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Abstract

Glacier retreat has received increased attention as a sensitive indicator of global warming. Based on medium-resolution Landsat Thematic Mapper (TM) images acquired between 1990 and 2009, high-resolution GeoEye IKONOS images acquired in 2005, and a digital elevation model (DEM) provided by NASA’s Shuttle Radar Topographic Mission (SRTM) carried out by the space shuttle Endeavour in 2000, this study focuses on the spatial and temporal variation of the moraine-covered Gangotri Glacier – one of the largest glaciers in the Himalayas. Image calibration was carried out to convert Landsat TM digital numbers (DN) into radiance and reflectance for better comparison between images acquired on different dates. Reflectance spectral curves were derived from both glacial and non-glacial features for more accurate image interpretation. IKONOS images were used for accurate mapping of glacier terrain features. SRTM DEM was used to determine glacial flow directions and aid in image interpretation. Multi-temporal analyses of Landsat TM images acquired in 1990, 2001, and 2009 show that the Gangotri Glacier retreated 345 meters from 1990 to 2009, with a retreating rate of approximately 18 meters per year. The results also show that there are no obvious changes in glacial retreating rates during 1990-2001 and 2001-2009. However, the River Ganges may potentially become a seasonal river as a result of continued glacier retreating, affecting hundreds of millions of people on the Indian subcontinent.

1. Introduction

A glacier is made up of fallen snow that compresses into large, thickened ice masse over many years. A moraine is any glacially formed accumulation of unconsolidated glacial debris (soil and rock). Ice, snow, and glaciers have important effects on land surface temperature and air/soil moisture. They are also important freshwater resources through surface runoff. Glacier
retreat has become a sensitive indicator of global climate change (Owen 2009, Yao et al. 2007, Ding et al. 2006, Gupta et al. 2005).

Many researchers have studied glaciers on local and global scales. Owen (2009) and Owen and England (1998) studied glacier fluctuations in the Himalaya and surrounding areas. Singh et al. (2006) investigated the hydrological characteristics of the Gangotri Glacier in the Himalayas. Racoviteanu et al. (2008) mapped Himalayan glaciers using remote sensing. Yao et al. (2007) studied glacier retreat on the Tibetan Plateau. Gupta et al. (2007) mapped dry/wet snow cover in the Indian Himalayas. Kulkarni et al. (2007) analyzed glacial retreat in the Himalayas using Indian remote sensing satellite data. Hall et al. (1995) discussed snow cover mapping using remote sensing. Kargel et al. (2005) provided a comprehensive review of multispectral imaging contributions to global land ice measurements from space. Because of their unique capabilities in acquiring spatial, spectral, and temporal information on earth surface features and phenomena, remotely sensed images have been widely used in glacial studies. However, there are some major limitations of existing studies on glacial mapping using remote sensing: (1) Images from a single year or limited timeframe are often used to map glacial features that may change over time; (2) High resolution images are not widely applied to glacial studies; and (3) Quantitative measures such as glacial retreating distances and rates are often inaccurate because of the above two limitations.

The objectives of this study are to (1) Detect moraine-covered glacier using medium-resolution Landsat Thematic Mapper (TM) and high-resolution IKONOS images; (2) Quantify changes of moraine-covered glacier from 1990 to 2009. Following this brief introduction, the following sections provide more details on the study area and data, methodology, results, and conclusions.

2. Study Area and Data

The Gangotri Glacier of the Indian Himalayas was selected as the study area because of the following reasons: (1) The Himalayas is the third pole of the Earth, and the first pole of the Earth in terms of direct impact to human population – several important river systems originate from the Himalayas, affecting over 3 billion people in East Asia, Southeast Asia, and the Indian Subcontinent. (2) As one of the largest glaciers in the Himalayas (about 25 km by 30 km) with high elevation, accessibility to the Gangotri Glacier is very difficult by traditional means; (3)
Gangotri Glacier is one of the major sources of the River Ganges – one of the major rivers of the Indian subcontinent. Figure 1(A) shows the location of the study area, and Figure 1(B) shows the location of the River Ganges.

Landsat TM images (30-m resolution) acquired from 1990-2009 were used in this study (Figure 2). Landsat TM images provide historic records of glacial changes in the past 30 years, but accurate mapping of glacier geomorphology has been a challenge because of the relatively low resolution (30 m) of Landsat TM images. GeoEye IKONOS images provide excellent spatial details of glacial terrains with 4-m resolution (multispectral bands) and 1-m resolution (panchromatic band), and can greatly help identify moraine-covered glaciers and other glacial and non-glacial features. IKONOS panchromatic and multispectral images acquired in 2005 were used to support Landsat TM image analysis in this research (Figures 3, 4, and 5). Digital elevation data collected by Space Shuttle Endeavour in 2000 was also used to derive glacial flow direction and topographic information (Figure 6).
Figure 2. Landsat TM image of the study area acquired in 1990.

Figure 3. IKONOS multispectral and panchromatic images acquired in 2005.
Figure 4. IKONOS multispectral and panchromatic images acquired in 2005.

Figure 5. IKONOS multispectral image acquired in 2005.
Figure 6. 90-m resolution digital elevation model (DEM) acquired by the Space Shuttle Endeavour during the Space Radar Topographic Mission (SRTM) in 2000.

3. Methodology

Before Landsat TM images can be digitally processed, they need to be calibrated using the following equations to convert digital numbers (DN) into radiance and reflectance. These conversions ensure that images acquired on different dates can be compared with one another more accurately.

\[
L_\lambda = \frac{(L_{\text{max}_\lambda} - L_{\text{min}_\lambda})}{Q_{\text{cal,max}}} Q_{\text{cal}} + L_{\text{min}_\lambda}
\]

\[
\rho_p = \frac{(\pi * L_\lambda * d^2)}{ESUN_\lambda} \cos \theta_s
\]

- \(L_\lambda\) = spectral radiance at sensor’s aperture in W/(m²*sr*μm);
- \(Q_{\text{cal}}\) = quantized calibrated pixel value in DNs;
- \(Q_{\text{cal,max}}\) = maximum quantized calibrated pixel value (DN = 255) corresponding to \(L_{\text{max}_\lambda}\);
- \(L_{\text{max}_\lambda}\) = spectral radiance that is scaled to \(Q_{\text{cal,max}}\) in W/(m²*sr*μm);
- \(L_{\text{min}_\lambda}\) = spectral radiance that is scaled to \(Q_{\text{cal,min}}\) in W/(m²*sr*μm);
\( \rho_p = \text{unitless planetary reflectance}; \)
\( d = \text{earth-sun distance in astronomical units}; \)
\( \text{ESUN}_\lambda = \text{mean solar exatmospheric units}; \)
\( \theta_s = \text{solar zenith angle in degree}. \)

Based on calibrated images, spectral properties of glacial and non-glacial features were then derived to discriminate different features in the Gangotry Glacier (Figure 7).

![Figure 7. Spectral curved derived from different features.](image)

Following image calibration and spectral curve analysis, glacial features were extracted from high resolution IKONOS images, and change detection and quantification using multi-temporal Landsat TM images acquired between 1990 and 2009 were carried out.

4. **Results and Discussion**

The results are shown in the following figures, and glacial retreating distances and rates are listed in Table 1.
Figure 8. Interpretation of the old glacial boundary. Because of melting ice, the old glacier became a glacial stream, but traces of the old glacier are obvious.

Figure 9. Detailed glacial and non-glacial features on the IKONOS image.
Figure 10. Evidence of glacier retreat from multi-temporal Landsat TM images.

Figure 11. Retreat of the moraine-covered glacier and advance of the glacial stream.

Table 1. Glacial retreating distances and rates in the Gangotri Glacier from 1990-2009.

<table>
<thead>
<tr>
<th>Time</th>
<th>Retreating Distance (m)</th>
<th>Retreating Rate (m/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990-2001</td>
<td>202</td>
<td>18.36</td>
</tr>
<tr>
<td>2001-2009</td>
<td>143</td>
<td>17.88</td>
</tr>
<tr>
<td>1990-2009</td>
<td>345</td>
<td>18.16</td>
</tr>
</tbody>
</table>
5. Conclusions

Based on the above results, the following conclusions can be drawn:

(1) The medium-resolution Landsat TM images provided important spatial, spectral, and temporal information on changes of the Gangotri Glacier from 1990 to 2009. The high-resolution IKONOS images and the medium-resolution SRTM digital elevation model provided additional information on glacial geomorphology and flow direction.

(2) From 1990 to 2009, the moraine-covered Gangotri Glacier retreated 345 meters, with a retreating rate of approximately 18 meters per year. There are no obvious changes in retreating rates during 1990 – 2001 and 2001 – 2009. We hope these new findings can provide some insight into the sometimes heated discussions on glacial retreating rates in the Himalayas, particularly the Gangotri Glacier.

(3) The River Ganges may potentially become a seasonal river as a result of continued glacier retreating, affecting hundreds of millions of people on the Indian subcontinent.

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References


