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研究課題名（和文）Investigating the long-term variations and interactions among glaciers, glacial lakes, and high altitude wetlands in the tropical Andean region as future water resources

研究課題名（英文）Investigating the long-term variations and interactions among glaciers, glacial lakes, and high altitude wetlands in the tropical Andean region as future water resources

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研究成果の概要（和文）：About 20% of the tropical glaciers are in Bolivian Andes, which are vulnerable to environmental forcing and strongly influence the regions rely on them as water resources. This study investigated the potential future water resources and make a valuable contribution to the sustainable development.

研究成果の概要（英文）：In the first stage (2015/4-12), methods of extracting glaciers, wetlands, and glacial lakes from Landsat data were established and validated with ALOS data and reflectance measurements. The second stage (2016/1-9) , the hydrological model IFAS was upgraded with snowmelt and evaporation functions. Water and energy budget analysis was done to validate the glaciermelt module. In the third stage (2016/10-2017/3), glaciers and glacial lakes were observed with shrinking and steady increasing trends in area (1986-2015). Snow/glacier-covered areas and wetlands were analyzed with size effect and environment forcing. In the last stage (2017/4-2018/3), an experiment as present climate (1979-2003) and 4 greenhouse gas emission scenarios (2075-2099) were input into the updated model with results in the previous stages to simulate runoff, glacier mass balance, and water budget. Resulted future predictions were compared with that in the past to evaluate climate change impacts on water resources.

研究分野：　水文水環境

キーワード：　Hydrological modelling　Climate change　Water resources　Glacier　Remote sensing

１．研究開始当初の背景

More than 99% of the tropical glaciers locate in the Andes, in which 71% are in Peru, 20% are in Bolivia, and 8% are in Ecuador, Colombia, and Venezuela (Kaser, 1999). Tropical glaciers are vulnerable to environmental forcing, and the regions where rely on them as water resources are strongly influenced from glacier retreat due to climate change. Cordillera Real, the target mountain range locates in Bolivia, glaciers in which have been undergoing increasingly retreat since 1980s, especially for the relatively small glaciers (Liu et al., 2013). If appropriate countermeasures are not taken to mitigate for rapid glacier retreat, water management and supply in these areas will become a serious issue and limitations may be imposed on future generations. However, governments in such developing countries have limited budget to prepare for this challenge, to adapt to the changes it brings, or to recover from the damages it causes, which is the motivation of this study, i.e. to investigate the potential future water resources for the region and make a valuable contribution to the sustainable development for such nations.

Many of previous studies showed interests in the topics related to the tropical glaciers. However, there are still some problems unsolved.

A) The existed studies and models applied to the glacierized regions concentrated either on glacier itself or mainly on runoff (Kaser, 1999; Liu et al., 2013). The characteristics of the high-altitude wetlands of the arid and semi-arid regions of the Andes (HAWAs) in South America were normally isolated studies (Earle et al., 2003; Chatterjee et al., 2010). Based on field observations and satellite data analysis, the symbiosis between HAWAs and glacial lakes is a noticeable and interesting phenomenon in this region. Both HAWAs and glacial lakes depend on water provided by precipitation, snowmelt and glacier meltwater; meanwhile, they influence regional hydrology through their water retention capacity and vegetation growth altering stream flow velocity. However, glacial lakes in the region were rarely covered in any studies before, which will be one the main aspects covered in this study.

B) Previous studies intended to predict the glacier shrinkage and runoff loss in the future, but rarely conducted any studies on the potential alternative future water resources (Liu, 2013).

C) Most of the previous studies developed sophisticated models that are only applicable to specific regions (Kinouchi et al., 2013), not open to the public, or not user-friendly. A model, which is open to the public, applicable to anywhere, and user-friendly, should be upgraded and utilized with more physical processes [i.e. IFAS “Integrated Flood Analysis System”, a Graphic User Interface for building distributed rainfall-runoff analysis model released by the International Centre for Water Hazard and Risk Management (ICHARM)].

２．研究の目的

Firstly, Landsat 8 is a recently launched American Earth observation satellite whose data is available since May 2013. It’s necessary to establish new methods with the Landsat 8 data to outline glaciers, glacial lakes, and HAWAs.

Secondly, the established methods will be applied and optimized with previous Landsat data base and ALOS data to determine the most effective and accurate methods of data processing, respectively. Meanwhile, a database with various temporal and spatial resolutions for continuous and long-term monitoring will be established for research as well as decision-making.

Thirdly, consulting the results obtained above, statistical analysis and hydrological model [IFAS “Integrated Flood Analysis System”, a Graphic User Interface for building Distributed rainfall-runoff analysis model released by the International Centre for Water Hazard and Risk Management (ICHARM) at the Public Works Research Institute (PWRI)] will be upgraded with snowmelt module and evapotranspiration function.

Finally, with predicted future climate scenarios, IFAS will be utilized to investigate the interactions among the glaciers, glacial lakes, and the HAWAs and to evaluate their variations and capacities as the major local water resources under the changing climate scenarios in the future.

３．研究の方法

The original research plan and methods are as following.

In the first stage (FY 2015, Apr. to Dec.), area of glaciers, HAWA, and glacial lakes will be extracted with remote sensing data (Otto et al., 2011, Liu et al., 2013). Landsat TM and ALOS AVNIR-2 data before 2013 will be utilized for the landcover analysis, while the new Landsat 8 data and ground truth information for that after 2013. Ground truth information and reflectance measurements will be obtained during field

observations that are planned in September 2015 and March 2016. In case that the field observations are insufficient, it's possible to apply to the local researchers from Universidad Mayor de San Andrés. Additionally, it's worth noticing that ALOS PRISM data are utilized for topographical information for better recognition of the potential extent of glacial lakes and HAWAs instead of the commonly used ASTER data. Besides, ALOS PALSAR that can be used for all-weather land observation is perfect for the analysis in wet season.

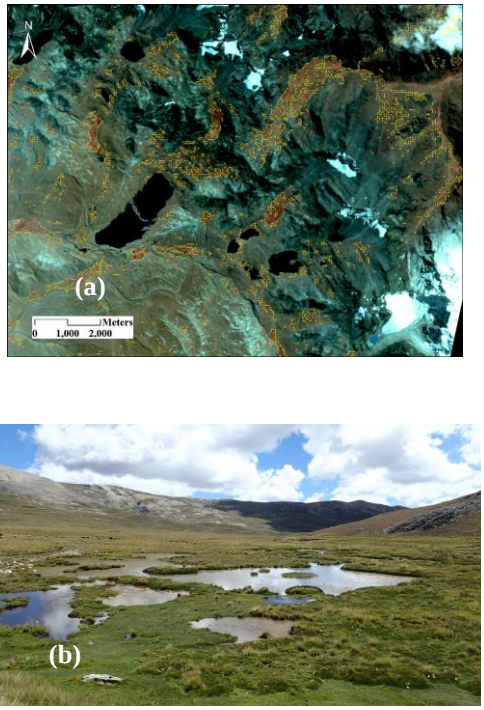
The second stage (FY 2015&2016, Jan. to Sep.) is planned to modify the IFAS. IFAS will be upgraded with snowmelt module and evapotranspiration function especially the glacier-covered area to obtain distributed glacier mass balance. The resulted runoff and the seasonal area variations of HAWAs and glacial lakes deduced from the remote sensing analysis together with the local topography (ALOS PRISM) will be used to predict the capacity of storage and to improve the retarding effects by HAWAs and glacial lakes.

As a next step (FY 2016, Oct. to Mar.), the long-term areal changing trend of glaciers, glacial lakes, and HAWAs will be obtained in the first stage based on satellite data from 1980s till now. This trend will be input into the updated model modified in the second stage with GCM reanalysis data to simulate runoff, glacier mass balance, and water balances of glacial lakes and HAWAs. The results of future prediction will be compared with that in the past to estimate how the major sources of the runoff will change. Some indices will be designed to evaluate the potential of glacial lakes and HAWAs as alternative water resources as glaciers retreat and even disappear in the far future.

４．研究成果

In the first stage (FY 2015, Apr. to Dec.), methods of extracting glaciers, HAWAs, and glacial lakes from Landsat TM and Landsat 8 were established and validated with ALOS AVNIR-2 data and reflectance measurements. Further analysis was conducted to investigate the changing trend of the landcover and its relationship with environment forcing in this region.

The second stage (FY 2015&2016, Jan. to Sep.) was planned for numerical modelling. The hydrological model IFAS was upgraded with snowmelt module and evapotranspiration function. Water budget and energy budget balance analysis has been done with observed data from 2011 to 2014 in the Tuni Basin to validate the equations selected for the glaciermelt module that was newly coded.

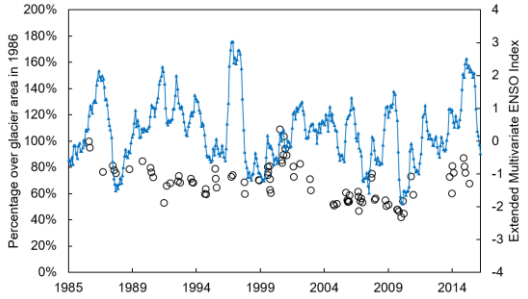


(a) Outlines of wetland derived from Landsat TM (26 July, 2008) compared with ALOS image (RGB = bands 4, 3, and 2; 31 July, 2008).
(b) Photo at the Huayna Potosi West (taken on 24 Mar, 2016).

From March 18 to 24, 2016 I stayed in Bolivia to conduct a field survey. With the support from the Institute of Hydraulics and Hydrology (IHH) and the government, I visited Hichukhota and Taypichaca to check the possible location of installing new meteorological stations. Field surveys at Huayna West and Condoriri were conducted. I was able to approach the glacier, locate the glacier terminus, inlets and outlets of glacial lakes and HAWAs, and measure the reflectance of the glacier surface.

Map and routes for field survey

In the third stage (FY 2016, Oct. to Mar. 2017), the runoff simulated by upgraded IFAS in the second stage and the seasonal area variations of HAWAs and glacial lakes deduced from the remote sensing analysis together with the local topography (ALOS PRISM) was used to predict the capacity of storage and to improve the retarding effects by HAWAs and glacial lakes. The long-term areal changing trends of glaciers and glacial lakes were observed with revealed shrinking and steady increasing trends in area between 1986 and 2015. Snow/glacier-covered areas in the region were analyzed with size effect and the environment forcing such as La Nina and El Nino events. Despite of seasonal variations and long-term changing trend, HAWA fluctuations in extent along with snow/glacier-covered areas and La Nina and El Nino events were observed.

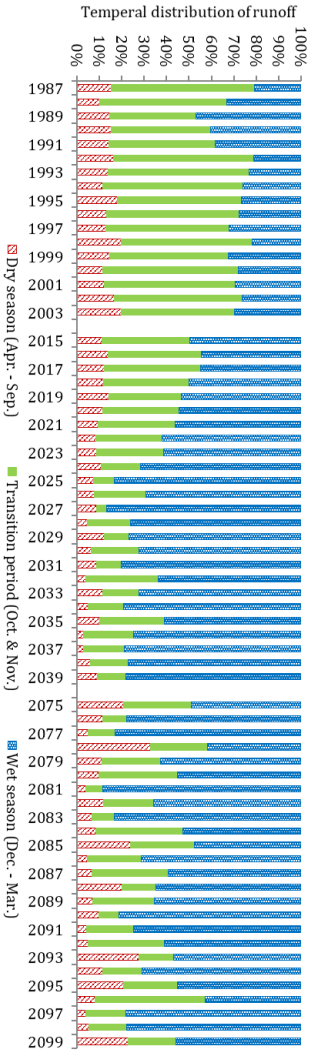


Change of glacier area in the Cordillera Real comparing to the extended Multivariate ENSO Index.

From March 17 to 25, 2017 I visited Bolivia. The main purpose of the trip was threefold. First, it was to attend workshop regarding the joint study for Bolivian Glacier catchment and present obtained results. Second, it was to conduct field survey of glaciers, glacial lakes, and wetlands in the tropical Andean region near La Paz. Third, it is to set up new experimental stations in Taypichaca and Hichukhota for further monitoring.

Glacial lake at Huayna West

The last stage (FY 2017, Apr. 2017 to Mar. 2018) was to evaluate the climate change impacts on local water resources using the climate model experiments. The climate model experiments included an experiment as present climate (1979-2003), and 4 members of RCP8.5 greenhouse gas emission scenario experiments with different sea surface temperature distributions as future climate ensembles for 2075 to 2099. The long-term areal changing trend of glaciers, glacial lakes, and HAWAs obtained in the first stage based on satellite data since 1980s was input into the updated model modified in the second stage with climate change scenarios to simulate runoff, glacier mass balance, and water budget balances of glacial lakes and HAWAs. The resulted runoff and the seasonal area variations of HAWAs and glacial lakes deduced from the remote sensing analysis together with the local topography was used to predict the capacity of storage and to improve the retarding effects by HAWAs and glacial lakes. The results of future prediction were compared with that in the past to estimate how the sources of the runoff will change. Indices was designed to evaluate the potential of glacial lakes and HAWAs as alternative water resources as glaciers retreat and even disappear in the far future.



Water resources assessed by temporal distribution of runoff from different seasons from 1987 to 2099.

The training and workshop planned in March 2018 was cancelled due to the principal investigator's pregnancy.

５．主な発表論文等
（研究代表者、研究分担者及び連携研究者には下線）

〔雑誌論文〕（計　3　件）

1. Liu, T., Tsuda, M., and Iwami, Y.: A study on flood forecasting in the Upper Indus Basin considering snow and glacier melt water, Journal of Disaster Research Vol.12, No.4, 793-805, 2017. DOI: 10.20965/jdr.2017.p0793 (Peer-reviewed).

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3. Iwami, Y., Tsuda, M., Yamazaki, Y., and Liu, T.: Research and Development and Challenge in Field Application for Strengthening Flood Warning and Management Capacity in Developing Countries, Civil Engineering Journal Vol.58, No.12, 10-13, 2016 (Japanese).

〔学会発表〕（計　9　件）
1. (Invited) Liu, T.: Challenges and solution of snowmelt in flood forecasting, 1st China-Japan-South Korea Water Science Research Forum -- Sustainable Development of Regional Water Resources Under Changing Environment organized by Dalian University of Technology and JiLin University, Dalian, China, 28-30 Oct. 2017.

2. (Invited) Liu, T.: Progress and challenges of meltwater simulation in the Upper Indus, International Workshop on "Strategic Data for Reliable Models and Timely Flood Forecasts" organized by UNESCO, Islamabad, 10-11 Apr. 2017.

3. Liu, T., Kinouchi,T., Tsuda, M., Iwami, Y., Asaoka Y., and Mendoza J.: Long-term variations of glaciers under the changing climate in the tropical Andean region, the International Symposium on 'The Cryosphere in a Changing Climate', Wellington, New Zealand, Feb. 2017.

4. Liu, T., Kinouchi,T., Asaoka Y., Mendoza J., and Iwami, Y.: ENSO impact on fluctuations of glaciers in the tropical Andean region, American Geophysical Union's 49th annual Fall Meeting, San Francisco, Dec. 2016.

5. Liu, T., Hasegawa, A., Jaranilla -Sanchez, P., Tsuda, M., and Iwami, Y.: Long-term Flood Assessment In The Upper Indus River Basin, Pakistan, Asia Oceania Geosciences Society (AOGS) 13th Annual Meeting and Geosciences World Community Exhibition, Beijing, Aug. 2016.

6. Liu, T., Kinouchi,T. Tsuda, M., Iwami, Y., Asaoka Y., and Mendoza J.: Long-term Variations Of Glaciers, Glacial Lakes, And High Altitude Wetlands In The Tropical Andean Region, Asia Oceania Geosciences Society (AOGS) 13th Annual Meeting and Geosciences World Community Exhibition, Beijing, Aug. 2016.

7. (Invited) Liu, T.: Progress in glacier and snow meltwater analysis in the Upper Indus River Basin, International Workshop on Standardizing Flood Forecasting and Warning Approaches in Transboundary Catchments" organized by UNESCO and PMD, Lahore, 19-20 Apr. 2016.

8. Liu, T., Kinouchi,T., Hasegawa, A., Tsuda, M., Iwami, Y., Asaoka Y., and Mendoza J.: Generation of the relationship between glacier area and volume for a tropical glacier in Bolivian Andes, American Geophysical Union's 48th annual Fall Meeting, San Francisco, Dec. 2015.

9. (Invited) Liu, T.: Investigating snowmelt in the Upper Indus River Basin, International Partners Technical and Capacity Building Meeting of "Strategic Strengthening of Flood Warning and Management Capacity of Pakistan – Phase II" organized by UNESCO and PMD, Lahore, 6-8 Aug. 2015.

〔図書〕（計　　件）

〔産業財産権〕

○出願状況（計　　件）

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発明者：
権利者：
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番号：
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〔その他〕
ホームページ等

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