Chin. Geogra. Sci. 2013 Vol. 23 No. 2 pp. 216–226
doi: 10.1007/s11769-012-0584-3

Springer Science Press
www.springerlink.com/content/1002-0063

Improvement of Glacial Lakes Detection under Shadow Environment Using ASTER Data in Himalayas, Nepal

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Abstract: The detection of glacial lake change in the Himalayas, Nepal is extremely significant since the glacial lake change is one of the crucial indicators of global climate change in this area, where is the most sensitive area of the global climate changes. In the Himalayas, some of glacial lakes are covered by the dark mountains' shadow because of their location. Therefore, these lakes can not be detected by conventional method such as Normalized Difference Water Index (NDWI), because the reflectance feature of shadowed glacial lake is different comparing to the ones which are located in the open flat area. The shadow causes two major problems: 1) glacial lakes which are covered by shadow completely result in underestimation of the number of glacial lakes; 2) glacial lakes which are partly identified are considered to undervalue the area of glacial lakes. The aim of this study is to develop a new model, named Detection of Shadowed Glacial Lakes (DSGL) model, to identify glacial lakes under the shadow environment by using Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) data in the Himalayas, Nepal. The DSGL model is based on integration of two different modifications of NDWI, namely $NDWI_s$ model and $NDWI_{she}$ model. $NDWI_s$ is defined as integration of the NDWI and slope analysis and used for detecting non-shadowed lake in the mountain area. The $NDWI_{she}$ is proposed as a new methodology to overcome the weakness of $NDWI_s$ on identifying shadowed lakes in highly elevated mountainous area such as the Himalayas. The first step of the $NDWI_{she}$ is to enhance the data from ASTER 1B using the histogram equalization (HE) method, and its outcome product is named $ASTER_{he}$. We used the $ASTER_{he}$ for calculating the $NDWI_{he}$ and the $NDWI_{she}$. Integrated with terrain analysis using Digital Elevation Model (DEM) data, the $NDWI_{she}$ can be used to identify the shadowed glacial lakes in the Himalayas. $NDWI_s$ value of 0.41 is used to identify the glacier lake ($NDWI_s \geq 0.41$), and 0.3 of $NDWI_{she}$ is used to identify the shadowed glacier lake ($NDWI_{she} \leq 0.3$). The DSGL model was proved to be able to classify the glacial lakes more accurately, while the NDWI model had tendency to underestimate the presence of actual glacial lakes. Correct classification rate regarding the products from NDWI model and DSGL model were 57% and 99%, respectively. The results of this paper demonstrated that the DSGL model is promising to detect glacial lakes in the shadowed environment at high mountains.

Keywords: glacial lake; shadow environment; DSGL model; ASTER; remote sensing; Himalayas; Nepal

Citation: Chen Wenbo, Hiromichi Fukui, Tomoko Doko, Gu Xingfa, 2013. Improvement of glacial lakes detection under shadow environment using ASTER data in Himalayas, Nepal. *Chinese Geographical Science*, 23(2): 216–226. doi: 10.1007/s11769-012-0584-3

1 Introduction

Known as the third polar of the world in climate change, the Himalayas play an important role in the regional climate dynamics. Since the second half of the 20th century, numerous glaciers in the Himalayan region

Received date: 2012-02-07; accepted date: 2012-07-04
Foundation item: Under the auspices of Taikichiro Mori Memorial Research Grants of Keio University (No. 19, 2010), Doctoral Students Research Support Program of Keio University (No. 87, 2010), Academic Frontier Fund's 'Integrated Research for Community Strategic Concept by Construction and Management of Digital Asia' by Ministry of Education, Culture, Sports, Science and Technology (MEXT) (No. 04F003, 2004—2008)
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have retreated due to climate changes (Dyurgerov, 2003; Shrestha *et al*., 2005; Bajracharya *et al*., 2007; Immerzeel *et al*., 2009; Owen *et al*., 2009; Kaltenborn *et al*., 2010). Ives *et al*. (2010) indicated that glaciers in many segments of the Himalayan region are currently thinning and retreating. Bajracharya *et al*. (2007) stated that most of the Himalayan glaciers have been melting at a rate between a few meters and several tens meters per year, and this formed a number of glacial lakes in the area. Chen *et al*. (2007) illustrated that the area of glaciers will continue to decrease, and both quantity and surface areas of glacial lakes will continue to increase in the Poiqu River Basin, Tibet, China. Thus, monitoring the changes of glacial lakes is a critical mission for providing early warnings of events such as Glacial Lake Outburst Flood (GLOF) in a regional environment (Xu, 1988; Richardson and Reynolds, 2000; Cenderelli and Wohl, 2001; Mool *et al*., 2001; Kattelmann, 2003).

The Himalayan region is characterized by large spatial scale, remoteness (Bishop and Shroder, 2004), high altitude, and atrocious weather (Barry, 2008). Hence, physically accessing the region and measuring the changes are the primary challenges for conducting scientific researches. Thus, remote sensing technique is an effective method to accomplish those arduous tasks. As a conventional method based on remote sensing, Normalized Difference Water Index (NDWI) has been commonly used for water detection. For instance, Gao (1996) used two Near Infrared bands of Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) data to calculate NDWI; McFeeters (1996) used Green band and Near Infrared band of MSS data to extract water; Xu (2006) used Green band and Middle Infrared band of TM data to modify NDWI. All of the above-mentioned studies focused on a relatively flat terrain.

However, the NDWI cannot be given full effectiveness to detect water under the shadow environment. In the alpine regions, the terrain is usually harsh and steep, and daily solar elevation is normally inconsistent. Thus, some of the glacial lakes located at the lower northern slope of mountain are fully or partly covered by dark shadow (Joseph, 2005). The reflectance feature of these shadowed lakes differs from the one located in the open area and it makes difficult to identify the shape of glacial lakes if the conventional methods are adopted.

Hence, the objective of this study is to propose an improved method of glacial lakes detection under shadow in the Himalayas, Nepal, based on integration of the NDWI with terrain analysis and histogram equalization using the Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) data. This method is named Detection of Shadowed Glacial Lakes (DSGL) model. The DSGL model integrates two different modification of NDWI, namely Normalized Difference Water Index integrated with slope ($NDWI_s$) model and Normalized Difference Water Index integrated with slope and histogram equalization ($NDWI_{she}$) model. The advantage of the DSGL model is to classify the shadowed glacial lakes more accurately than the conventional NDWI method. Thus, the DSGL model is expected to contribute to preventing glacial lakes from being underestimated in terms of number and area. By applying the DSGL model, inventory and statistics of glacial lakes could be enhanced with numerical accuracy. Moreover, the DSGL model is potentially applicable not only to detect glacial lakes in the Himalaya, but also to detect any water boundary located at high mountains.

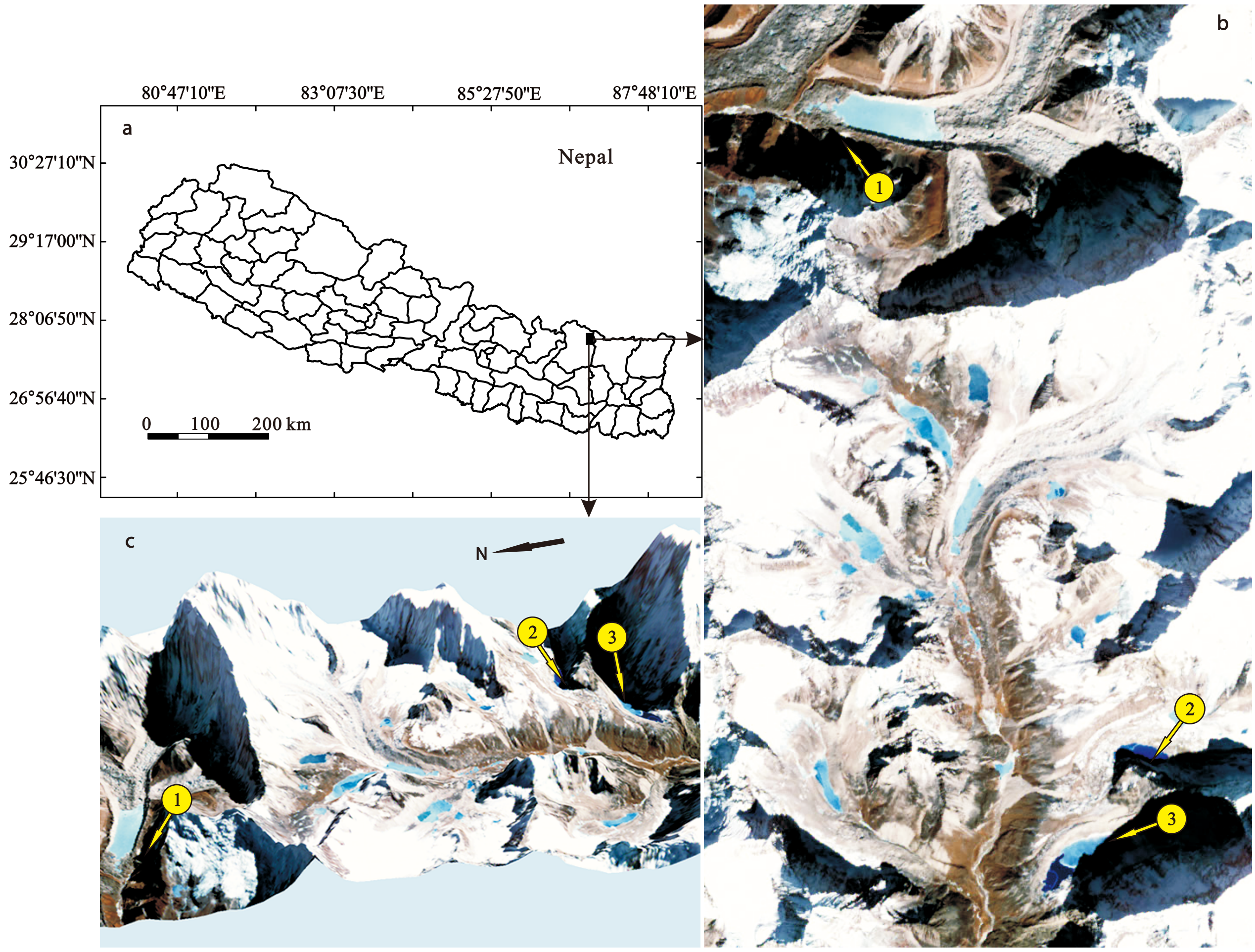
2 Material and Methods

2.1 Study area

The study area is located in the Dudh Koshi Basin (27°46′08″–27°54′59″N, 86°53′23″–86°59′10″E), at the northeast of Nepal in the Himalayas (Fig. 1). The Dudh Koshi Basin is one of the largest and remarkable basins in terms of regional glacial lakes and glaciers, and it is surrounded by intensive glaciers (Bajracharya *et al.*, 2009). This region is characterised by a semi-arid climate. Spatial distributions of maximum temperature showed high warming trends from 1971 (Shrestha *et al*., 1999). Summer monsoon circulation may play an important role in the distribution of seasonal temperature as well as temperature trends. High Himalayan regions are more sensitive to climate change due to the geomorphologic characteristics. The altitude of this area is from 4846 m to 7300 m above sea level, and the ground slope ranges from 0 to 84°. The specific samples from the Himalayas, Nepal in this study includes a fully shadowed glacial lake, Ambulapcha Lake, and two partly shadowed glacial lakes with a given name of Shadowed Lake 1 and Shadowed Lake 2, individually.

2.2 Data and processing

The Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) instrument on Terra satellite is an advanced optical sensor comprised of 14 spec-



①, ② and ③ present Ambulapcha Lake, Shadowed Lake 1 and Shadowed Lake 2, respectively

Fig. 1 Administrative boundary of Nepal (a), location of three sample glacial lakes (b), and 3D map of study area (c)

tral channels ranging from visible bands to thermal infrared bands. In this research, two satellite imageries of ASTER 1B data, which include visible channel 1 (0.52–0.60 μm) and near infrared channel 3 (0.76–0.86 μm) with spatial resolution of 15 m were used. The first dataset was a cloud-free imagery captured on January 6th, 2008. This imagery was selected to meet criteria of shadowed image to apply Detection of Shadowed Glacial Lakes (DSGL) model. The second dataset was an imagery captured on March 26th, 2008 without shadow due to high solar elevation. This dataset was used to validate the accuracy of the shadow lake classification. Since the ASTER 1B imagery merely presents the digital number, it was needed to convert it to the Top of Atmosphere (TOA) reflectance in order to calculate the NDWI using reflectance data. The TOA reflectance was calculated using equation by Yamamoto *et al*. (2008).

Digital Elevation Model (DEM) data such as Shuttle Radar Topography Mission (SRTM, 90 m) and ASTER Global Digital Elevation Model (GDEM, 30 m) are available through the websites, and can be used to extract the elevation of the geometrical unit (Bolch *et al*., 2005; Wang *et al*., 2012). In this study, considering that ASTER GDEM can offer more geomorphologic details (Bolch *et al*., 2005), ASTER GDEM data (http://www.gdem.aster.ersdac.or.jp/) were used for terrain analysis in the process of DSGL model. The ground surface slope was calculated from ASTER GDEM. Satellite imagery analysis and data processing was conducted by ENVI® 4.7.

2.3 DSGL model for detecting shadowed glacial lakes

2.3.1 Overall introduction of DSGL model

Instead of the conventional method only using the NDWI (hereinafter referred to as NDWI method), an integrated model named as DSGL model was developed. The DSGL

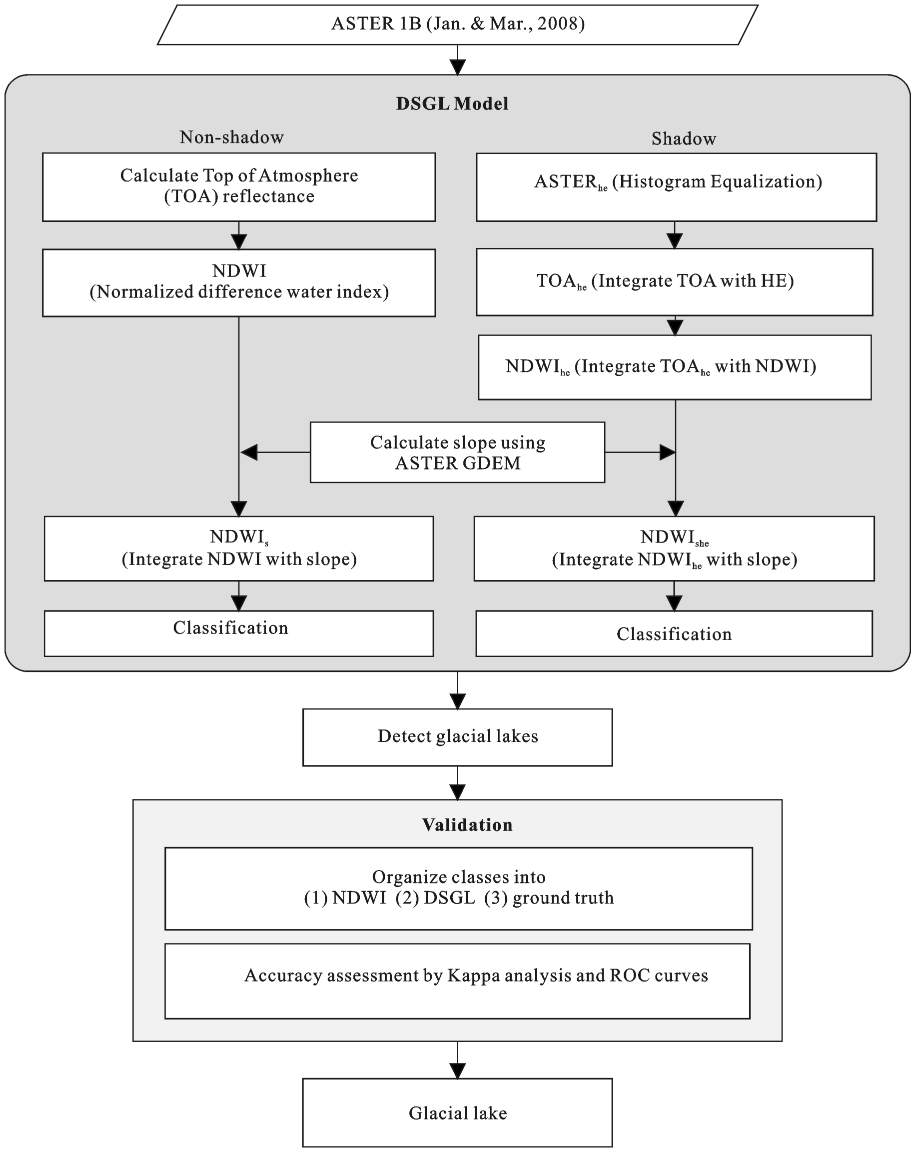


Fig. 2 Flowchart of DSGL model for detection of shadowed glacial lakes

model includes $NDWI_s$ model for non-shadowed lakes and $NDWI_{she}$ for shadowed lakes. The $NDWI_s$ model integrates the NDWI with terrain (slope) analysis, and the $NDWI_{she}$ model integrates NDWI with slope analysis and histogram equalization. The overall flow of DSGL model is presented in Fig. 2.

2.3.2 Non-shadowed glacial lake identification model ($NDWI_s$)

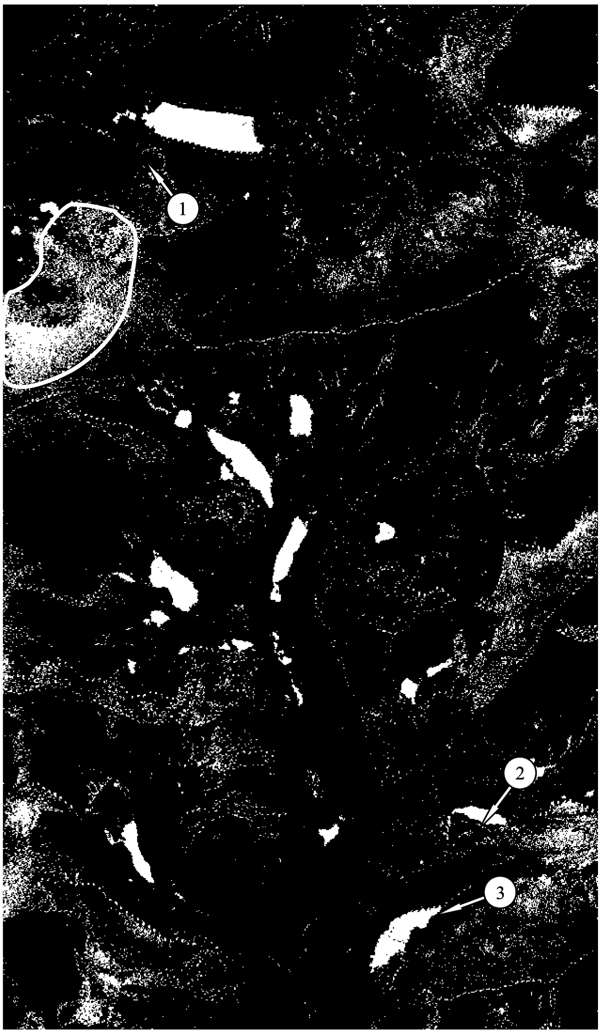
(1) Normalized Difference Water Index (NDWI)

The NDWI model takes an advantage of the differencing wavelength reflectance of the objects. Because water presents a higher reflectance in green band and it strongly absorbs in near infrared band (NIR), the NDWI was calculated by Equation (1) (McFeeters, 1996). The value of index could range from –1 to 1.

$$NDWI = \frac{\rho_{\text{Green}} - \rho_{\text{NIR}}}{\rho_{\text{Green}} + \rho_{\text{NIR}}} \qquad (1)$$

where ρ_{Green} and ρ_{NIR} are reflectance in green and near infrared bands, respectively.

In the flat area, most glacial lakes were correctly classified by the NDWI method (Fig. 3). Since the melting ice has the same reflectance characteristics as water, some places located on the slope and crest of mountain were also classified as water body although they were not glacial lakes (the white circle in Fig. 3). In contrast, the shadowed glacial lakes were not identified as water body. Figure 3 showed that Ambulapcha Lake (fully covered by the shadow of mountain) was not accounted as water signature, and Shadowed Lake 1 and 2 (partly covered by the shadow of mountain) were partly accounted as water (only non-shadowed water body are identified as water by NDWI model).



White colour indicates glacial lakes; ①, ② and ③ present Ambulapcha Lake, Shadowed Lake 1 and Shadowed Lake 2, respectively

Fig. 3 Classification result by NDWI method

(2) Integrate NDWI with slope analysis

Based on the field work in the Himalaya and Tibet, China for more than four years, it was recognized that the terrain slope at which the melted water drained away was greater than 10°. Experiences from Reynolds (2000) in Bhutan and Quincey *et al.* (2007) in China and Nepal demonstrated the similar result. Thus, a threshold value of the ground surface slope less than or equal to 10° was adopted in this study. The equation to calculate $NDWI_s$ was as follows.

$$NDWI_s = \begin{cases} NDWI, & \text{if } slope \le 10 \\ 0, & \text{if } slope > 10 \end{cases} \quad (2)$$

where $NDWI_s$ is the result of the terrain analysis, depending on the threshold value of the slope.

(3) Identify and classify non-shadowed lake

Under the non-shadowed environment, the glacier lake was identified with the $DSGL_{part1}$ as follows.

$$DSGL_{part1} = \begin{cases} \text{Non-shadowed lake}, & \text{if } NDWI_s \ge 0.41 \\ \text{Non-lake}, & \text{if } NDWI_s < 0.41 \end{cases} \quad (3)$$

After a re-classified process combining the criteria of NDWI and slope, most of the water signature located on the slope and crest of mountain that corresponds to the white circle in Fig. 4 were successfully eliminated.

White colour indicates glacial lakes; ①, ② and ③ present Ambulapcha Lake, Shadowed Lake 1 and Shadowed Lake 2, respectively

Fig. 4 Classification results after integrating NDWI into slope analysis

2.3.3 Shadowed glacial lake identification model ($NDWI_{she}$)

(1) Enhancing ASTER 1B with histogram equalization analysis

In order to identify the glacial lakes under shadow environment at the foot of a mountain, the Histogram Equalization was used in this study in order to enhance ASTER 1B. The calculation was as follows.

$$ASTER_{\mathrm{he}} = ASTER1\mathrm{B}\left(\frac{cdf(x) - cdf_{\min}}{M \times N - cdf_{\min}} \times (L-1)\right) \quad (4)$$

where the $ASTER_{\mathrm{he}}$ is enhanced $ASTER$1B with histogram equalization analysis; $cdf_{\min}$ is the minimum value of the cumulative distribution function; M and N are columns and rows of image respectively; and L is the number of grey levels used (256 in this case). $cdf(x)$ is the value of the cumulative distribution function which was calculated by using the following equation.

$$cdf(x) = \sum_{j=0}^{x} h(j) \quad (5)$$

where x is a gray value and $h(j)$ is the histogram for pixel j of image.

(2) $NDWI_{she}$ model of integrating $ASTER_{he}$ with TOA, $NDWI_{he}$ and slope analysis

$NDWI_{he}$ was calculated from the following equation.

$$NDWI_{\mathrm{he}} = \frac{\rho_{\mathrm{Green\_he}} - \rho_{\mathrm{NIR\_he}}}{\rho_{\mathrm{Green\_he}} + \rho_{\mathrm{NIR\_he}}} \quad (6)$$

where $NDWI_{\mathrm{he}}$ is the result of $NDWI$ after Histogram Equalization; $\rho_{\mathrm{Green\_he}}$ and $\rho_{\mathrm{NIR\_he}}$ are reflectance in green band of $ASTER_{\mathrm{he}}$ and reflectance in near infrared band of $ASTER_{\mathrm{he}}$, respectively.

Integrating the $NDWI_{he}$ into the slope data, the threshold value of the ground surface slope less than or equal to 10° was adopted in this study. The equation of integrating $NDWI_{he}$ with terrain analysis was as follows.

$$NDWI_{\mathrm{she}} = \begin{cases} NDWI_{\mathrm{he}}, & \text{if } slope \le 10 \\ 0, & \text{if } slope > 10 \end{cases} \quad (7)$$

where $NDWI_{\mathrm{she}}$ is the result of the $NDWI_{\mathrm{he}}$ integrated with the terrain analysis in which the slope is equal or less than 10°.

(3) Classification for identifying shadowed lakes

Based on the $NDWI_{she}$, the data were classified into two groups as follows to represent $DSGL_{part2}$.

$$DSGL_{\mathrm{part2}} = \begin{cases} \text{Shadowed lake}, & \text{if } NDWI_{\mathrm{she}} \le 0.3 \\ \text{Non-lake}, & \text{if } NDWI_{\mathrm{she}} > 0.3 \end{cases} \quad (8)$$

Here, pixels, presented shadowed glacial lakes, fell in the lower reflectance range, and were selectively extended in greater proportion to higher values. This procedure produced a histogram in which the spaces between the lower values were increased, and the higher values were combined and compressed. In this study, the threshold value that is equal or less than 0.3 was adapted.

2.3.4 Integration of $NDWI_s$ and $NDWI_{she}$ for DSGL model

Integrating the $DSGL_{part1}$ for identifying non-shadowed lakes and $DSGL_{part2}$ for identifying shadowed lakes, the integrated DSGL model was as follows:

$$DSGL = \begin{cases} \text{Non-shadow lake}, & \text{if } NDWI_{\mathrm{s}} \ge 0.41 \\ \text{Shadow lake}, & \text{if } NDWI_{\mathrm{she}} \le 0.3 \\ \text{Non-lake}, & \text{if } NDWI_{\mathrm{s}} < 0.41 \text{ or } NDWI_{\mathrm{she}} > 0.3 \end{cases} \quad (9)$$

where $DSGL$ is the result of classification: non-shadow lake, shadow lake, and non-lake; $NDWI_{\mathrm{s}}$ is the result of the $NDWI$ where slope ≤ 10°, and $NDWI_{\mathrm{she}}$ is the result of the histogram equalization where slope ≤ 10°.

2.4 Validation

2.4.1 Ground truth data from field work

As field validation, the ground truth survey was carried out from April to May, 2008 in the Himalaya, Nepal. The surface photos, survey of the lake areas, coordinate data and related information were collected, which provide necessary references information for validation to the DSGL classification result. One of the target glacial lakes in this study, the Ambulapcha Lake, was fully covered by the shadow of mountain in the satellite image captured on January 6th, 2008. Figure 5 presented the photo of Ambulapcha Lake which was mosaic with four photos taken on May 1st, 2008, at 11:17 am the Kathmandu time. From visual inspection, the shape of the glacial lake was almost identical to the one of the satellite image on March 26th, 2008.

2.4.2 Ground truth data from satellite imagery

Hence, the satellite image of March 26th, 2008 was considered to be suitable as the ground truth data which represent glacial lakes where there were no effects by shadow. First, three lakes from the Himalaya, Nepal: the

Fig. 5 A mosaic photo as ground truth data of Ambulapcha Lake in Himalayas, Nepal

Ambulapcha Lake as a fully shadowed lake, Shadowed Lake 1 and Shadowed Lake 2 as the partly covered shadow lake, were selected for comparison. These three sample lakes were presented in order to illustrate the advantages of the DSGL model. Secondly, the imageries produced by NDWI model and DSGL model on January 6th, 2008 were presented and used to compare with the ground truth imagery.

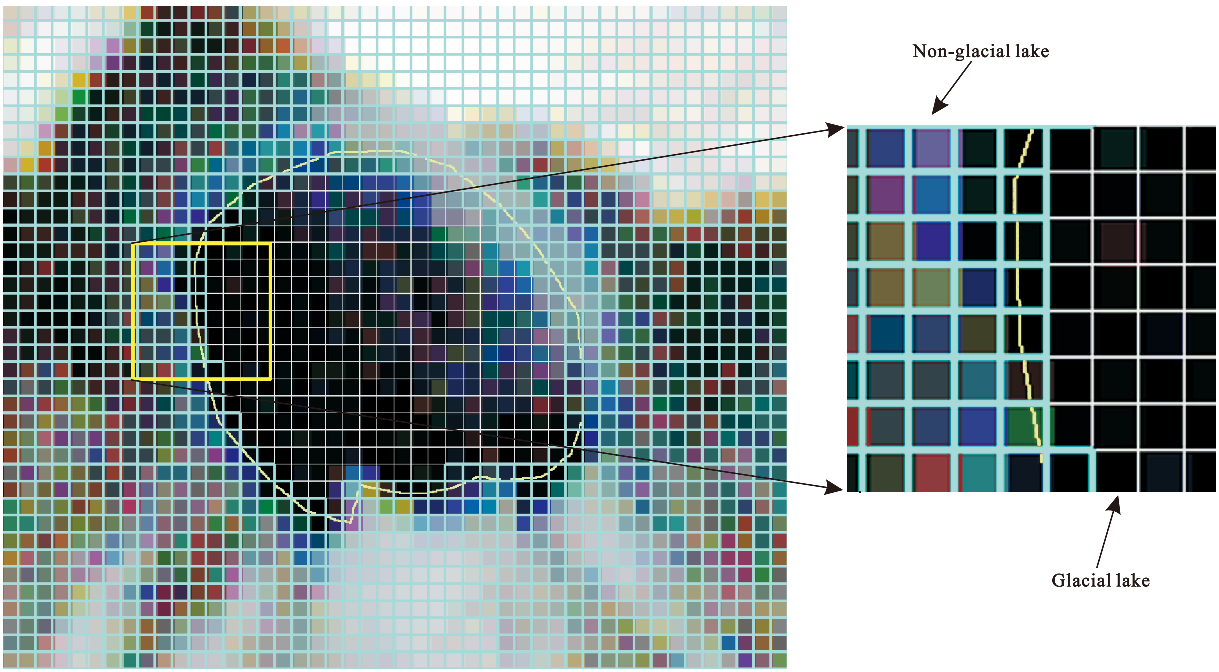
2.4.3 Accuracy assessment

The accuracy of the NDWI model and the DSGL model were compared by Area Under Curve (AUC) and Kappa statistics. First, AUC was calculated using Receiver Operating Characteristic (ROC) curves (Krzanowski and Hand, 2009). Secondly, based on a confusion matrix, the correct classification rate, sensitivity, specificity, and Kappa coefficients were calculated. Figure 6 illustrates the sampling grids with the spatial resolution of 15 m. The sampling grids were prepared for target three lakes by ArcGIS 9.3® software to validate two classification models.

3 Results

3.1 Comparison of NDWI and DSGL models with ground truth information

The results from NDWI model and DSGL model were



Light green line is boundary of glacial lake

Fig. 6 An example of sampling grids taking from Ambulapcha Lake in Himalayas, Nepal compared with the ground truth imagery on March 26th, 2008 (Fig. 7). The shadowed glacial lake of Ambulapcha Lake completely emerged so that the boundary of glacial lakes was able to be identified visually in DSGL model. On the contrary, using NDWI model, glacial lakes in the ASTER imagery either looked disappear (Ambulapcha Lake) or were partly visible (parts of Shadowed Lake 1 and Lake 2) due to shadow effects.

The classified imageries by NDWI model and DSGL model were presented and compared to the ground truth imagery (Fig. 8). While Ambulapcha Lake was not classified, Shadowed Lake 1 and Shadowed Lake 2 were partly classified by the NDWI model (see yellow polygon in Fig. 8). However, using the DSGL model, the three target shadowed glacial lakes were all classified (red polygon in Fig. 8), which were almost identical to the ground truth result (blue polygon in Fig. 8).

The area of three target glacial lakes by two classification models were compared with ground truth data (Table 1). The conventional NDWI model can not ex-

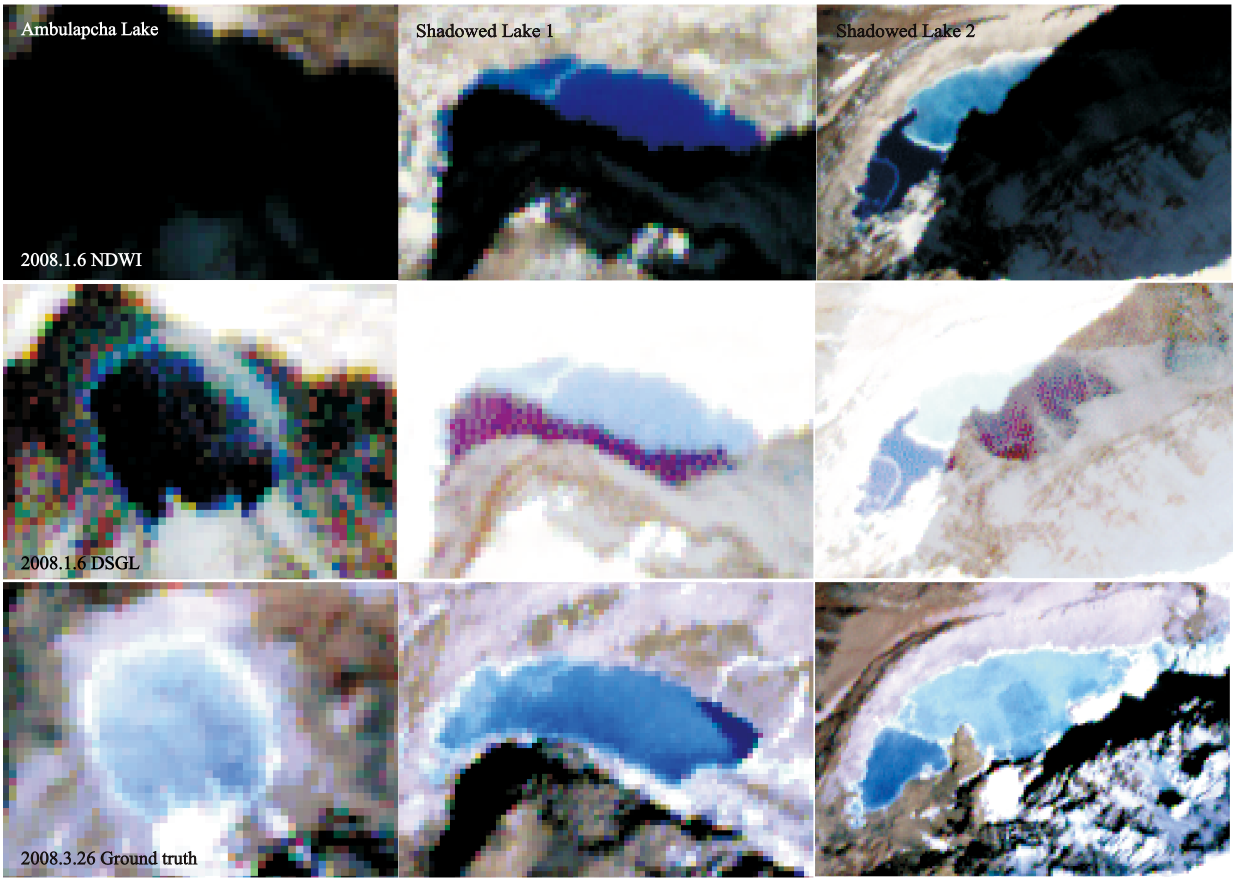


Fig. 7 Imageries produced by NDWI, DSGL models and ground truth data for shadowed Ambulapcha Lake, Shadowed Lake 1 and Shadowed Lake 2 in Himalayas, Nepal

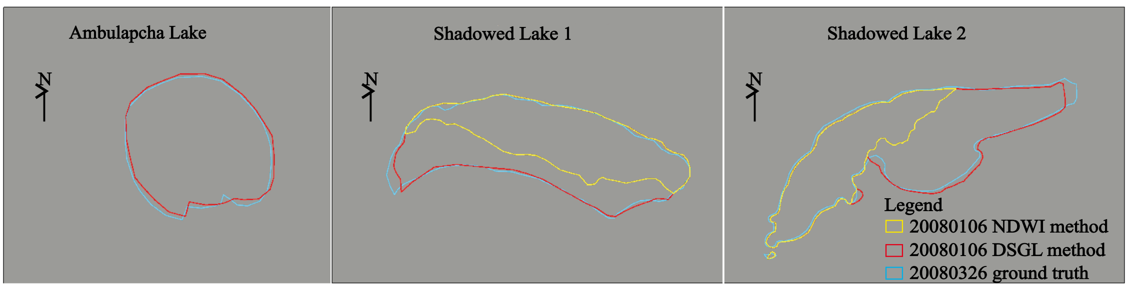


Fig. 8 Boundaries identified by NDWI and DSGL models and ground truth data

tract the Ambulapcha Lake at all. By NDWI, Ambulapcha Lake, Shadowed Lake 1 and Shadowed Lake 2 were identified 0, 61% and 46% of their total area, respectively. While the DSGL model was able to identify 99% of the total area for all three target lakes.

Table 2 presented the confusion matrix of classification result from two methods. By using the NDWI method, 1885 samples were correctly identified as glacial lakes, and 2225 samples were wrongly classified as non-glacial lakes among 4110 samples of actual glacial lakes. On the other hand, non-glacial lakes were efficiently predicted; all 17 281 samples were correctly accounted as non-glacial lakes by NDWI method. In contrast, with the DSGL model, however, among actual glacial lakes, 4077 samples were accounted as glacial lakes, and 33 samples were wrongly accounted as non glacial lakes in the sample area. Whereas, among actual non glacial lakes, 17 249 samples were accounted as non glacial lakes, and 32 samples were mistakenly accounted as glacial lakes by the DSGL model in the sample area.

Table 1 Extracted area of Ambulapcha Lake, Shadowed Lake 1 and Shadowed Lake 2 using different methods (m^2)

Method	Ambulapcha Lake	Shadowed Lake 1	Shadowed Lake 2
NDWI model	0 (0%)	119 399 (61%)	370 406 (46%)
DSGL model	84 639 (99%)	194 587 (99%)	794 000 (99%)
Ground truth	84 852 (100%)	194 868 (100%)	796 904 (100%)

Notes: Number shown in parentheses indicates proportion of area if area from ground truth data is considered to be 100%; Ambulapcha Lake is completely covered by shadow; Shadowed Lake 1 and 2 are partly covered by shadow

Table 2 Confusion matrix comparison between NDWI and DSGL models

Model			Predicted: Glacial lakes	Predicted: Non-glacial lakes	Total
NDWI	Actual	Glacial lakes	1885	2225	4110
		Non glacial lakes	0	17281	17281
	Total		1885	19506	21391
DSGL	Actual	Glacial lakes	4077	33	4110
		Non glacial lakes	32	17249	17281
	Total		4109	17282	21391

Note: Cut-off value of 0.5 was used for classification

3.2 Comparison of NDWI and DSGL models

Results of Kappa analysis as well as AUC were presented in Table 3. In general, accuracy of the DSGL model was higher than that of the NDWI model. The sensitivity of the NDWI model was much lower than that of the DSGL model. However, the specificity of both two methods was nearly the same. Comparing to the NDWI model, the DSGL model was almost perfect in Kappa analysis. Moreover, the correct classification rate (CCR) showed that the DSGL model (0.99) outperformed the NDWI model (0.89). The DSGL model presented an outstanding AUC value (0.99) comparing to the NDWI model (0.72).

Table 3 Classification results of NDVI and DSGL models

Model	AUC	Sensitivity	Specificity	CCR	Kappa coefficient
NDWI	0.72	0.45	1.00	0.89	0.57
DSGL	0.99	0.99	0.99	0.99	0.99

Notes: AUC means Area Under Curve; CCR denotes correct classification rate; cut-off value for CCR and Kappa was 0.5

4 Discussion

In the high altitude mountains, it is known that shadow occurs in remote sensing imageries due to the lower solar elevation (Gibson, 2000). If the glacial lakes are covered by shadow partly or fully, these lakes can not be identified (Giles, 2001; Chen *et al*., 2007; UNEP, 2009), resulting in underestimation of the number and area of glacial lakes. Nevertheless, the shadowed glacial lakes have been neglected by previous studies, and no countermeasures have been investigated till now.

The proposed DSGL model in this paper is expected to identify shadowed glacial lakes more effectively than the NDWI model in the high mountains. Accuracy assessment suggests that the DSGL model exceeds the NDWI model generally. Correct classification rate of the DSGL model is much higher than that of NDWI model. The Kappa statistics showed that NDWI model tends to underestimate actual glacial lakes; moreover, the DSGL model can classify most of actual glacial lakes correctly.

Hence, the DSGL model may prevent glacial lakes from being undervalued in terms of number and area. In this study, we tested the DSGL model in the Himalayas, Nepal; however, fundamentally, the DSGL model can be applied to detect water boundaries in the regions with steep terrain. For future study, the more accurate and latest DEM data would be beneficial to improve the accuracy of terrain analysis and to monitor constant and frequent change of glacial lakes.

5 Conclusions

As a high altitude region, the Himalayas can cause shadow effects in satellite imageries. Using conventional method such as NDWI model, it is hard to detect glacial lakes under shadowed environment. Hence, a new model, named DSGL model, was proposed to identify glacial lakes under the shadow environment by using ASTER data. The products from NDWI model and DSGL model were compared. The NDWI model tended to underestimate the presence of actual glacial lakes, while the DSGL method could correctly classify the glacial lakes. Kappa coefficients of the results from NDWI model and the DSGL model were reached to 0.57 and 0.99, respectively. It shows that the DSGL model is more accurate than NDWI model in detecting the glacial lakes in the shadow environment in the Himalayas, Nepal.

Acknowledgements

The authors are thankful to the Global Earth Observation Grid, Japan (GEOGrid; http://www.geogrid.org/en/ index.html) for providing the ASTER data through the 'GEO Grid' project aiming at providing an E-Science infrastructure for worldwide Earth Sciences community. The authors would also like to thank Prof. Yamamoto (Information Technology Research Institute, National Institute of Advanced Industrial Science and Technology) for the technical support of ASTER data.

References

Bajracharya S R, Gurung D R, Uddin K *et al*., 2009. *Mapping and Inventory of Glaciers Using Remote Sensing Data and Techiques-Hands-on Training Manual*. Kathmandu: International Centre for Integrated Mountain Development (ICIMOD).

Bajracharya S R, Mool P K, Shrestha B R, 2007. *Impact of Climate Change on Himalayan Glaciers and Glacial Lakes*: *Case Studies on GLOF and Associated Hazards in Nepal and Bhutan*. Kathmandu: International Centre for Integrated Mountain Development (ICIMOD).

Barry R G, 2008. *Mountain Weather and Climate*. Cambridge: Cambridge University Press.

Bishop M P, Shroder J F, 2004. *Geographic Information Science and Mountain Geomorphology*. Springer. Available at: http://www.springer.com/earth+sciences+and+geography/geographical+information+systems/book/978-3-540-42640-0

Bolch T, Kamp U, Olsenholler J, 2005. Using ASTER and SRTM DEMs for studying geomorphology and glaciation in high mountain areas. In: Oluić M (ed.). *New Strategies for European Remote Sensing*, 119–127. Rotterdam, Holand: Millpress.

Cenderelli D A, Wohl E E, 2001. Peak discharge estimates of glacial-lake outburst floods and 'normal' climatic floods in the Mount Everest region, Nepal. *Geomorphology*, 40(1–2): 57–90. doi: 10.1016/S0169-555X(01)00037-X

Chen X, Cui P, Li Y *et al*., 2007. Changes in glacial lakes and glaciers of post-1986 in the Poiqu River basin, Nyalam, Xizang (Tibet). *Geomorphology*, 88(3–4): 298–311. doi: 10.1016/j.geomorph.2006.11.012

Dyurgerov M, 2003. Mountain and subpolar glaciers show an increase in sensitivity to climate warming and intensification of the water cycle. *Journal of Hydrology*, 282(1–4): 164–176. doi: 10.1016/S0022-1694(03)00254-3

Gao B C, 1996. NDWI-A normalized difference water index for remote sensing of vegetation liquid water from space. *Remote Sensing of Environment*, 58(3): 257–266. doi: 10.1016/S0034-4257(96)00067-3

Gibson P J, 2000. *Introductory Remote Sensing*: *Principles and Concepts*. London: Routledge.

Giles P T, 2001. Remote sensing and cast shadows in mountainous terrain. *Photogrammetric Engineering and Remote Sensing*, 67(7): 833–839.

Immerzeel W W, Droogers P, de Jong S M *et al*., 2009. Large-scale monitoring of snow cover and runoff simulation in Himalayan river basins using remote sensing. *Remote Sensing of Environment*, 113(1): 40–49. doi: 10.1016/j.rse.2008.08.010

Ives J D, Shrestha R B, Mool P K, 2010. *Formation of Glacial Lakes in the Hindu Kush-Himalayas and GLOF Risk Assessment*. Kathmandu: International Centre for Integrated Mountain Development (ICIMOD).

Joseph G, 2005. *Fundamentals of Remote Sensing*. Delhi: Universities Press.

Kaltenborn B P, Nellemann C, Vistnes I I, 2010. *High mountain glaciers and climate change-Challenges to human livelihoods and adaptation*. Birkeland: United Nations Environment Programme (UNEP). Available at: http://www.unep.org/publications/contents/pub_details_search.asp?ID=4168

Kattelmann R, 2003. Glacial lake outburst floods in the Nepal Himalaya: A manageable hazard? *Natural Hazards*, 28(1): 145–154. doi: 10.1023/A:1021130101283

Krzanowski W J, Hand D J, 2009. *ROC Curves for Continuous Data*. Boca Raton: Chemical Rubber Company (CRC) Press.

McFeeters S K, 1996. The use of the Normalized Difference Water Index (NDWI) in the delineation of open water features. *International Journal of Remote Sensing*, 17(7): 1425–1432. doi: 10.1080/01431169608948714

Mool P K, Bajracharya S R, Joshi S P, 2001. *Inventory of Glaciers, Glacial Lakes and Glacial Lake Outburst Floods-Monitoring and Early Warning Systems in the Hindu Kush-Himalayan Region, Nepal*. Kathmandu: International Centre for Integrated Mountain Development (ICIMOD).

Owen L A, Robinson R, Benn D I *et al*., 2009. Quaternary glaciation of Mount Everest. *Quaternary Science Reviews*, 28(15–16): 1412–1433. doi: 10.1016/j.quascirev.2009.02.010

Quincey D J, Richardson S D, Luckman A *et al.*, 2007. Early recognition of glacial lake hazards in the Himalaya using remote sensing datasets. *Global and Planetary Change*, 56(1–2): 137–152. doi: 10.1016/j.gloplacha.2006.07.013

Reynolds J M, 2000. On the formation of supraglacial lakes on debris-covered glaciers. In: Nakawo M (eds.). *Workshop on Debris-Covered Glaciers*, 153–161. Seattle, Washington, USA: International Association of Hydrological Sciences (IAHS).

Richardson S D, Reynolds J M, 2000. An overview of glacial hazards in the Himalayas. *Quaternary International*, 65–66: 31–47. doi: 10.1016/S1040-6182(99)00035-X

Shrestha A B, Kumar R, Shen Y, 2005. An overview of glaciers, glacier retreat, and subsequent impacts in Nepal, India and China. In: Thomas K J (eds.). *WWF Nepal Progra*. Gland: World Wide Fund for Nature (WWF).

Shrestha A B, Wake C P, Mayewski P A *et al*., 1999. Maximum temperature trends in the Himalaya and its vicinity: An analysis based on temperature records from Nepal for the period 1971-94. *Journal of Climate*, 12(9): 2775–2786. doi: 10.1175/1520-0442(1999)012<2775:MTTITH>2.0.CO;2

UNEP (United Nations Environment Programme), 2009. *Recent Trends in Melting Glaciers*, *Tropospheric Temperatures over the Himalayas and Summer Monsoon Rainfall over India*. Kenya.

Wang W C, Yang X X, Yao T D, 2012. Evaluation of ASTER GDEM and SRTM and their suitability in hydraulic modelling of a glacial lake outburst flood in southeast Tibet. *Hydrological Processes*, 26(2): 213–225. doi: 10.1002/hyp.8127

Xu D, 1988. Characteristics of debris flow caused by outburst of glacial lake in Boqu river, Xizang, China, 1981. *GeoJournal*, 17(4): 569–580. doi: 10.1007/BF00209443

Xu H, 2006. Modification of normalised difference water index (NDWI) to enhance open water features in remotely sensed imagery. *International Journal of Remote Sensing*, 27(14): 3025–3033. doi: 10.1080/01431160600589179

Yamamoto H, Tsuchida S, Yoshioka H, 2008. A study on ASTER/MODIS radiometric and atmospheric correction. IEEE International Geoscience & Remote Sensing Symposium, IV1352–1355. Boston, Massachusetts, U.S.A. doi: 10.1109/IGARSS.2008.4779982