

The Hydrology and Water Resources of the Proglacial Zone of a Monsoonal Temperate Glacier

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Keywords: Monsoonal temperate glacier; Hydrology; Water resource; Proglacial zone

Abstract. The ongoing retreat of temperate glaciers is expected to have substantial impacts on the water resources in mountainous environments. Located on the eastern slope of Mount Gongga, China, Hailuoguo Catchment is an ideal location to investigate the complex hydrological systems of the proglacial zone. Physical variables (e.g., water temperature) were measured from the main stem of Hailuoguo River and its selected tributaries in July 2011. During the recent twenty years, there appears to be a slightly increasing trend of air temperature, whereas precipitation exhibits a slightly decreasing trend. Air temperature shows a decreasing trend with altitude, whereas precipitation has a reverse one. The results of this work indicate that: (i) air temperature is the main factor and precipitation is only the secondary factor regulating the glacial river runoff; (ii) the annual runoff was seasonally well distributed, with a strong summer maximum and a winter minimum; (iii) the increasing trend of water temperature in the main stem with flow distance is mainly caused by mixture from tributary water inputs with relatively higher temperature..

Introduction

For many mountain regions, glacier is a key component of the complicated hydrological regime. The temporal and spatial variations of runoff are closely linked to the cryospheric processes [1]. As the largest reservoir of freshwater on Earth, glaciers support about one third of the global population [2]. Being an important source of water, which usually stored as glacier and snow, mountains are referred to as the “water towers” for the mountainous zones and the lowland regions [3]. Glacier and snow are crucial components of the hydrological processes in mountain regions. There is approximate 40% of world’s population living in the river basins, which originate in the mountainous regions [4]. Meltwater will contribute increasingly to river flows in the short term, caused by the shrinkage of glacier masses. But as glaciers diminish, the variability of river flows will increase and the river runoff decline in the long run [5]. The understanding of the mountain hydrology in the proglacial zones remains largely limited due to scanty observed data and complex modeling conditions [6, 7].

Monsoonal temperate glaciers, which account for more than 22% of China’s total glacier area and are featured by relatively high accumulation and ablation, are more active than continental glaciers. Mainly distributed in the southeastern part of the Tibetan Plateau in China, monsoonal temperate glaciers have led to significant local hydrological variability with climatic change [8]. Mount Gongga is the highest mountain on the eastern margin of the Tibetan Plateau. There are 74 glaciers with a total area of 257.7 km² on the east and west slopes of Mount Gongga, and major of these monsoonal temperate glaciers have retreated continuously throughout the 20th century [9]. Many of scientific investigations have been conducted in the mountainous areas owing to the distinct features [e.g. 10-12]. Affected by the variations in glaciation and snow cover, the complicated hydrological systems, however, are not well known in the proglacial zones in Mount Gongga.

As a highly glacierized area in the eastern slope of Mount Gongga, Hailuoguo (HLG) catchment is an ideal location to study the distinctive hydrologic regimes of the proglacial region. To develop a baseline assessment for the hydrological characteristics in the study area, the hydrologic and meteorological data and physical variable (water temperature) have been generated in July 2011.

Combined with available meteorological and hydrological data in this alpine region, we report here our attempts to explain the complex hydrology and water resources in the proglacial zone.

Study Area

The peak of the Mount Gongga, the highest one of Hengduan Mountains situated on the southeastern edge of the Tibetan Plateau, is up to 7556 m a.s.l. There are 74 glaciers developed around the summit of the Mount Gongga, which is one of the major glacierized regions controlled by monsoonal climate in the southwest of China. Situated on the eastern slope of Mount Gongga, the HLG catchment dominates an area of 94.75 km². As a highly glacierized region, 36.6% of its total area (34.67 km²) is glacierized [13]. The HLG catchment ranges from 2756 to 7556 m a.s.l. and belongs to the wet monsoonal climate. With a total area of about 25.7 km² and a length of 13.1 km, HLG glacier is the largest one among the seven glaciers in HLG Catchment. HLG River, a typical glacial river, has a length of 30.21 km and a mean slope of 69.3 ‰, and the HLG glacier is covered in its upper reach. Most of the tributaries of HLG River are non-glacial streams with no glacier in their upper reaches. The forest distributed widely and the bushes and meadow spread in the mountainous region.

HLG catchment is featured by large discharge, complex water resource supply in stream flow, abundant precipitation and small evaporation. A hydrological station (2920 m a.s.l., located about 1 km from the HLG glacier terminus) and two meteorological stations (HLG Station, 3000m a.s.l. and Moxi (MX) Station, 1640m a.s.l.) were established and maintained by the Gongga Mountain Alpine Ecosystem Station of the Chinese Academy of Sciences in the study area (Fig 1).

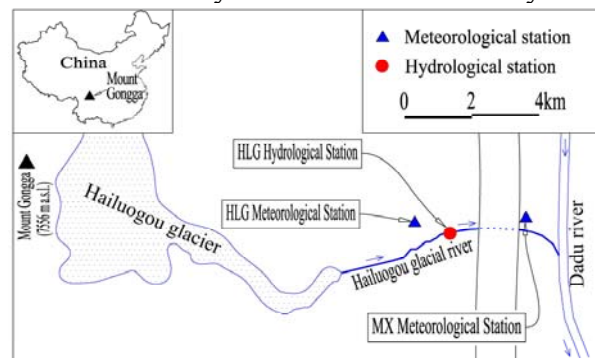


Fig 1. Map of the study area, with the hydrological and meteorological stations

Data and Methods

Physical variables (e.g., water temperature) were measured from over two dozen locations along the HLG River and its tributaries. The site investigation was carried out in July 2011. The available hydrological and meteorological data were provided by the Gongga Mountain Alpine Ecosystem Station, Chengdu Institute of Mountain Hazard and Environment, the Chinese Academy of Sciences. The hydrological and meteorological gauge measurements are bound to some range of errors. Before analyzing the variation trends of hydrology, it is necessary to use the continuous and accurate data for hydrological variables.

Carefully measured data on water temperature in July 2011 and the available hydro-climatic data in the study region are analyzed to evaluate the extent and magnitude of the hydrological variations. Using least square linear regression method, hydrological trends are analyzed in the proglacial zone.

Results and Discussion

Climatic characteristics. Mount Gongga is situated geomorphologically and climatically in the transitional belt between the Sichuan Basin with warm-wet monsoon climate and the Tibetan Plateau with dry-cold climate. Located on the east slope of the Mount Gongga, the study area belongs to the wet monsoonal climate of the subtropical mountain which is affected by the southeast monsoon. Fig 2a shows temporal changes in annual mean temperature (AMT) at HLG Meteorological Station

during the investigated period. According to the temperature data at HLG Station, the mean annual air temperature is 4.32 °C. Within the observation period, the highest AMT is 5.36 °C observed in 1998, and the lowest AMT is 3.35 °C observed in 1989. There is a trend toward air temperature increase during 1988-2009 period. Fig 2b shows the monthly mean temperature (MMT) of the selected two meteorological stations, HLG Meteorological Station and MX Meteorological Station in 2009. The measured MMT are above 0 °C all year round in MX Station, and Most of the MMT are above 0 °C in HLG Meteorological Station except for -4.06°C in January and -2.97 °C in December. July is the warmest month and January is the coldest month in the study region. It is evident that the decrease of air temperature with altitude is well developed.

Owing to the influence of southeast monsoon, the precipitation is plentiful. Fig 2c shows inter-annual variation of annual precipitation at HLG Meteorological Station during the investigated period. There is a large magnitude of variations in annual precipitation, ranging from 1250.9 mm in 2009 to 2175.4 mm in 1997. A year can be divided into wet season (May-October) and dry season (November-April) for precipitation. The distribution of precipitation is relatively concentrated, the wet season receives about 80% of the annual precipitation, while the dry season receives only about 20%. A slightly declining trend of the annual precipitation can be detected during the study 1988-2009 period. Fig 2d displays monthly precipitation at observed two meteorological stations in 2009. The monthly values of precipitation at the higher region are generally larger than those observed at the lower region. This indicate that precipitation increases generally with the elevation rise. On the whole, the temperature exhibits a decreasing trend with altitude, whereas precipitation has the reverse trend in the proglacial region.

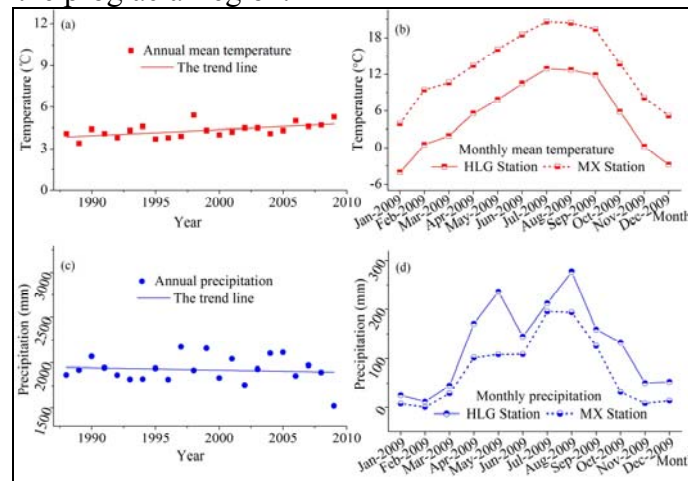


Fig 2. Inter-annual and intra-annual variations of air temperature and precipitation

Characteristics of river runoff. The proglacial zone is featured by large discharge, abundant precipitation and small evaporation. The glacial-river runoff changes synchronously with the dominative heat conditions (air temperature) and another factor (precipitation) in the monsoonal-temperate-glacierized area. The precipitation are mainly observed at night (about 70% of the annual amount) in HLG Catchment, while both the air temperature and runoff are generally higher in the daytime than those observed at night. Analyzing the hydrological and meteorological data in the proglacial zone show that the river runoff at the HLG Hydrological Station is a function of air temperature and precipitation. The relationship were calculated using the observed hydro-climatic data, as follows (Eq. 1):

$$Q=7.07+1.78T+0.005P \quad (1)$$

where Q, T and P denote the monthly discharge (m^3/s) observed at the HLG Hydrological Station, air temperature (°C) and precipitation (mm) at the HLG Meteorological Station. Air temperature is the main factor and precipitation is only the secondary factor regulating the river runoff.

The stream flow in HLG River is mainly a mixture of meltwater, precipitation and groundwater. It is dominated by meltwater in mountainous-proglacial-headwater region. HLG River discharges increasingly both annually and seasonally in recent years [14]. Fig 3 shows the monthly discharge of

HLG River observed at the hydrological station. The annual runoff was well distributed, with a strong summer maximum and a winter minimum. Of the annual runoff, on average, about 14.51% occurred in spring (March-May), 51.66% in summer (June-August), 25.40% in autumn (September-November) and 8.43% in winter (December-February). Approximately, 80.2% of the annual runoff occurred in the wet season months (May-October), whereas the dry season months (the remaining 6 months) received only 19.8% of the annual runoff. Peak monthly discharge occurred in August with an average value of 27.2 m³/s, and February was the driest month with a mean discharge of 3.7 m³/s.

The discharge of HLG River observed at the hydrological station changes relatively slightly. The runoff stability can be expressed by the conservation index β as follows (Eq. 2):

$$\beta = Q_{LM}/Q_{AM} \quad (2)$$

where β is the conservation index, and Q_{LM} and Q_{AM} are the lowest monthly mean discharge and the annual mean discharge, respectively. According to the hydrological data at HLG Hydrological Station, the calculated value of the conservation index β is about 0.313 that is equal to the best grade.

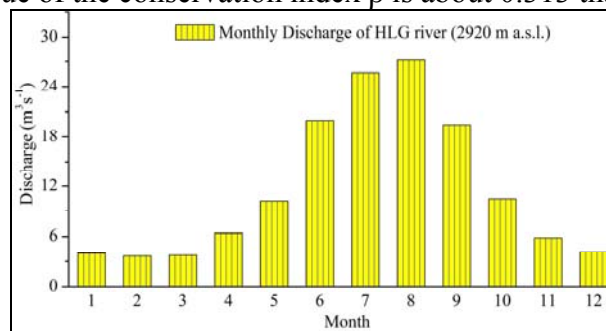


Fig 3. Seasonal variation of river runoff (m³/s) at the hydrological station (2960 m a.s.l.).

Fig 4a shows the 21 water-temperature-measured sites, and Fig 4b shows downstream changes in water temperature collected along the main stem the HLG River and its tributaries in July 2011. Water temperature generally increases from the upper basin downward from the main stem of HLG River. Lowest water temperature was observed at Section 7 (0.5 °C) at the most upstream sampling section, and highest water temperature was observed Section 25 (10.3 °C) at the most downstream section. Water temperature observed from the tributaries is generally larger than that observed from the main stem. This can be interpreted that the increasing trend of water temperature in the main stem is in large part caused by mixture from tributary water inputs featured by relatively higher water temperature.

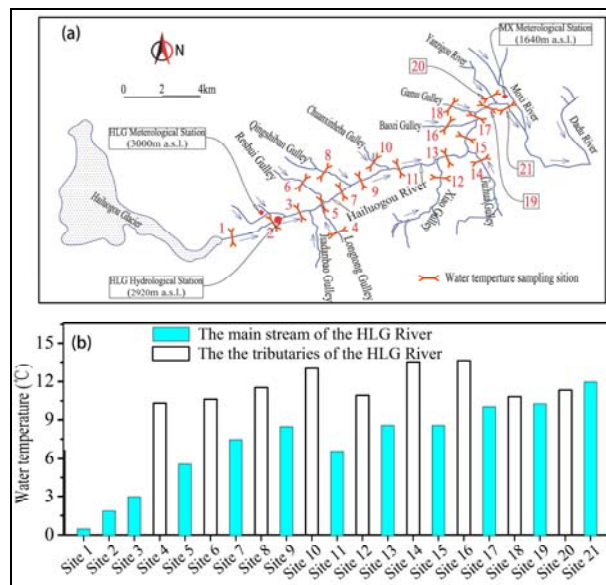


Fig 4. Water temperature measured sites (a) and downstream changes in water temperature (b)

Conclusions

HLG Catchment is situated on the southeastern edge of the Tibetan Plateau, and is a highly glacierized area. The study region, affected by the southeast and southwest monsoons in summer and the westerly circulation in winter, belongs to the wet monsoon climate. HLG River is a typical glacial river and most of its tributaries are non-glacial streams with no glacier in their upper reaches. The water temperature was measured from over two dozen locations along the main stem of HLG River and its tributaries in July 2011. On the basis of the hydro-meteorological data, the complex hydrological features in the proglacial zone were investigated. Air temperature exhibits a decreasing trend with altitude, whereas precipitation has the reverse trend in the proglacial region. During the recent twenty years, annual air temperature shows a slightly increasing trend, whereas a slightly decreasing trend of precipitation was observed.

The stream flow in HLG River is mainly a mixture of meltwater, precipitation and groundwater, and is dominated by meltwater. The air temperature is the main factor and precipitation is only the secondary factor regulating the river runoff in the study area. The annual runoff was well distributed, with a strong summer maximum and a winter minimum in the study proglacial zone. The increasing trend of water temperature in the main stem with flow distance is mainly caused by mixture from tributary water inputs featured by the relatively higher water temperature. We expected that the results will provide an insight for future water resource and watershed management in the proglacial zone.

Acknowledgements

This work was financially supported by Youth Foundation of Sichuan University (Grant No. 2015SCU11048) and the Key Projects of Natural Science Foundation of China (Grant No. 40730634). The authors are grateful to the Gongga Mountain Alpine Ecosystem Station, Chengdu Institute of Mountain Hazard and Environment, the Chinese Academy of Sciences, Sichuan, China, for supplying necessary meteorological data.

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