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RS analysis of glaciers change in the Heihe River Basin, Northwest China, during the recent decades

HUAI Baojuan[1,2], LI Zhongqin[1,3], WANG Shengjie[3], SUN Meiping[3], ZHOU Ping[1], XIAO Yan[4]

1. State Key Laboratory of Cryospheric Sciences, Cold and Arid Regions Environmental and Engineering Research Institute/Tianshan Glaciological Station, CAS, Lanzhou 730000, China;
2. University of Chinese Academy of Sciences, Beijing 100049, China;
3. College of Geography and Environmental Sciences, Northwest Normal University, Lanzhou 730070, China;
4. College of Environment and Planning, Liaocheng University, Liaocheng 252059, Shandong, China

Abstract: The Heihe River Basin is the second largest inland river basin in Northwest China and it is also a hotspot in arid hydrology, water resources and other aspects of researches in cold regions. In addition, the Heihe River Basin has complete landscape, moderate watershed size, and typical social ecological environmental problems. So far, there has been no detailed assessment of glaciers change information of the whole river basin. 1:50,000 topographic map data, Landsat TM/ETM+ remote sensing images and digital elevation model data were used in this research. Through integrated computer automatic interpretation and visual interpretation methods, the object-oriented image feature extraction method was applied to extract glacier outline information. Glaciers change data were derived from analysis, and the glacier variation and its response to climate change in the period 1956/1963–2007/2011 were also analyzed. The results show that: (1) In the period 1956/1963–2007/2011, the Heihe River Basin's glaciers had an evident retreat trend, the total area of glaciers decreased from 361.69 km^2 to 231.17 km^2; shrinking at a rate of 36.08%, with average single glacier area decrease 0.14 km^2; the total number of the glaciers decreased from 967 to 800. (2) Glaciers in this basin are mainly distributed at elevations of 4300–4400 m, 4400–4500 m and 4500–4600 m; and there are significant regional differences in glaciers distribution and glaciers change. (3) Compared with other western mountain glaciers, glaciers retreat in the Heihe River Basin has a higher rate. (4) Analysis of the six meteorological stations' annual average temperature and precipitation data from 1960 to 2010 suggests that the mean annual temperature increased significantly and the annual precipitation also showed an increasing trend. It is concluded that glacier shrinkage is closely related with temperature rising, besides, glacier melting caused by rising temperatures greater than glacier mass supply by increased precipitation to some extent.

Keywords: remote sensing detection; glacier; object-oriented extraction method; shrinkage; Landsat TM/ ETM+; Heihe River Basin

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Author: Huai Baojuan (1988–), PhD, specialized in GIS and glaciology. E-mail: huaibaojuan@126.com

1 Introduction

With global warming and rapid shrinkage of glaciers in recent decades (IPCC, 2001), the cryosphere system has gained an unprecedented attention for scientific research (Haeberli *et al*., 2000; Wang *et al*., 2014). Cryospheric science is considered to be one of the most active sections of current global change investigation, which is critical for regional and global sustainable development. Glaciers, as an important part of the cryosphere system, are solid reservoir of freshwater resources (Wang *et al*., 2003). Impacted by global warming, glaciers shrinking is a common trend especially for the mountain glaciers in the High Asia, and China's glaciers were predicted to reduce by 27.20% in the first half of the 21st century (Qin *et al*., 2006). Many studies show that the indicative role of glaciers change in global climate change in this century is more obvious (Shi *et al*., 2000; Houghton *et al*., 2001; Yao *et al*., 2004). River runoff and other water resources are significantly influenced by glaciers change, especially in the arid and semi-arid regions in Northwest China (Shi, 2001). Timely and correct assessment of glaciers change and revealing effects of glaciers change on Northwest China's river runoff are also important. The Heihe River Basin is the second largest inland river basin in Northwest China. Due to its typical natural landscapes and complex man-land relationship, this drainage basin is widely considered to be a representative region of inland river basin (Ning *et al*., 2008). A comprehensive observation system has been established in this river basin in the recent 30 years, and many researches focused on the regional water resources influenced by the mountain glaciers. In the Heihe River Basin, the annual glaciers melt water from high-altitude glacier in Qilian Mountains is approximately 2.98×10^8 m^3, accounting for 8% of the total river runoff (Yang, 1991; Feng *et al*., 2002).

During the past decades, remote sensing (RS) and geographic information systems (GIS) have become widely-used technologies to monitor the dynamic changes of glaciers (Paul *et al*., 2000; Shangguan *et al*., 2004). Besides, RS and GIS are also an effective solution to obtaining high mountain glaciers vector data in the study of modern glaciers. Artificial visual interpretation method and computer-assisted classification method are the main steps in extracting glaciers boundary information from the remote sensing images (Serandre *et al*., 1999; Bolch *et al*., 2007; Hall *et al*., 2001). Traditional image analysis methods usually ignore the interrelated information of spatial characteristics within the images; thereby reduce the accuracy of information extraction. In the traditional process, complex shape, texture and other information in images are easy to be considered as noise, which may lead to wrong judgments in image interpretation and misclassification (Huai *et al*., 2013; Sidjak *et al*., 1999; Zhang *et al*., 2011b; Zhang, 2005). Basically, the above-mentioned phenomena in pixel-based image analysis methods is caused by the spectral characteristics for each pixel itself, and internal message within pixel-based image analysis is limited (Wei *et al*., 2007). Object-oriented extraction method (Nie *et al*., 2010; Blaschke *et al*., 2001; Benz *et al*., 2004; Baatz *et al*., 2000) provides strong technical support to avoid or reduce the disadvantage of the traditional method only using spectral characteristics. In the new method, remote sensing image can be segmented, and then various features of the divided units were extracted, recognized and identified in the feature space, which means that the classification is completed (Laliberte *et al*., 2004; Schiewe *et al*., 2001). This paper applied this method in the glaciers information extraction of the Heihe River Basin. Detailed investigations were done for glaciers change under climate warming in this river basin.

2 Study area

The Heihe River Basin (38°N–42°N, 98°E–101°30'E) lies on the west of Shiyang River Basin, and on the east to Shule River Basin (Figure 1). The total length of the Heihe River is 821 km from headstream in Qilian Mountains to Juyan Lake. The upstream watershed of the Heihe River is defined as drainage basin above Yingluoxia (a debouchure out of Qilian Mountains), and the catchment area and average altitude of upstream watershed is 10,009 km^2 and 3738 m, respectively. The total surface runoff of the upstream watershed is 25.11×10^8 m^3 (Yellow River Conservancy Committee, 2010; http://www.yellowriver.gov.cn). The Heihe River Basin includes three main landform types, i.e., Qilian Mountains (upstream), Hexi Corridor plains (midstream) and Alxa Highland (downstream). Modern glaciers are widely distributed at the high-altitude mountains of the upstream watershed. Based on the aerial photographs taken in 1956 and 1963 (painted in 1964 and 1972), the first Glacier Inventory of China (GIC) of Qilian Mountains was completed by the former Lanzhou Institute of Glaciology and Cryopedology (LIGG), Chinese Academy of Sciences (CAS) in 1981 (Wang *et al*., 1981). According to the first GIC, there are 1078 glaciers in the Heihe River Basin with a total area and an ice volume being 420.55 km^2 and 13.67 km^3, respectively. The average area of single glacier is 0.39 km^2, and the average snow line is 4410–4850 m.

It should be noted that the boundary of the Heihe River Basin is not completely consistent in different researches. According to the map of the Heihe River Basin drawn in 1985–1986, the whole basin is composed of three hydrologic balance units, namely, Heihe River, Beida River and Maying-Fengle Mountain Front, respectively. In general, this boundary includes Heihe River and Beida River. However, according to the first GIC, glaciers in the Heihe River and Beida River are listed separately. In this study, the generalized glaciers located in the Heihe River and Beida River are all included for analyzing distribution and variation of glaciers.

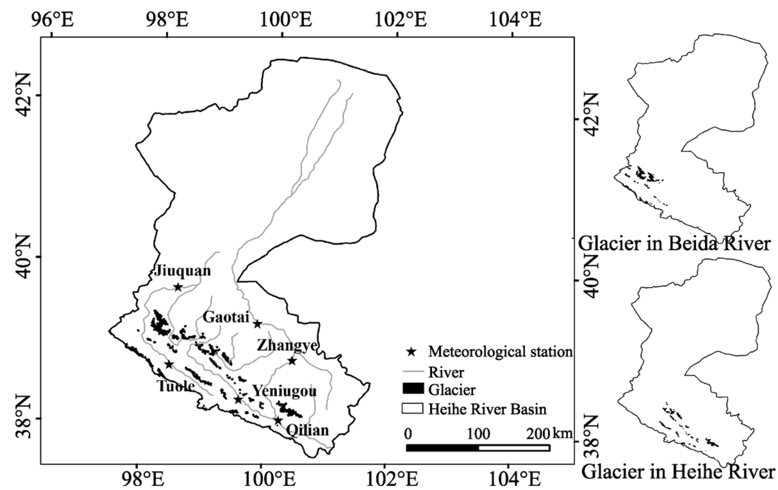


Figure 1 Location of the Heihe River Basin

3 Data processing and method

3.1 Data sources

The glacier vector boundary in the 1960s was derived from topographic maps using aerial photographs. The glaciers of the Heihe River Basin involve 16 topographic maps at a scale of 1:50,000 and 14 topographic maps of 1:100,000. The original aerial photographs were taken in 1956 and 1963 and then painted in 1964 and 1972, respectively. In 1973, the first edition of these maps was published. The coordinates system is Beijing 1954, and the elevation system is Yellow Sea system 1956. In this study, the topographic maps were scanned with a resolution of 300 dpi.

A total of 4 scenes of Landsat TM/ETM+ digital images were also used in this work, and the data are acquired from U.S. Geological Survey (USGS, http://www.usgs.gov) data sharing platform (Table 1). Digital elevation model (DEM) is derived from Shuttle Radar Topography Mission (SRTM), which is jointly measured by National Aeronautics and Space Administration of USA (NASA) and the Department of Defense National Mapping Agency of USA (NIMA). The revision V4.1 with a horizontal resolution of 90 m was used in this study. This version data was obtained with new interpolation algorithm by International Center for Tropical Agriculture (CIAT), which was considered to be better than the previous versions by filling the void SRTM90 data. The nominal absolute elevation data accuracy is ±16 m, and the absolute accuracy of plane surface is ±20 m.

Table 1 Remote sensing images of the Heihe River Basin used in this study

ID	Receive date	Sensor	Resolution (m)	Path
L5135033_03320070601	2007-06-01	TM	28.5	135/033
L5133034_03420090928	2009-09-28	TM	28.5	133/034
L71133033_03320110809	2011-08-09	ETM+	28.5/15	133/033
L5134033_03320100805	2010-08-05	TM	28.5	134/033

The first GIC data was also applied in interpreting the vector data of glaciers in the 1960s as a consult. The data was provided by the Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI), Chinese Academy of Sciences. Besides, boundary vector data of the Heihe River Basin was provided by the Cold and Arid Regions Science Data Center at Lanzhou (http://westdc.westgis.ac.cn). Meteorological data from six stations (Tuole, Yeniugou, Qilian, Zhangye, Gaotai, Jiuquan) were supplied by the Chinese Meteorological Science Data Sharing Service Network (http: //cdc.cma.gov.cn).

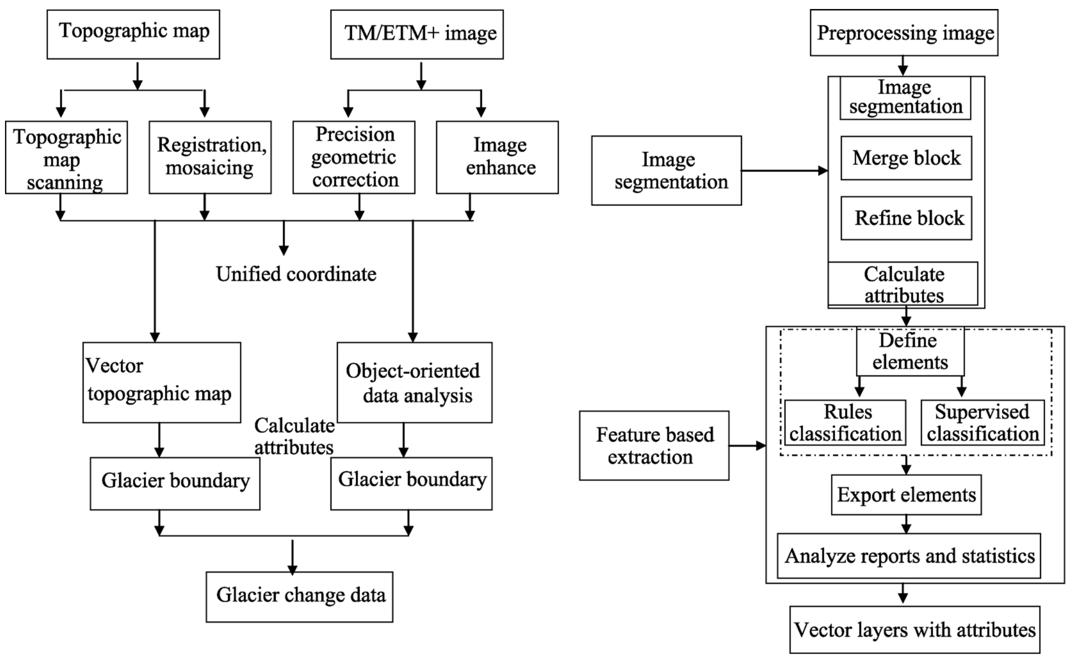
3.2 Data preprocessing

Preprocessing of topographic map data included scanning, registration and mosaicing. The topographic maps were scanned into digitized products, and then were corrected using grid. Root mean square error (RMSE) of geometric correction is less than one pixel. Preprocessing of image data included accurate geometric correction and image enhancement. All the data were presented in a Universal Transverse Mercator (UTM) coordinate system and World Geodetic System 1984 (WGS84) referenced to the topographic maps.

3.3 Method

Glacier boundary vector data in the 1960s were digitized from topographic maps in the Heihe River Basin using ArcGIS10. Recent glaciers boundary vector data in 2007/2011 were extracted through object-oriented classification method, besides, computer automatic interpretation and visual interpretation methods were also used as a consult. Above all, we referred to the expert guidance to further revise glaciers boundaries in 2007/2011. To sum up, glaciers area, average length and other attributes such as latitude and longitude information of the two periods were obtained by ArcGIS10. Moreover, through the use of SRTM-DEM V4, glaciers terminus elevation, glaciers average elevation, slope, orientations and other attribute information were also calculated. Eventually, overlay analysis of topographic maps glaciers vector data in the 1960s and recent glaciers vector data in 2007/2011 were carried out by ArcGIS10 spatial module to obtain glaciers change information and also to obtain glaciers area variation rules (Figure 2a).

By collecting objects near the pixel, these objects were used for identifying interest spectral features by object-oriented classification. This classification is divided into two processes (Wei *et al*., 2007): image objects construction and image objects classification (Figure 2b). Firstly, specifically segmentation method was used for remote sensing image segmentation. Then, the various features of dividing cells were extracted. Finally, objects in the feature space were recognized and identified, thus the classification was completed. Compared with pixel-based image classification methods, the object-oriented classification can effectively restrain the 'salt and pepper' effect and improve classification accuracy by segmentation and establishing homogeneous regions (Nie *et al*., 2010; Blaschke *et al*., 2001; Benz *et al*., 2004).

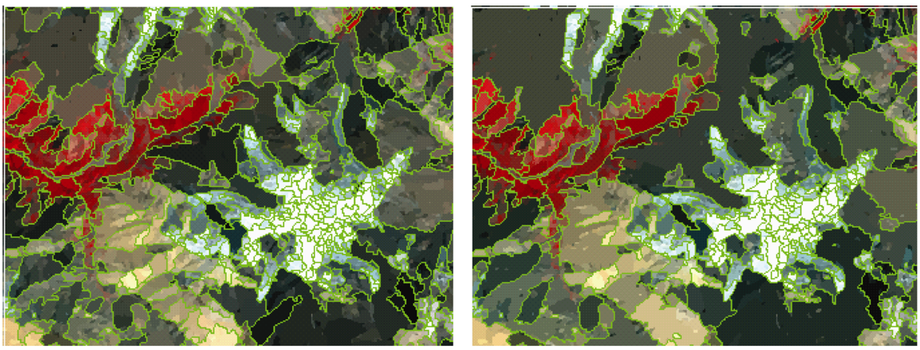


(a) Glacier change flowchart (b) Object-oriented method flowchart

Figure 2 Technical flowchart of derived glaciers

3.3.1 Image segmentation

As a first step, spectral features and shape features of Landsat image were integrated to compute comprehensive values of spectral heterogeneity and shape heterogeneity of each band with multi-scale segmentation algorithm. As a second step, all the bands' integrated weight values were calculated according to the share weight of each band. Then, if the divided objects' integrated weight values were less than a specified threshold value; repeat the iteration calculation until all the segmented objects' integrated weight value greater than the specified threshold value. Finally, the image multi-scale segmentation operation was completed (Guo *et al*., 2008). In order to achieve the multi-scale segmentation process and the original image objects extraction, we use ENVI EX performs for the calculation. In the process of image segmentation, continuous tests for different scale parameters were executed based on artificial visual effects for the accuracy of information extraction. Eventually, the appropriate scale parameters were chosen. Through trial and error again and again, finally we determine the segmentation scale parameter and the combined scale parameter of pure ice were 70% and 80%, respectively (Figure 3).



(a) Segmentation scale 50%, combination scale 70% (b) Segmentation scale 70%, combination scale 80%

Figure 3 Different scales of segmentation and combination image in the Heihe River Basin

3.3.2 Build knowledge rules

In this section, the most important thing is to find the threshold value of each related band manually. Certainly, spectral characteristics of each band, correlative index of spatial structure and histogram of images were referred to for the process of finding the threshold value. Indexes with target objects and other objects differing obviously are selected to set thresholds of target objects and other objects respectively, then the threshold of the index test was repeatedly set according to visual preview. Finally, all the thresholds of correlative index were integrated to determine the boundary of the target objects. The various types of knowledge rules used were as follows (Blaschke, 2010; Lahousse *et al*., 2011): (1) The Normalized Difference Snow/Ice Index (NDSII) was used to distinguish glaciers and other landform types. The formula is NDSI = (CH (2) – CH (5)) / (CH(2) + CH(5)). Due to ice in the visible band has a high spectral reflectance value and has a lower spectral reflectance in short wave infrared spectral band, the combination of the two bands can effectively extract ice and snow (Xiao *et al*., 2001; Willmes *et al*., 2009). (2) Band ratio method is not obvious when distinguishing and enhancing spectral brightness value, but effect is obvious when band ratio value of different types of landscape with larger differences. Selecting TM3 and

TM5 band ratio as threshold value of 2 to extract the glacier boundary. (3) In addition, glaciers elevation, area size and other characteristics were used to take a certain threshold. The defined threshold is extremely important for extracting glaciers. Definitive knowledge of glacier boundary extraction rules are as follows: TM3/TM5 > 2.0, & 0.46 < NDSI <0.58, & DEM > 4200 m, & (TM4–TM1) / (TM4+TM1) > –0.44, & 0.01 km^2 < area < 6 km^2.

3.3.3 Glacier ridgeline extraction

For automatic extraction of glaciers from Landsat images, the extraction of ridgeline is essentially the extraction of watershed lines. This ridgeline automatic extraction method is based on regular grid of SRTM-DEM V4 data, using the plane curvature and slope-shaped combination algorithms to achieve (Tang *et al*., 2006). The purpose of extracting the plane curvature and positive terrain is that the maximum plane curvature of the positive terrain is just the ridgeline. However, problems arose as the plane curvature is relatively cumbersome to extract. To achieve this, aspect variability which to some extent can be a good characterization of plane curvature is obtained to replace the plane curvature in ArcGIS10. Object-oriented automated extraction process is shown in Figure 4.

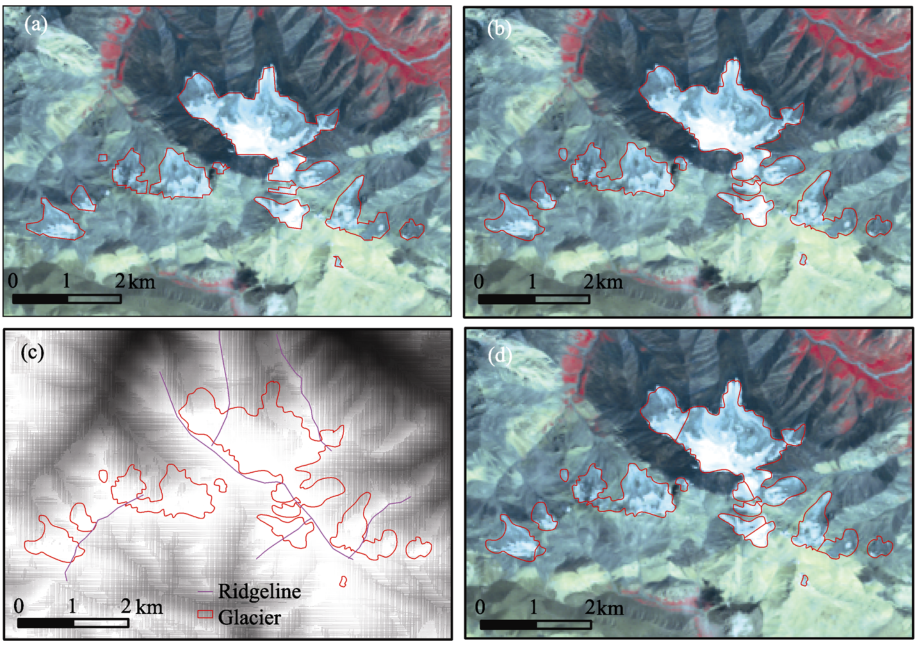


Figure 4 Object-oriented extraction process
(a) Glaciers boundary by object-oriented method; (b) Glaciers boundary by manual correction and smoothing; (c) Ridgelines of glacier region; (d) Ridgelines cutting glaciers

3.3.4 Accuracy assessment

Errors in the linear uncertainty from remote sensing image interpretation were affected by the image resolution and co-registration error. This study evaluated object-oriented method extraction errors by two ways: (1) Image resolution and co-registration errors. Remote sensing images spatial resolution (28.5 m for TM or ETM+ data) and RMSE of co-registration affect the accuracy of measurement. The uncertainty of each position can be calculated by the following formulas (Hall *et al*., 2003; Silverio *et al*., 2005; Ye *et al*., 2006):

$$U_T = \sqrt{\sum \lambda^2} + \sqrt{\sum \varepsilon^2} \quad (1)$$

$$U_A = 2U_T\sqrt{\sum \lambda^2} + \sqrt{\sum \varepsilon^2} \quad (2)$$

where U_T is the uncertainty of glacier length; λ is the image resolution; ε is the co-registration errors; U_A is the uncertainty of glacier area. Result of single glacier area uncertainty is ±0.002 km^2. (2) Glaciers extraction errors affected by debris. The greatest difficulty in mapping glaciers using remote sensing automatic classification is the presence of debris cover on glaciers. Currently, computer automatic classification method is not able to fully resolve same object with different spectral and different objects with same spectral phenomena. For debris-covered glaciers, as computer automatic extraction method is still in constant exploration, object-oriented extraction method did not consider this part of glaciers. This research used artificially visual interpretation for its accurate correction.

4 Results and discussion

4.1 Spatial characteristics of recent glaciers change in the Heihe River Basin

Due to the quality problem of Landsat images, part of the glaciers covered with snow or clouds, so just 967 glaciers(464 glaciers in Heihe River and 503 glaciers in Beida River) were focused on in this basin (total number of glaciers is 1078 in the Heihe River Basin) in this study. The results show that: 967 glaciers were decreased to 800 in the Heihe River Basin from the 1960s to 2007/2011, and the rate of recession in the number of glaciers was 17.27%, showing obvious shrinkage trends (Figure 5). The glaciers area was decreased from 361.69 km^2 to 231.17 km^2 which means a total area of 130.51 km^2 was lost, shrinking rate was 36.08%. Apparently, the average reduction of each glacier was 0.14 km^2 from the 1960s to 2007/2011. The magnitude of glaciers change, regional difference, and climate background in the past 50 years and so on will be presented as follows.

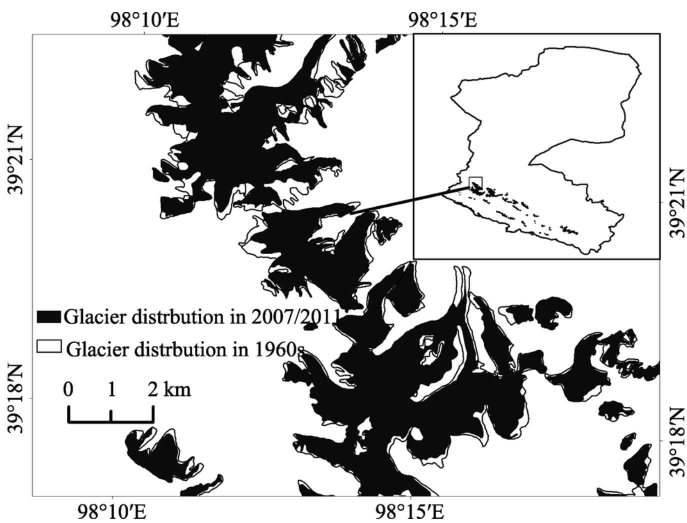


Figure 5 Glacier shrinkage in the Heihe River Basin

4.1.1 Glacier area and number change

Glaciers were divided into nine grades because the sizes of glaciers area in the Heihe River Basin are generally small (most glaciers is less than 1 km^2): ① <0.1 km^2; ② 0.1–0.2 km^2; ③ 0.2–0.3 km^2; ④ 0.3–0.4 km^2; ⑤ 0.4–0.5 km^2; ⑥ 0.5–1 km^2; ⑦ 1–2 km^2; ⑧ 2–5 km^2; ⑨ >5 km^2. As shown in Figure 6: glaciers which have area size <0.1 km^2 have its area and number increased by 10.01% and 42.44% respectively; and area size 0.1–0.2 km^2 have its area and number decreased by 32.09%, 31.47%; 0.2–0.3 km^2 decreased by 37.32%, 46.09% respectively; and 0.3–0.4 km^2 were 30.16%, 28.89% respectively; 0.4–0.5 km^2 were 48.48%, 48.68% respectively; 0.5–1 km^2 were 45.63%, 46.09% respectively; 1–2 km^2 were 28.61% and 28.30%; 2–5 km^2 were 34.94% and 38.89%; glaciers >5 km^2 were 100% and 100%. There is only one glacier with an area greater than 5 km^2, the number of which is 5Y433B0039 and glacier area is 5.61 km^2. This glacier was split into two glaciers (area being 4.62 km^2 and 0.13 km^2 respectively) in 2011. Apparently, high recession of glaciers in the Heihe River Basin directly resulted in an increase of glaciers with area <0.1 km^2 and decrease in number.

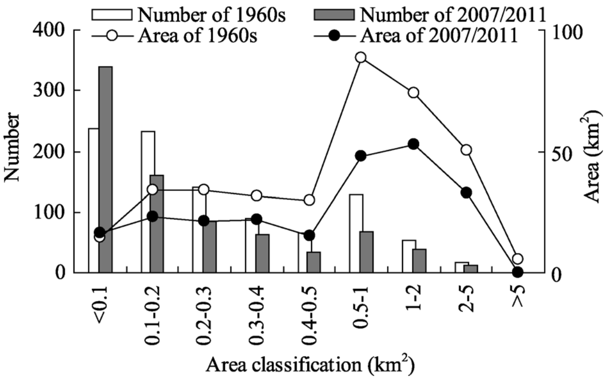


Figure 6 Change of glacier area and number in the Heihe River Basin

4.1.2 Characteristics of glacier variation in different altitude ranges

Using SRTM-DEM V4 data, vertical variations were calculated for each 100 m elevation gradients according to the elevation of glacier terminal. Statistical analysis was carried on for the two phases of the glacier data (Figure 7): glaciers termini in the Heihe River Basin were mainly distributed at 4300–4400 m, 4400–4500 m and 4500–4600 m, accounting for 20%, 24.5% and 19.38% of the total number respectively, or 63.88% of the grand total.

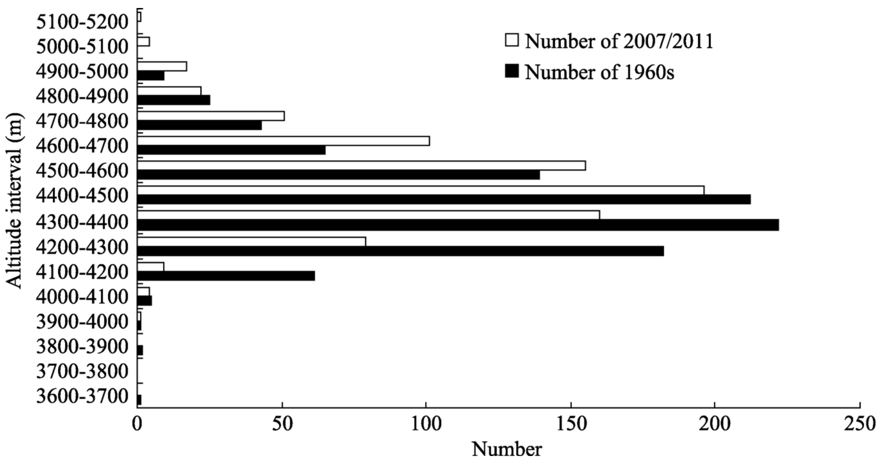


Figure 7 Change of terminal elevation of the Heihe River Basin

From the changing trend of the glaciers, the number decreased in four elevation ranges: 4100–4200 m, 4200–4300 m, 4300–4400 m and 4400–4500 m. The reduction rates of the four ranges were: 85.25%, 56.59%, 27.93% and 7.55% respectively. The most obviously reduction ranges are in the altitude range of 4100–4200 m and 4200–4300 m. Apparently, the high shrinking rate of glaciers at the altitude range of 4100–4500 m directly led to an increasing trend at altitude range of 4500–4800 m. Rates of glaciers number increasing at range of 4500–4600 m, 4600–4700 m and 4700–4800 m were 11.51%, 55.38% and 18.60% respectively. These facts show clearly that, as global temperatures rising generally, the snowline is going up with the terminal elevation of glaciers ascending in the Heihe River Basin.

4.1.3 Glacier distribution and regional differences

In this section, the differences in glaciers change between Heihe River and Beida River are compared, and each branch of the two subbasins are analyzed. Statistical information of Heihe River and Beida River are shown in Table 2. It is clear that distribution and changes of glaciers have significant regional differences. Glacier shrinking rate in Heihe River was 46.07%, which is much higher than that of Beida River (29.55%). These differences were mainly related with glacier area. Average area of 464 glaciers in Heihe River was 0.31 km^2, and average area of 503 glaciers of Beida River was 0.43 km^2. Generally, small glaciers were more sensitive to climate change. In previous research (Jia *et al*., 2008), summer warming trend in the Heihe River Basin is 0.27℃ per decade during the 1960s–2005, greater than that in Beida River (0.21℃/10a). In this study, the rate of glacier retreat in Heihe River was about 16% higher than that of Beida River.

Statistical results of glaciers distribution in Heihe River (Table 3) revealed that glaciers number in Dahe River (a tributary of Heihe River) remain unchanged, but with the rate of area change being –43.8%. Although the number of glaciers did not change in this tributary, area decreased significantly. Eight small glaciers disappeared completely, and 3 small

Table 2 Glaciers change of Heihe River and Beida River

Subbasin	Number of glaciers			Area of glaciers (km^2)		
	1960s	2007/2011	Change rate (%)	1960s	2007/2011	Change rate (%)
Heihe River (5Y42)	464	365	–21.34	143.18	77.22	–46.07
Beida River (5Y43)	503	435	–13.52	218.51	153.95	–29.55
Total	967	800	–17.27	361.69	231.17	–36.08

Table 3 Glaciers change of Heihe River

Branch	Number of glaciers			Area of glaciers (km^2)		
	1960s	2007/2011	Change rate (%)	1960s	2007/2011	Change rate (%)
Dahe River	61	61	0	21.04	11.82	–43.80
Jiadao-Panjia River	18	20	11.11	5.76	3.29	–42.97
Babao River	42	35	–16.67	12.58	5.69	–54.77
Kekeli River	53	41	–22.64	19.46	10.01	–48.54
Upstream of Heihe River	79	56	–29.11	20.99	11.34	–45.95
Changqian River	41	22	–46.34	6.83	1.43	–79.14
Liyuan River	66	51	–22.73	17.56	8.88	–49.40
Bailang River	31	29	–6.45	16.24	12.28	–24.36
Maying River	73	50	–31.51	22.72	12.48	–45.07
Total	464	365	–21.34	143.18	77.22	–46.07

glaciers developed newly. In addition, 4 large glaciers split into 9 glaciers. Glaciers number in Jiadao-Panjia River increased from 18 to 20, 2 glaciers disappeared in this tributary. Three large glaciers split into 7 small glaciers, and no new glaciers developed. The rate of glaciers number recession in Changqian River was the largest, accounting for 46.34%, while Bailang River was smaller, 6.45%, and rate of glaciers number recession was equal in other branches. The largest area shrinking rate was also found in Changqian River, 79.14%; other tributary glaciers area recession were equal, being about 40%–50%. The statistical results in Beida River showed that (Table 4): compared with Fengle River and Hongshuiba River, rate of glaciers number and area recession in Zhulongguan River and Right bank of Beida River were higher. Glaciers number of Gaoya Well increased by two, but the rate of area shrinkage was 24.78%, similar to Dahe River.

Table 4 Glaciers change of Beida River

Branch	Number of glaciers			Area of glaciers (km^2)		
	1960s	2007/2011	Change rate (%)	1960s	2007/2011	Change rate (%)
Fengle River	60	53	–11.67	24.94	18.06	–27.58
Hongshuiba River	150	131	–12.67	79.98	56.61	–29.23
Zhulongguan River	149	110	–26.17	62.86	41.83	–33.46
Right bank of Beida River	23	18	–21.74	4.05	2.34	–42.12
Gaoya Well	121	123	1.65	46.67	35.11	–24.78
Total	503	435	–13.52	218.51	153.95	–29.55

4.2 Discussion

4.2.1 Comparative recession analysis of typical mountain glaciers

Under the background of global warming, global mountain glaciers showed widespread shrinking trend (Haeberli, 2000; Shi *et al.*, 2002). While the high resolution satellite image data have been widely used in glacier dynamic monitoring in recent years, studies of glaciers change in large area are possible to achieve. In order to further analyze characteristics of glaciers change in the Heihe River Basin, we choose typical mountains and basins glaciers in western China to compare with this study (Table 5). Considering the research period, combined with researches that scholars have made including Lenglong Range of Qilian Mountains (Zhang *et al.*, 2010), Shulenan Range of Qilian Mountains (Zhang *et al.*, 2011a), Yeniugou Watershed in Qilian Mountains (Yang *et al.*, 2007), the statistical analysis of glaciers change research in west regions of China was made. It is found that compared with other glaciers in western mountains, the rate of glaciers retreat was significantly higher in this study. Zhang *et al.* (2010) found that glaciers decreased by 0.67%/a in Lenglong Range during 1972–2007; Yang (2007) discovered that glaciers in Yeniugou Watershed showed a recession rate of 0.54%/a from 1956 to 2003. Our research revealed that 967 glaciers in the Heihe River Basin decreased by 0.60%/a from the 1960s to 2007/2011. Compared with the glaciers recession rate of other mountains of western China, such as Tianshan Mountains (Wang *et al.*, 2011b) (0.22%/a), A'nyêmaqên Mountains (Liu *et al.*, 2002a) (0.49%/a), Geladaindong Mountains (Lu *et al.*, 2002) (0.05%/a), Naimona Nyi Mountains (Ye *et al.*, 2007) (0.26%/a), the Heihe River Basin showed a higher retreat trend.

Table 5 Shrinkage of the typical mountain glaciers in China

Study areas	Area change (km^2)	Change rate %	Recession rate (%/a)	Data source	Method	Period	Author
Lenglong Range of Qilian Mountains	–24.29	–23.57	–0.67	Topographic map, ETM	Visual interpretation	1972–2007	Zhang *et al*., 2010
Shulennan Range of Qilian Mountains	–55.00	–12.80	–0.36	Topographic map, ETM	Visual interpretation	1970–2006	Zhang *et al*., 2011a
Yeniugou River Basin of Qilian Mountains	–16.22	–25.71	–0.54	Topographic map, ASTER	Visual interpretation	1956–2003	Yang *et al*., 2007
Western Qilian Mountains	–124.2	–10.3	–0.29	Aerial photo, ETM	Visual interpretation	1956–1990	Liu *et al*., 2002b
Heihe River Basin	–32.41	–29.6	–	Topographic map, ASTER	Visual interpretation	1950s/1970s–2003	Wang *et al*., 2011a
Chinese Tian-shan Mountains	–	–11.5	–0.22	–	–	1960–2010	Wang *et al*., 2011b
Urumqi River Basin	–6.65	–13.8	–0.45	Aerial photo, Topographic map,	Aerophoto gramety	1962–1992	Chen *et al*., 1996
Kaidu River Basin	–38.5	–11.6	–0.31	Topographic map, TM, ETM+	Visual interpretation	1963–2000	Liu *et al*., 2006
Gez River Basin	–188.1	–10	–0.26	Topographic map, TM, ETM+	Visual interpretation	1960–1999	Liu *et al*., 2006
A'nyêmaqên Mountains	–21.7	–17.0	–0.49	TM	Visual interpretation	1966–2000	Liu *et al*., 2002
Geladaindong Mountains	–14.91	–1.7	–0.05	Aerial photo, TM	Visual interpretation	1969–2000	Lu *et al*., 2002
Naimona Nyi Mountains	–7.12	–8.44	–0.26	MSS,TM, ASTER	Unsupervised Classification, NDSI, Manual correction	1976–2003	Ye *et al*., 2007
Pumqu River Basin	–131.24	–8.98	–0.30	Topographic map, ASTER	Visual interpretation	1970s–2000	Jin *et al*., 2004
Mt. Qomo-langma	–501.91	–15.63	–0.52	MSS, TM	Object-oriented method	1976–2006	Nie *et al*., 2010
Heihe River Basin	–130.51	–36.08	–0.60	TM, ETM	Object-oriented method	1960s–2007/2011	This study

To investigate reasons why glaciers area reduced so fast in the Heihe River Basin, the affect of regional climate change (temperature and precipitation) was the important reason, single glacier area size was also the main affecting factor (Jóhannesson *et al*., 1989). The area of 895 glaciers in this region was less than 1 km^2, its number accounted for 92.55% in the whole area. Moreover, the smaller the glaciers were, the more sensitive of glaciers to climate change, area reducing and terminal shrinking were faster (Jóhannesson *et al*., 1989).

4.2.2 Effects of climate change on glaciers change

Water (precipitation), heat (temperature) and their combination are the main climate factors affecting glaciers development. Precipitation and temperature and their inter-annual change jointly determine glaciers nature, development and evolution (Xie *et al*., 2010), temperature decide the melting, and precipitation affect the accumulation (Li *et al*., 2003). In order to analyze the influence of temperature and precipitation on glaciers change in this region, six meteorological stations were chosen according to location of the study region, i.e. Tuole, Yeniugou, Qilian, Zhangye, Gaotai and Jiuquan. In Figure 8, the average temperature of the six stations showed increasing trends. The rate of temperature increasing in Tuole, Yeniugou, Zhangye and Qilian was larger than 0.30℃/10a (statistically significance at the 0.001 level), and the increasing rate of Jiuquan and Gaotai was larger than 0.20℃/10a (significance at the 0.001 level). The trend magnitudes were all higher than the rate of global average temperature increasing rate (0.148℃/10a) (IPCC, 2007). And the increasing warming trend of each meteorological station after 1990 was generally obvious. Similar to temperature change, the trend of annual precipitation of each meteorological station also rose slightly. The increasing rate of Tuole and Yeniugou was higher than 13.0 mm/10a, and the average increasing rate of Jiuquan, Zhangye, Gaotai and Qilian was higher than 2.0 mm/10a. According to Kang(1996) about relationship between glacial equilibrium line (ELA) and summer temperature from 12 glaciers in the High Asia, glacier equilibrium lines increased by a height of 100–160 m if

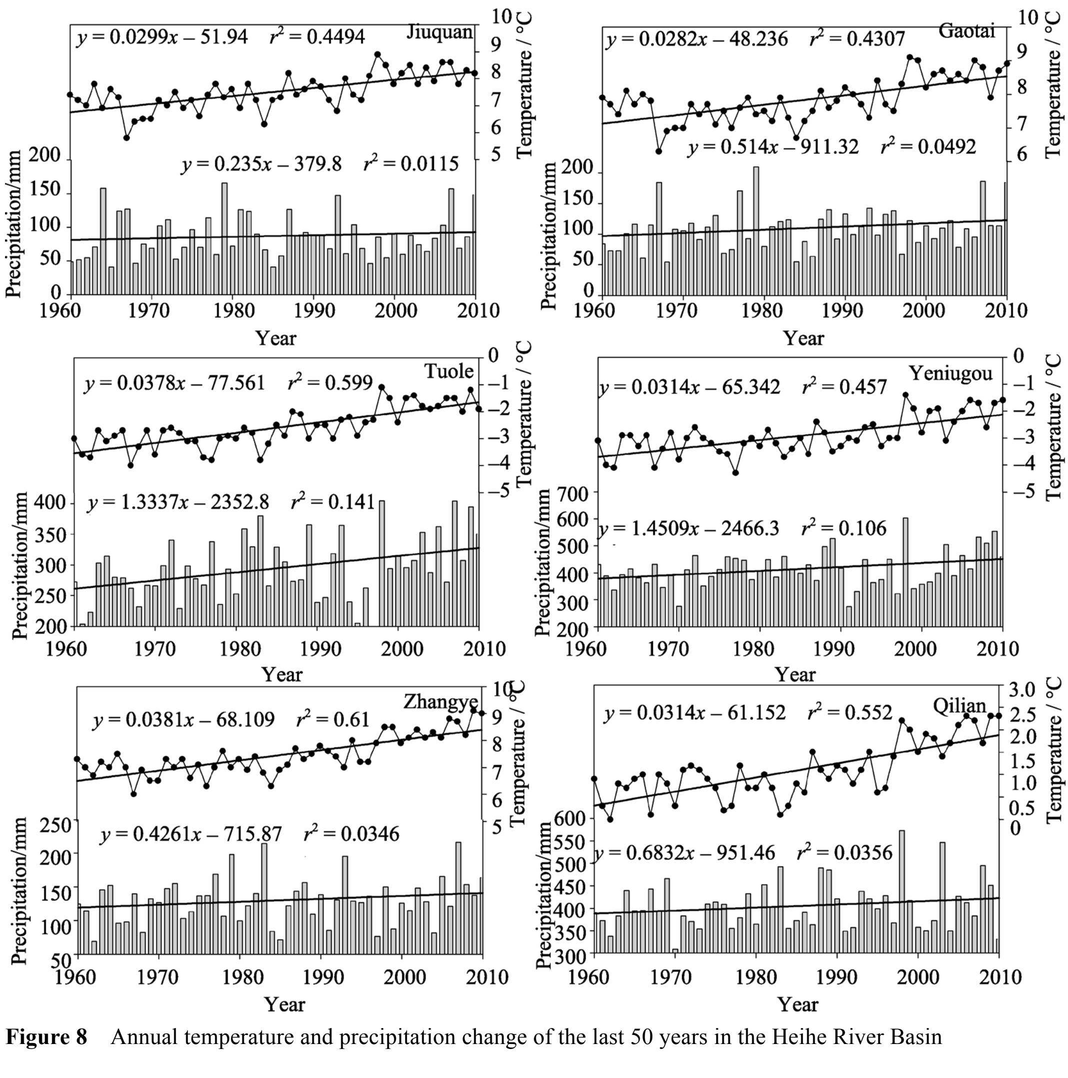


Figure 8 Annual temperature and precipitation change of the last 50 years in the Heihe River Basin

summer temperature rose by 1℃. If keep the glacial equilibrium line unchanged, solid precipitation needed to add more than 40%, or even an increase of approximately 1 times (Kang *et al.,* 1996). Obviously, under this climate change background, although precipitation increased, the sensitivity of glaciers on temperature became stronger. With temperature rising, the supply from increased precipitation can not compensate for the loss of glaciers mass ablation, and then the glaciers in the Heihe River Basin were still shrinking.

5 Conclusions

This paper studied the glaciers change information using object-oriented information extraction technology in the Heihe River Basin (including Heihe River and Beida River) since the 1960s to 2007/2011. Some conclusions can be drawn as follows:

(1) The number of 967 glaciers decreased to 800 in the Heihe River Basin from the 1960s to 2007/2011; glaciers area reduced from 361.69 km^2 to 231.17 km^2, a total of 130.51 km^2 was lost, the ratio of area shrinking was 36.08%, and the average of each glacier decreased by 0.14 km^2.

(2) The regional differences of glacier distribution and changes in the Heihe River Basin were obvious: the rate of glacier retreat in the Heihe River is 16% larger than Beida River; glacier terminal mainly distributed in 4300–4400 m, 4400–4500 m and 4500–4600 m; the number of glacier decreased significantly at 4100–4200 m and 4200–4300 m, but 4500–4800 m showed an increasing trend.

(3) A total of 895 glaciers were less than 1 km^2 in the Heihe River Basin, accounting for 92.55% of the whole area, due to small glaciers were more sensitive to climate change, compared with other glaciers in mountains of western China, recession rate of glaciers was higher in the Heihe River Basin.

(4) Data from six meteorological stations showed that, with temperature rising, supply from increased precipitation can not compensate for the loss of glacier mass ablation, which is the key factor affecting glacier retreat in the Heihe River Basin.

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