciers are rapidly decreasing in the last three decades [1], [2]. About 20% of tropical glaciers distribute in Bolivia and they are also decreasing after the late 1970s [3]. Meltwater from glacier is one of the main water resources for the capital of Bolivia. Rapid decrease and disappearance of glaciers cause the depletion of water resources. Therefore, monitoring long-term trend and recent condition of glaciers are curtail. Satellite remote sensing is commonly useful for spatial and temporal analysis for glacial area. Morizawa et al. [4] showed that glaciers in the Coundoriri Mountain, Bolivia lost about 40% of its area between 1988 and 2010 with Landsat imageries. Liu et al. [5] also showed that glaciers in the Cordillera Real lost 34.5% of its glacier-covered area between 1987 and 2010 with the Landsat, the Advanced Land Observing Satellite (ALOS) and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) imagery.

In general, accumulation and ablation area are separated in a glacier by the equilibrium line. The equilibrium line connects all the points which have zero annual mass balance in a glacier. Hence, accumulation area, where annual mass balance is positive, is above the equilibrium line and ablation area, where annual mass balance is negative, is below the equilibrium line. Most of glacial meltwater comes from ablation area. Thus, it is essential to evaluate change in ablation area as well as that in the glacial area for better water resources management.

This research selected three glaciers: Condoriri, Tuni and Huayna Potosi West Glacier which distribute in Tuni Reservoir catchment, Bolivia. Tuni Reservoir covers about 30% of drinking water for the cities of La Paz and El Alto in Bolivia. The aim of this study is to evaluate long-term change in glacial area and its ablation area for selected glaciers. For this purpose, Landsat imageries were used to identify glacial area from 1984 to 2014 and the equilibrium-line altitudes (ELA) were estimated with digital elevation model (DEM).

2. Study area

Study area is Tuni Reservoir catchment shown in Fig.1. Three rivers flow into this catchment, thus, it is divided into three sub-catchment: Condoriri River catchment (20 km², 4400 to 5300 m a.s.l.), Tuni River catchment (15 km², 4400 to 5300 m a.s.l.) and Huayna Potosi River catchment (40 km², 4500 to 6000 m a.s.l.). They are partially covered by Condoriri, Tuni Glacier, Huayna Potosi West Glacier, individually. The climate of this region is characterized by outer tropics. It has two marked seasons which are wet season from November to April and dry season from May to October. Annual range of temperature is small in this region. Moreover, Accumulation and ablation mainly occurs during wet seasons.
3. Data and method

3.1. Satellite data and glacial area detection

In order to determine glacier area, we used Landsat-5 Thematic Mapper (TM) and Landsat-8 Operational Land Imager (OLI) sensors with a 30-m spatial resolution from 1984 to 2014. We obtained Landsat images from LandsatLook Viewer which is operated by the United States Geological Survey. Characteristics of Landsat-5 TM and Landsat-8 OLI sensor are summarized in Table 1. Satellite images contain geometric distortion due to attitude and position of satellite. Therefore, geometric correction of satellite images was proceeded with ground control points which were typically river junction and were selected in the Google Earth. Datum is the World Geodetic System 1984 (WGS84).

We applied the Normalized Difference Snow Index (NDSI) \[ 6 \] to identify glacial area for each grid of Landsat image. NDSI is defined by following equation and it ranges from -1 to 1.

\[
NDSI = \frac{Red - MIR}{Red + MIR}
\]  

where \( Red \) and \( MIR \) are the reflectance of the red (0.63 to 0.69 \( \mu \)m) and middle infrared (1.55 to 1.75 \( \mu \)m). We determined a threshold value of NDSI for the detection of glacial area by comparing with fine resolution images which are observed by AVNIR-2 sensor of the Advanced Land Observing Satellite (ALOS) and about 10 m resolution. Initially, The ALOS AVNIR-2 images were proceeded into a true-color composite (bands 3, 2 and 1 as RGB). Secondly, outline of glacier were visually compared among the NDSI map of Landsat image from August, 2010 and the true composite of the ALOS AVNIR-2 images from August, 2010 to optimize the threshold value of NDVI for Landsat images on a GIS display. We determined the resulting NDVI threshold value of 0.65.

Eight scenes observed by satellite, roughly one scene per five years, were selected to determine temporal change in glacial area. Observation date of Landsat images is shown in Table 2.

### Table 2. Satellite data of observation date

<table>
<thead>
<tr>
<th>Date</th>
<th>Satellite/sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1984/7/8</td>
<td>Landsat-5/TM</td>
</tr>
<tr>
<td>1987/8/2</td>
<td>Landsat-5/TM</td>
</tr>
<tr>
<td>1992/11/3</td>
<td>Landsat-5/TM</td>
</tr>
<tr>
<td>1997/8/29</td>
<td>Landsat-5/TM</td>
</tr>
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</tr>
<tr>
<td>2010/9/18</td>
<td>Landsat-5/TM</td>
</tr>
<tr>
<td>2014/5/8</td>
<td>Landsat-8/OLI</td>
</tr>
</tbody>
</table>

3.2. Elevation data

We used the Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM) to determine the altitude distribution of glacial area and to estimate the equilibrium-line altitude (ELA) of the glacier. The horizontal resolution is 30 m same as that of Landsat images. Datum is also same as that of Landsat images.
3.3. Equilibrium-line altitude

We used the kinematic Equilibrium Line Altitude (ELA) [7], a type of an ELA, to separate a glacier into accumulation area and ablation area. The kinematic ELA was determined from topographical map on a glacier and was assumed to be the best represented counter inflection between the regions of surface concavity (accumulation area) and convexity (ablation area). Initially, contour map with 10 m interval was created from ASTER GDEM which was observed in 2011. Secondly, contour map was overplayed on the detected glacial area from 2010. Finally, counter inflection was selected as the kinematic ELA. The kinematic ELA for each glacier was assumed to be constant during study period. The kinematic ELA of the Huayna Potosi West Glacier is shown in Fig. 3.

3.4. Glacial front altitude

A glacial front altitude was also determined from area-altitude distribution in a glacier. We assumed that a glacial front altitude was one percentile of altitude in the glacial area. Note that the largest ice body was selected for the estimation of a glacial front altitude since a glacier contains several segments of ice.
4. Results and discussion

4.1. Glacier area

Fig. 4 shows long-term change in glacial area. Tuni, Condoriri and Huayna Potosi West Glacier lost about 1.4 km$^2$ (70%), 2.1 km$^2$ (53%) and 2.6 km$^2$ (50%), individually, between 1984 and 2014. Tuni Glacier was the smallest area among three glaciers in 2014. The heat capacity of glaciers are thought to be low with decrease in glacial area.

4.2. Kinematic ELA and front altitude

Fig. 5 shows the estimated kinematic ELAs and the estimated front altitudes for three glaciers. Kinematic ELAs were estimated to be about 4930 m a.s.l. for Tuni, 4900 m a.s.l for Condoriri, and 5030 m a.s.l for Huayna Potosi West Glacier, individually. The front altitudes increased by 129 m (4894 to 5023 m) for Huayna Potosi West, 129 m (4736 to 4865 m) for Condoriri and 103 m (4810 to 4913 m) for Tuni Glacier between 1984 and 2014.
Difference between the kinematic ELAs and front altitudes were estimated to change from 120 to 17 m for Tuni Glacier, from 64 to 35 m for Condoriri Glacier, and from 136 to 7 m for Huayna Potosi West Glacier, individually, between 1984 and 2014.

Increase rate of front altitude for Condoriri Glacier was 12.9 m/decade between 1984 and 1997, and 57.5 m/decade between 2003 and 2014. Similarly, that for Huayna Potosi West Glacier was 0 m/decade between 1984 and 1997 and 86.7 m/decade between 2003 and 2014. That for Tuni Glacier was 12.1 m/decade between 1984 and 1997, and 60.0 m/decade between 2003 and 2014. Increase rates of glacial front altitude between 1984 and 1997 were higher than those between 2003 and 2014. See stated above, this is inferred to be caused by decrease in heat capacity with decrease in glacial area.

4.3. Ablation area
Fig. 6 shows long-term change in ablation area between 1984 and 2014. It showed that Tuni, Condoriri and Huayna Potosi West Glacier lost ablation area of 0.66 km², 0.80 km² and 1.39 km², individually, between 1984 and 2014. Fig. 7 shows the area-altitude distribution between 1984 and 2010. Ablation area were 0.02 km² for Tuni, 0.07 km² for Condoriri and 0.09 km² for Huayna Potosi West Glacier. If the linear trend of the glacial area is extrapolated into the future, Tuni, Huayna Potosi West and Condoriri Glacier will virtually disappear by 2026, 2039 and 2041. Furthermore, the linear trend of ablation area retreat is extrapolated into the future in the case of constant ELA, the ablation area will virtually disappear by 2015 for Tuni, 2020 for Huayna Potosi West and 2021 for Condoriri, individually. This implied that an accumulation area ratio increase with decrease in ablation area. Accumulation area were estimated to be 0.55 km² for Tuni, 1.65 km² for Condoriri and 2.43 km² for Huayna Potosi West in 2014 according to Fig.7. The kinematic ELA estimated in this paper was assumed to be constant during study period in this paper. However, glaciological observation of Zongo Glacier, which was located on opposite site of Huayna Potosi West Glacier in the mountain, by the French Institute IRD [8] showed that annual ELA fluctuated and its range was roughly from 5100 to 5500 m between 1991 and 2000. Therefore, application of multi temporal topographic maps derived from satellite to ELA estimation enable to estimate inter-annual change in ELA. This will useful for understanding current situation of glacial ablation area or potential water resources fed by glacier.
5. Conclusions

This study evaluated long-term change in glacial area and its ablation area for Tuni, Condoriri, and Huayna Potosi West Glacier, Bolivia. Major conclusions are summarized as below.
1) Area for the Tuni, Condoriri and Huayna Potosi West Glacier lost 1.4 km$^2$, 2.1 km$^2$ and 2.6 km$^2$, individually, between 1984 and 2014.
2) Glacial front altitudes increased by about 103 m for Tuni, 129 m for Condoriri and 129 m for Huayna Potosi West Glacier, individually, between 1984 and 2014. Especially, increase ratio was higher after 2000.
3) The kinematic equilibrium line altitudes were estimated with topographic map and an ablation area was separated from a glacial area. Tuni, Condoriri and Huayna Potosi West Glacier lost ablation area of 0.66 km$^2$, 0.80 km$^2$ and 1.39 km$^2$, individually, between 1984 and 2014.

In conclusion, in case of the kinematic ELA of constant, ablation areas for three glaciers were decreased, thereby accumulation area ratios increased. This can lead to decrease in water resources fed by study glaciers. Further study is necessity to estimate annual variation in equilibrium line altitudes.

Acknowledgements

This research was partially supported by JSPS KAKENHI Grant Number 15H06642 and JSPS Bilateral Joint Research Program.

References