Understanding cryospheric hydrology and the effects of cryospheric changes on river runoff is critical for sustainable water management especially in arid inland river basins such as those in northwest China where water resources mainly come from alpine areas. A cryospheric hydrometeorology observation system (CHOICE) has been established since 2008 in the Hulu catchment, which is a well-instrumented experimental and representative catchment in the upper reaches of the inland Hei River, Qilian Mountains, northwest China. The CHOICE includes dense meteorological measurements from 2980 to 4800 m asl (e.g. glacier, snow, and permafrost hydrology) and water and heat balance in the vertical landscape zones including alpine grassland, meadow, shrub, coniferous forest, marshy meadow, and moraine-talus zones. The comprehensive long-term observations available for the CHOICE provide the basis for model development and application in cryospheric hydrological research. We focus on cryospheric hydrometeorological process of precipitation, freeze–thaw cycle, energy balance, soil–vegetation–atmosphere transfer (SVAT), runoff, groundwater reservoir, and hydrological resiliency within vertical elevation in CHOICE. Data from CHOICE, an open cryospheric hydrology observation and research system, is accessed through a website (http://hhsy.casnw.net/) and the WestDC database (http://westdc.westgis.ac.cn/).

Abbreviations: AWS, automatic weather station; CBHM, Cryosphere Basin Hydrological Model; CHOICE, cryospheric hydrometeorology observation system; DFR, double reference intercomparison reference; DWHC, distributed water–heat coupled; EC, eddy covariance; ELE, equilibrium line elevation; EMP, elevation of maximum precipitation; HiMACs, high-mountain and cold regions; LST, land surface temperature; OTC, open-top chamber; RCP, representative concentration pathway; SMF, standard meteorological field; SVAT, soil–vegetation–atmosphere transfer; UHR, Upper Hei River basin; WMO, World Meteorological Organization.

The Earth’s cryosphere is facing rapid changes in the duration, extent, and mass of snow and ice, which have had multiple impacts on the environment across a range of temporal and spatial scales (Qiu et al., 2017). Changes in mountain snow, glaciers, and permafrost have resulted in significant downstream impacts in terms of the quantity, seasonality, and quality of water (Beniston et al., 2018). The latest findings have suggested that rapid changes were amplified with elevation (Ohmura, 2012; Yang et al., 2014b; Pepin et al., 2015), and mountainous cryosphere shrinkage has been reported all over the world (e.g., Euskirchen et al., 2014; Guo and Wang, 2016; Huang et al., 2017; IPCC, 2013; Qin and Xiao, 2009). This shrinkage has modified the water cycle (Euskirchen et al., 2014; Fichot et al., 2013) and river discharge (Chen et al., 2018b; Connan et al., 2014; Peterson et al., 2002; Ye et al., 1999) in cold regions and caused the rise of global mean sea level (IPCC, 2013; Oerlemans et al., 2007). Particular attention has been paid to understanding the effects of these cryospheric changes in recent decades (Qin et al., 2014). Changes in the extent, duration, and mass of frozen water in the cryosphere have had multiple and complex impacts on natural hydrological processes, ecological patterns, and human activities by exerting impacts on ecosystems, the water supply, agricultural development, and disaster mitigation.
Serving as a solid reservoir for many endorheic and exorheic basins (Xiao et al., 2015), the mountain cryosphere is the regulator of major rivers and provides most of the water resources in arid regions in China and its neighboring countries. Moreover, the mountain cryosphere is very sensitive to climate change, and its changes can have significant impacts on the hydrological cycle and water resource management in arid endorheic basins. However, because of inadequate observation data and the lack of knowledge about many aspects of cryospheric hydrometeorology at regional scales in alpine regions, the significance of the impacts of cryospheric changes and the severity of their consequences remain unclear in China (Chen et al., 2015, 2018b; Li et al., 2018). In alpine regions, the key goal is to understand environmental changes (Guo, 2018) and their effects (Qin and Xiao, 2009) using observations, models, and other techniques.

As a result, a cryospheric hydrometeorology observation system has been established since 2008 in the Hulu Catchment (CHOICE) upstream of the Hei River Basin, Qilian Mountains, northwest China (Chen et al., 2014). The CHOICE is an integrated observation system used to observe alpine hydrometeorology in a small catchment with evident vertical landscape zones. Alpine meteorology, cryospheric hydrology, and water balance data on different land covers, groundwater, and streamflow are included. This paper provides an overview of the CHOICE.

Motivation and Science Questions

Over the past decades, observation systems on the watershed scale have become increasingly popular, and several watershed observation systems have been established in cold environments. The US National Science Foundation supports the Critical Zone Observatories. The European Network of Hydrological Observatories includes three hydrological observatories: the Terrestrial Environmental Observatories catchments in Germany (Zacharias et al., 2011; Bogaert et al., 2015), the HOBE Hydrological Observatory in Denmark (Jensen and Illangasekare, 2011), and the Hydrological Open Air Laboratory in Austria (Blöschl et al., 2016). There are other observation systems, such as the Nansen and Amundsen Basins Observations System II of the United States and Russia (Ivanov et al., 2016), the Cape Bounty Arctic Watershed Observatory (Lamoureux and Lafrenière, 2018), the Changing Cold Regions Network of Canada (Debeer et al., 2015), and the Hei Watershed Allied Telemetry Experimental Research in China (Li et al., 2013; Cheng and Li, 2015). Most of the above integrated watershed observation systems have focused on high-mountain and cold regions (HiMACs). Understanding such changes in these vulnerable regions has posed significant challenges because of their remoteness and sparse observations (Qiu et al., 2017). With global climate warming, the hydrological processes of HiMACs will continue to dramatically change. For example, the transition from snow to rain is moving to higher elevations as changes in precipitation are predicted to be complex and variable with location, requiring robust and accurate precipitation measurements (Trenberth, 2011). These changes can alter the timing of downslope water delivery (Godsey et al., 2018). Nevertheless, precipitation observations are still beset with significant biases and errors (Yang et al., 2005; Scaff et al., 2015). To determine how these changes impact the hydrological and ecological processes in this climatologically sensitive region, comprehensive cryospheric hydrometeorology observations from the vegetation-to-periglacial transition zone are required. Better characterizing these changes to understand the linkages between cold regions requires more accurate, coordinated, and integrated observations.

The Qilian Mountains are located on the northern margin of the Qinghai-Tibetan Plateau, northwestern China. This mountain system, which strikes in the NW–SE direction, is ~ 100 km wide, ~ 1000 km long, and 2800 to 5570 m asl (Song et al., 2013). The second glacier catalog of China shows that from 2005 to 2010 there were 2684 glaciers in the Qilian Mountains with an area of 1597.81 ± 70.30 km² and an ice reserve of ~ 84.4 km³. As a water tower and ecological barrier of the Hexi Corridor and the Silk Road Economic Belt, the Qilian Mountains are the source region of several large arid endorheic basins (Shiyang, Hei, and Shule rivers) in northwest China. The changes in hydrological processes in the Qilian Mountains are significant to the socioeconomic development and natural ecology of their middle and lower reaches.

The CHOICE is an integrated system that includes the scales of field, hillside, catchment, and mountainous basin. It also integrates the methods of observation and modeling to assess the changes and interactional relations of ecological and hydrological processes in the mountain cryosphere under climate change. The scientific objective of the CHOICE is to obtain comprehensive observation data about environmental factors to determine the hydrological processes in a mountainous region and to evaluate the effects of climate, cryosphere, and land cover changes on mountainous hydrology and water resources in the lower arid regions. Four key science questions have been identified:

1. The spatial and temporal distribution of alpine precipitation need to be determined. Because of the lack of precipitation gauge measurements and complex topography in the higher mountains, the precipitation grade along elevation and in the watershed is still unclear. In addition, the systematic errors of precipitation gauge measurements and variations in the elevation of maximum precipitation (EMP) need to be considered.
2. The effects of cryospheric changes on streamflow need to be determined.
3. The effects of changes in the vegetation pattern in the vertical landscape zones on water balance and river runoff in the mountains must be assessed.
4. A suitable distributed hydrological model including cryospheric hydrology is needed in mountainous areas. Based on long-term and integrated cryospheric hydrometeorology observations in such a complex mountainous catchment, we attempted to characterize the hydrological process of this mountain region by using the parameterized Cryosphere Basin Hydrological Model (CBHM) to evaluate the effects of cryospheric changes on streamflow.
Catchment Characteristics

Catchment Description and Location

Serving as a subwatershed of the Heihe watershed allied telemetry experimental research, the Hulu catchment (38°12’–38°17’ N, 99°50’–99°54’ E) is located in the upper reaches of Hei River (Fig. 1a) in the central part of the Qilian Mountains. It comprises an area of ~23.1 km², and it represents a pristine alpine catchment with rugged terrain and little human disturbance on the southeastern region of the Qilian Mountains.

Two minor tributaries are sourced from glacier and moraine–talus zones and then merge at the catchment outlet. The elevation fluctuates from 2960 to 4820 m asl, with a span of 1860 m, and it gradually increases from north to south. The slope ranges from 0 to 85°. Because the vertical landscape exhibits obvious spatial differentiation, the catchment was chosen to study the integrated research and observation experiments of hydrological processes in a mountain cryospheric region (Fig. 1b).

Landscapes

The Hulu catchment is characterized by the transition of vegetation from grassland at lower elevations to glaciers at higher elevations (Fig. 2a). The landscapes vary and exhibit a gradient distribution with increasing elevation including grassland, meadow, shrub, forest (Pinus crassifolia Kom. and Juniperus przewalskii Kom.), marshy meadow, and cushion plant, among others. Permafrost, frozen soils, moraine–talus, snow, and glaciers are also widespread (Li et al., 2013; Chen et al., 2014). The proportion of land cover is shown in Fig. 2b. The vegetation in the study area is characterized by Kobresia humilis (C. A. Mey. ex Trautv.) Serg., Carex moorcroftii Falconer ex Boott, Stipa purpurea Grisebach, Nachr. Königl. Ges. Wiss., and Potentilla fruticosa L. Vegetation becomes sparser with increasing elevation. The cushion plant is sporadically distributed in high-elevation mountain regions (3800–4800 m asl).

Soils

The soils in the Hulu catchment are relatively young and mostly poorly developed. The representative soil types are Entisols, Inceptisols, Mollisols, Gelisols, Histosols, and other types, according to the dominant US Soil Taxonomy (Soil Survey Staff, 2014, p. 37–40). Gelisols only appear above 3600 m asl, and Histosols are sporadically distributed in depressions. The dominant parental
Fig. 2. (a) Vertical landscape zones in the Hulu catchment; (b) different distribution and proportions of landscapes in the Hulu catchment—the region in the red rectangle is the region shown in (a); and (c) mean monthly precipitation (2009–2017, in blue) and mean monthly evapotranspiration (2012–2016, in yellow) for the Hulu catchment. The bold red line with gray shading represents the mean runoff and standard deviation (2009–2017). Data available from the Dryad Digital Repository (https://doi.org/10.5061/dryad.sh6n0tc).
The Hulu catchment has an annual average air temperature of 
−0.3°C, and the annual average precipitation is 599.8 mm (Fig. 2c).

**Geology**

Previous studies have shown that the groundwater storage in a fractured basement influences significantly the mountainous river discharge cycle (Andermann et al., 2012). The geology of the Hulu catchment is dominated by bedrock in the high mountains that comprises lower Ordovician metamorphic and volcanic rock including interbedded metasandstone and slate (Ma et al., 2017). Above the low-permeability bedrock, moraine deposits and till of varying depths range from 5 m on the hillslopes to 30 m in the valley bottom, and moraine–talus covers up to 50% of the catchment. These drift deposits, which include moraine–talus and alluvial–alluvial deposits, have a relatively low hydraulic conductivity ($10^{-6}$–$10^{-4}$ m s$^{-1}$) and form the main source of groundwater storage. The role of these drift deposits in basement maintenance and hydrological regulation is strongly dependent on the volume and thickness of the sediment, the degree of stratification, and the amount of the bedrock fissure.

**Climate**

The Hulu catchment belongs to a continental climate. This climate is mainly driven by contrasting wind systems: high-elevation westerlies; the East Asian Summer Monsoon; and the cold, dry Winter Monsoon. The fluctuations in the intensity of these three circulations bring about a complex precipitation distribution on monthly, seasonal, and yearly scales. Eighty-nine percent of the precipitation falls during the wet season from May to September (Wang et al., 2004; Bourque and Mir, 2012). During the summer half-year, the westerly winds predominate in the study area and provide the most precipitation in the form of water vapor. During the winter half-year, the Siberian–Mongolian high-pressure cell drives the cold, dry Winter Monsoon north, resulting in rare snow and heavy dust storms (Nottebaum et al., 2014).

The Hulu catchment has an annual average air temperature of −0.3°C, and the annual average precipitation is 599.8 mm (Fig. 2c). The precipitation is mainly concentrated in the wet season, which accounts for 80 to 93% of annual precipitation (Han et al., 2013). The prevailing wind direction is from the south. When water vapor sources are blocked by the mountains, the water vapor cools and condenses to form precipitation. This phenomenon is the reason why more precipitation occurs in the high-elevation region (Wang et al., 2017).

The representative characteristics of the Hulu catchment are complicated by various landscapes, obvious differentiations in the vertical gradient, and the intensive spatial variability of soil properties. Meanwhile, the study area is located in the rain–snow transition zone, which is a typical area for research in a complex landscape and geological environment. In conclusion, all of the above description explain why we chose the Hulu catchment as the research area in this study.

**Basic Long-Term Observations**

**Overview of the CHOICE Network**

The CHOICE was established in 2008 in the Hulu catchment (Chen et al., 2014). It is a comprehensive network that focuses on limited hydrometeorological data from the mountain cryosphere at the catchment scale including alpine meteorology; glacier, snow, and permafrost hydrology; water and energy balance in forests, grasslands, meadows, and moraine–talus areas; groundwater; and watershed runoff. All observation experiments are listed in Fig. 1b. The CHOICE is a focus experimental area of the ecohydrological processes of the Hei River Basin (Li et al., 2017). The CHOICE is also a CryoNet site of the Global Cryosphere Watch and is part of the World Meteorological Organization (WMO) and the Land Surface Process Observation Network of the Chinese Academy of Sciences.

The CHOICE mainly includes six in situ fields in elevation gradients spanning different landscape zones (Hulu-1 to Hulu-6 in Table 1). Each field includes different types of observation experiments, and details are shown in Table 1. These observations include meteorology, cryosphere, SVAT observation system, and runoff observations (Table 2).

**Meteorology**

Meteorological observations represent direct evidence of climate changes in the mountain cryosphere and serve as input elements of the hydrological system. Therefore, since the first...
meteorological sensors were installed in the Hulu catchment, the CHOICE network has continuously improved (Table 3). In the first phase in September 2008, four automatic weather station (AWS) networks were arranged at different elevations (2980, 3380, 3711, and 4164 m asl) and landscapes (grassland, meadow, marshy meadow, and moraine–talus), respectively. The CHOICE network was complemented by two other AWS at different elevations (3232 and 4484 m asl) and landscapes (shrub and moraine) in 2013 and 2014, respectively (Fig. 3). Each AWS features the long-term monitoring of the following meteorological variables: air temperature, relative humidity, wind speed and direction, four-component radiation, soil heat flux, land surface temperature (LST), soil temperature, soil moisture, snow depth, and precipitation amount. We also conducted long-term standard meteorological field (SMF) manual observations for reference to those obtained at AWS (Fig. 4a). The meteorological quantities measured are presented in Table 3, which lists the sensors with which the AWS is equipped and their respective height to the surface and stated accuracy. All the sensors, calibrated once every half-year, record the half-hourly means of the measurements, and raw data are recorded every 30 min.

Cryosphere

The mountain cryosphere is comprised of glaciers, snow, frozen soil, and lake or river ice. Mountain glaciers are a key indicator of rapid and global climate change (Beniston et al., 2018). Snow cover is the most important interface between the atmosphere and the ground, and it strongly influences the surface energy balance of the cryosphere (Zhang, 2005). Permafrost is not just a water-resisting layer but an active layer; thus, changes in hydrothermal processes, actual porosity, and saturated hydraulic conductivity will change the migration pathways of frozen soil water processes and annual and interannual runoff processes, which are the core links of hydrological processes in the mountain cryosphere. To study the mountain cryosphere, in addition to obtaining routine meteorological observations, we also obtained some observations of cryospheric elements, that is, glaciers, snow, and permafrost, which are presented in Table 2.

### Soil–Vegetation–Atmosphere Transfer Observation System

The SVAT observation system is a feasible method for researching the soil surface heat and water balance and requires the specification of a large number of parameters controlling the vertical fluxes over a single homogeneous area (Franks et al., 1997). In addition to basic meteorological observations, datasets about vegetation and soil were collected in the different land cover types in the Hulu catchment at the same time as the AWS installation. These details are shown in the soil

<table>
<thead>
<tr>
<th>Monitoring items</th>
<th>Main monitoring content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meteorology</td>
<td>Precipitation type and amount, air temperature, relative humidity, wind speed and direction, barometric pressure, sunshine hours, four radiation components, evaporation</td>
</tr>
<tr>
<td>Cryosphere</td>
<td>Automatic weather station, eddy covariance system, surveillance cameras, glacier stakes, snow depth, snow and ice sublimation, river ice, snow pillow, freezing soil depth</td>
</tr>
<tr>
<td>SPAC</td>
<td>Surface temperature, soil temperature, soil moisture, soil heat flux, microlysimeter, open top chambers, soil respiration, soil infiltration, sap flow, throughfall, stem flow, microbiological sampling</td>
</tr>
<tr>
<td>Runoff</td>
<td>Runoff fields, small subcatchment runoff, discharge (stream-gauging stations), groundwater level, isotope sampling</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variable</th>
<th>Type of sensor</th>
<th>Manufacturer</th>
<th>Stated accuracy</th>
<th>Height m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature</td>
<td>41382VC; HMP 155A</td>
<td>R.M. Young; Vaisala</td>
<td>±0.05 and ±0.2°C</td>
<td>1.5, 2.5</td>
</tr>
<tr>
<td>Wind speed and direction</td>
<td>WindSonic; Young 05103</td>
<td>Gill; R.M. Young</td>
<td>±0.01 and ±0.3 m s⁻¹</td>
<td>1.5, 2.5</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>41382VC; HMP 155A</td>
<td>R.M. Young; Vaisala</td>
<td>±1 and ±2%</td>
<td>1.5, 2.5</td>
</tr>
<tr>
<td>Land surface temperature</td>
<td>SI-111</td>
<td>Apogee</td>
<td>±0.2°C</td>
<td>1.5, 2.5</td>
</tr>
<tr>
<td>Precipitation</td>
<td>TRwS204; T-200B</td>
<td>MPS; Geonor</td>
<td>±0.1 and ±0.1 mm</td>
<td>1.5</td>
</tr>
<tr>
<td>Snow depth</td>
<td>SR50A</td>
<td>Campbell Scientific</td>
<td>10 mm</td>
<td>1.5</td>
</tr>
<tr>
<td>Sunshine duration</td>
<td>CSD3</td>
<td>Kipp &amp; Zonen</td>
<td>±10%</td>
<td>1.5</td>
</tr>
<tr>
<td>Soil heat flux</td>
<td>HFP01SC</td>
<td>Hukseflux</td>
<td>±3%</td>
<td>1.5</td>
</tr>
<tr>
<td>Soil moisture</td>
<td>EnviroSMART</td>
<td>Sentek</td>
<td>±0.1%</td>
<td>1.5</td>
</tr>
<tr>
<td>Soil temperature</td>
<td>1095S-L</td>
<td>Campbell Scientific</td>
<td>±0.2°C</td>
<td>2.0</td>
</tr>
<tr>
<td>Four-component radiation</td>
<td>CNR1</td>
<td>Kipp &amp; Zonen</td>
<td>±1%</td>
<td>1.5</td>
</tr>
<tr>
<td>Datalogger</td>
<td>CR1000</td>
<td>Campbell Scientific</td>
<td>±0.2%</td>
<td>1.0</td>
</tr>
</tbody>
</table>
pit section. The plant survey included the plant types, coverage, height, leaf area index, and root depth data in the steppe, shrub meadow, moist meadow, and swamp meadow research sites. The multilayered soil data, including saturated hydraulic conductivity, field capacity, saturated moisture content, porosity, dry density, heat capacity, and thermal conductivity, were collected by field sampling and laboratory analysis in the different land cover sites.

Runoff

Daily river and stream discharge measurements within the catchment are used to evaluate the effects of landscape and soil moisture assimilation on hydrologic responses. The Hulu catchment is potentially vulnerable to glacier meltwater and snowmelt runoff events. Freeze–thaw processes and high-intensity rain events are quickly transferred to runoff through the catchment. The Hulu stream is fed by the eastern and western tributaries in
front of the narrow valley (Fig. 2a). Both tributaries and their branches originating from the alpine region are all ephemeral and mainly fed by glacier and snow meltwater, frozen soil water, and groundwater. From the headwaters to the plain, these tributaries receive runoff from the subcatchments that is derived from precipitation. The tributaries are intermittently dry throughout the cold season (from October to May of the following year; Fig. 2c).

Only the main stream in the narrow valley is perennial, although it is ice-covered during winter.

The total discharge has been monitored by a continuously stream-gauging station at the catchment outlet since 2009 (Fig. 4b). Discharge is measured at the outlet using two rectangle weirs that are bound together. Water levels and temperature are monitored by a two-pressure-transducer water level logger (HOBO...
U20-001-01, Onset). Then, discharge is calculated on the basis of the existing head–discharge relationship. From 2009 to 2012, we also manually used the float protocol and a stopwatch to estimate the nonfreezing period discharge in a meadow subcatchment and a moraine–talus subcatchment.

**Dedicated Long-Term Observations Soil Pit**

To apply hydrological models in the alpine catchment, we have obtained long-term continuous soil parameter data in the soil pit synchronously with those collected at AWS. Two soil heat flux plates (HFP01SC) (Hukseflux Thermal Sensors) were used to measure soil heat flux at depths of 7, 12, and 17 cm. A set of moisture probes (Sentek Sensor Technologies, Inc.) was placed in soil to measure soil moisture at depths of 10, 20, 30, 40, 50, 60, 80, and 100 cm. A set of 109SS-L probes (Campbell Scientific, Inc.) was installed in soil to measure soil temperature at depths of 20, 40, 60, 80, 100, 120, 160, and 200 cm. An SI-111 infrared radiometer (Apogee Instr. Inc.) was used to measure the LST.

**Evapotranspiration**

There are three ways to observe evapotranspiration in the CHOICE: automatic and manual weighing minilysimeters and eddy covariance (EC) systems. During the early stage of the CHOICE, evapotranspiration was measured with two manual weighing microlysimeters, which were 40 cm in depth and 31.5 cm in diameter and were installed in the SMF at the Hulu-1 field on 1 July 2009 with an electronic scale of 2 g (0.026 mm) in precision (Yang et al., 2017b). With the development of the CHOICE, five automatic microlysimeters (CHOICE-LYS40, T&D) were arranged in the same field as the AWS of the Hulu-1 to Hulu-5 field in August 2013 (Fig. 4c). The observation time and interval followed those of the AWS (Yang et al., 2017c), with a balance of 1 g (0.01 mm) in precision. And an EC150 system (Campbell Scientific Inc.) was installed on a lattice mast at 5.8 m at the Hulu-2 field in September 2011.

**Groundwater**

There are 17 groundwater wells with which the CHOICE has monitored the groundwater under different landscapes, geological conditions, and elevations. Four cluster wells were installed in 2011 and 2014 for groundwater monitoring and sampling. Each cluster included three to four wells with different interval screen depths. During the installation of each cluster well, both the groundwater table (if available) in the cluster wells and stream stage were measured using electronic pressure sensors (HOBO U20-001-02 water level logger Onset). The data were recorded every 15 min to be consistent with ground temperature measurements (Ma et al., 2017).

**Snow**

Snow changes rapidly and plays a key role in the climate through its power to cool the Earth (Sturm et al., 2017). In the Hulu catchment, snow observation datasets are automatically and manually collected on point, line, subwatershed, and small watershed scales. On fixed-point scale, six SR50A Sonic Ranging Sensors (Campbell Scientific Inc.) measure snow depth synchronously with AWS. Snow depth is a routine measurement variable in the SMF after every snow event. We also set a snow measurement field in the Hulu-2 field, including a snow pillow (3 by 3 m), a Flowcapt sensor, and a T-200B series precipitation gauge (Fig. 4d). After heavy snowfall events, the density, and water content of the snow are recorded using a snow fork (Toikka) along the two fixed lines near the main branches of the Hulu catchment (Chen et al., 2014). Furthermore, nine surveillance cameras were installed to monitor snow depth, snow drift, and precipitation data by photographing the stake gauge in front of the cameras hourly.

**River Ice**

River ice is widely distributed in the Hulu catchment from October to the following April. An observation system was established in 2016 on a smooth channel of the Hei River near the Hulu-1 field. In this system, three thermistor cables were installed that crossed the riverbed–water, water–ice, and ice–air interfaces. A CR1000 datalogger recorded the temperatures of the riverbed, water, and ice column at an interval of 5 cm and a total of 2 m. Meanwhile, three surveillance cameras were installed to record the processes of ice freeze-up and break-up.

The evaporation or sublimation of river ice was also surveyed in 2016 and 2017. These observations were the same as those obtained from glaciers, with the difference being that the evaporation or sublimation of river ice was observed during cold seasons and divided into three periods: a freeze period of ice growth (29 December to 9 January), a stable period of a completely ice-covered river (19 February to 2 March), and a thaw period of ice melt (30 March to 6 April).

**Dedicated Campaigns and Experiments**

**Precipitation**

Precipitation is the key variable for accumulation; however, it is difficult to assess because of its highly spatially heterogeneous and elevation-dependent variability in mountains (Šikorska and Seibert, 2018). These inaccuracies, together with runoff model limitations, translate into uncertainty in runoff estimates. Using observations from point gauges, that is, station network precipitation, remains the most common method for measuring catchment precipitation (Volkmann et al., 2010; Lorenz et al., 2014).

**Precipitation Type and Intercomparison**

Because of sampling constraints, wind, temperature, and noise affect the weighing-gauge measurements (Rasmussen et al., 2012). Snowfall, sleet, drizzle, and light rainfall events are often difficult to detect in a short period of time. In many cases, the noise observed in the data sample may be greater than the detectable signal in an actual precipitation event (Landolt et al., 2012).
This mainly is due to the daily variability in wind and is the reason for the low catch ratio of snowfall (Thériault et al., 2012) and environmental temperature (Duchon, 2008).

We conduct the work of precipitation intercomparisons by referring to the Solid Precipitation Intercomparison Experiment of the WMO using pit gauges and a double reference intercomparison reference (DFIR) gauge (Fig. 4c). The pit gauges are the WMO reference configuration for liquid precipitation measurements, and the DFIR is the reference configuration for solid precipitation measurements, which has been operated at 25 stations in 13 countries around the world (Sevruk et al., 2009; Chen et al., 2015).

### Intensive Observation of Topographic Precipitation

Precipitation measurements in the Hulu catchment were performed with six total rain-weighing sensors (TRwS204, MPS System Ltd) with a single alter shield and synchronized with AWS. It represents one type of universal weighing gauge for measuring all types of precipitation over a wide range of temperatures and wind and snow conditions.

To study the distribution characteristics of precipitation in complex mountain regions, 18 tipping-bucket rainfall gauges were installed in August 2015 at the Hulu catchment. These gauges were divided into six lines that formed fan-shaped distribution characteristics, and they were mainly distributed at different aspects from 3000 to 3600 m asl based on the original six TRwS204 and 18 tipping-bucket rainfall gauges, the gradient effects of precipitation, and the influence of complex terrain and wind fields on precipitation could be investigated.

### Precipitation Grid Matrix Net Observations

The shortage of high-elevation mountain precipitation data has restricted research on the quantity and distribution of alpine precipitation. To further study the spatial–temporal distribution of precipitation in the Qilian Mountains, we conducted an Alpine Precipitation Observation Project in the Qilian Mountains, which consisted of 23 T-200BM3 series precipitation gauges. The installation plan considered not only the elevation gradient but also factors such as slope, aspect, and landscapes. Therefore, the Alpine Precipitation Observation Project selected the high-elevation areas around the Hulu catchment, assembled a precipitation grid in the northern region of the Qilian Mountains, and obtained reliable precipitation data for the validation of satellite-based precipitation estimates. In this way, it formed a precipitation observation matrix with a length of ~400 km and a width of ~100 km in the Qilian Mountains. At the same time, a DFIR also was installed at high-elevation regions to obtain accurate precipitation data.

### Land Surface Temperature

Land surface temperature causes the phase change of water, is linked to the partitioning of surface water and the energy budget, and is an important parameter in studies of hydrology, meteorology, and ecohydrology in alpine cold regions.

### Influences of Topography on Bare Land Surface Temperature

Fourteen LST observation sites with similar elevations but different aspects and slopes were built around the Hulu-3 field. To measure the LST on bare ground, grass that was <15 cm was removed before the sensors were installed on an ~1 by 1 m patch of bare ground. An automatic temperature-measuring sensor (UTBi-001 TidbiT v2, Onset) was installed in each field on 7 Aug. 2011, and LST observations were obtained every 30 min with the same temporal resolution as the AWS. (Yang et al., 2017d).

### Influences of Plants on Land Surface Temperature

Two LST observation sites were built to analyze the influences of plants on LST. One site was built on four land cover types: bare soil land and different heights of grass (5 and 10 cm and natural height) in the Hulu-1 field on 3 Apr. 2013. Each type was 1.5 by 1.5 m in size, and the bare soil land and 5 and 10 cm height grass sites were artificially plowed, trimmed, and maintained every month. The other LST plant observation site was built on three different land cover types: bare soil land, grass, and shrub in the Hulu-2 field on 24 Oct. 2014. The height of grass was ~10 to 15 cm, and the height of shrub was ~60 to 70 cm. The LST observation sensors (U23-003, Onset) with a temporal resolution of 30 min were installed in the different land cover types.

### Runoff Fields

As transitional zones from the vegetation-to-periglacial zone, shrubs and meadows are widely distributed in the Qilian Mountains. To study the runoff process of canopy precipitation to surface runoff in different landscapes, two runoff fields (shrubs and meadows) (15 by 3 m) were established at a shrub-encroached alpine meadow hillslope in September 2010. The two runoff fields are adjacent with a slope of 20° and an elevation of 3370 m asl. The boundary of the runoff field was dug to a depth of 1.5 m, and it was sealed with rubber as a water barrier. Based on the size of the field, an iron sheet was inserted into the soil (40 cm depth) to divide the surface and subsurface flow, and it was connected by pipes with a tipping gauge. The comparative observations also included physiological and ecological parameters, the physical properties of the soil, and evapotranspiration with microlysimeters.

### Soil Infiltration

Soil water infiltration and hydraulic conductivity in alpine mountainous regions are quite different during freezing and thawing processes and directly affect soil water movement and land surface hydrological processes. Four methods were used to measure soil water infiltration and hydraulic conductivity in the Hulu-1 field including a single-ring infiltrometer, a double-ring infiltrometer, a Hood infiltrometer (Hood IL-2700, Germany), and the ring cutter method. The first three methods were performed in the field and the last one was conducted within a laboratory. There were seven groups of double-ring infiltrometers (Table 4), and each group had three infiltrometers with the same size (Yang et al.,...
2017a). The single-ring infiltration method used the double-ring infiltration apparatus but used only the inner ring for experiments. The infiltration diameters of the Hood IL-2700 were 24 and 16 cm. The infiltrometers were installed in August 2014, and field experiments began in October 2014. The soil hydraulic conductivity data during the soil freezing, thawing, and thawed periods were collected from April to May, July to August, and October to November, respectively. No field infiltration experiments were conducted in the frozen period because water would have frozen in the ring, and it was very hard to observe soil infiltration during the frozen period.

### Isotope Sampling

Isotopic and geochemical tracers can provide valuable information about the origin of streamflow components, runoff processes, and flow paths especially in complex hydrological systems such as the Hulu catchment which has diverse vertical landscape zones.

Groundwater samples used for isotope analysis were collected from 12 wells between 2014 and 2016, and stream water samples were collected from 12 sites that were approximately evenly distributed from upstream to downstream between 2011 and 2016. Both types of samples were collected at 7- to 14-d intervals during the warm season (June to September) but were collected less frequently during the cold season. Samples were collected three to four times in January and April. In addition to the 12 regularly sampled wells, groundwater was also irregularly sampled from seven springs and 18 shallow wells with depths of <3 m. Glacier meltwater was collected at 13 periglacial sites at elevations ranging from 4261 to 4432 m asl between 2013 and 2015. Weekly precipitation (rainfall and snowmelt) was sampled from three plots that were distributed at ~200 m elevation intervals between 2012 and 2015. Meanwhile, pH, dissolved oxygen, electrical conductivity, and temperature measurements were synchronous during sampling. All samples were reserved in bottles, tightly sealed with Parafilm, and retained in a portable refrigerator until they were transported back to the laboratory.

### Chamber Measurements in the Permafrost Zone

Permafrost landscapes in HiMAC, which have enormous organic carbon reserves, are an important but poorly studied component of the global carbon cycle. However, in light of future climate warming, the sustainability of these carbon pools is uncertain. A Picarro GasScouter G4301 gas concentration analyzer with a re-entry control system and six respiration chambers installed on the permafrost zone of the Hulu catchment in August 2017 (Fig. 4f); the distance between the respiration chamber and the multiplex controlling system was <15 m. The monitoring interval of each respiration chamber is 300 s. Chamber measurements can be used for the long-term field investigation of CO₂, CH₄, and H₂O concentrations.

### Canopy Interception of Alpine Shrubs

The process of the redistribution of rainfall by canopy can be divided into three parts: interception, stem flow, and throughfall. It is difficult to directly observe interception. Therefore, in field experiments, the precipitation up the canopy, throughfall, and stem flow were measured, and the quantity of interception was determined based on the principle of water balance.

The precipitation up the canopy was observed using manual observations combined with a weighing gauge. Each precipitation event is separated by at least 8.0 h.

Throughfall collectors were made using a circular iron container with a diameter of 15 cm and a height of 12 cm. For multiple shrubs, 16 collectors were randomly placed on each plot. For single shrubs, with the shrub as the center, nine collectors were placed in three directions at an angle of 120° (Fig. 5).

Six stem flow collectors were sampled to obtain stem flow observations at each shrub plot. Single shrubs were measured below all branches of base stem. Multiple shrubs were used for the standard branch; the base diameters were measured for each branch of the selected shrub, and the mean diameter was obtained. We selected the stem equivalent to the average of the base diameter as the standard branch. In our experiment, all branches under the

![Fig. 5. A diagrammatic sketch of throughfall collectors for the single shrubs.](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DR1</th>
<th>DR2</th>
<th>DR3</th>
<th>DR4</th>
<th>DR5</th>
<th>DR6</th>
<th>DR7</th>
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</thead>
<tbody>
<tr>
<td>Inner diam., cm</td>
<td>15</td>
<td>15</td>
<td>20</td>
<td>20</td>
<td>25</td>
<td>25</td>
<td>30</td>
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<td>30</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>Buffer index</td>
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<td>0.50</td>
<td>0.33</td>
<td>0.50</td>
<td>0.17</td>
<td>0.38</td>
<td>0.50</td>
</tr>
</tbody>
</table>
shrub stems were packaged with a polyethylene plastic hose (10.0 mm diam.). The tube was directly connected to the stem collection bottle, and the size of the bottleneck was the same as that of the plastic pipe. Using this method, the stem flow could be collected completely and accurately through manual tests (Liu et al., 2012). The observation period of canopy precipitation interception began in June 2010.

**Forest Water Balance Field**

In the forest water balance field, outside of the forest, precipitation data come from the automatic meteorological station Hulu-2, a TRwS204 series precipitation gauge and its surrounding tipping-bucket gauges. The throughfall and stem flow of four *P. crassifolia* trees were measured manually using a homemade circular iron container. A total of four sap flow sensors (CAF, ECOMATIK) were installed to estimate transpiration. Two manual homemade microlysimeters were also implemented in 2012 to measure soil evaporation in the forest during the growth period.

**Microbiological Sampling**

Soil microbes are an important component of the soil ecosystem and play a key role in nutrient and energy cycling. Variations in the diversity of the soil microbial community under meadow, shrub, marshy meadow, and moraine–talus were observed along an elevation gradient in the Hulu catchment in July 2013. In each type, the litter layer was removed then five soil cores (3.8-cm diameter) were randomly collected from the 0- to 20-cm layer and mixed to obtain a homogenous sample. A portion of each soil sample was air dried for the analysis of soil properties. The remaining portion of each sample was stored at 4°C until undergoing soil microbial biomass and Biolog analyses (Zhu et al., 2015).

**Snow and Ice Sublimation**

The glaciers in the Hulu catchment are not suitable for long-term monitoring. To clearly understand the roles of glaciers in the hydrological cycles of mountainous areas, we chose the Aug-one Glacier in the source area of the Hei River Basin to conduct AWS and EC system observations (Fig. 6a and 6b).

The Aug-one Glacier, which has a high elevation (4800 m asl) and a relatively homogeneous and flat surface, can obtain better meteorological observations than many other research sites on glaciers. An AWS was erected at the top of the glacier (4817 m asl) in September 2015; the site is not affected by the surrounding mountains. The AWS is located in the accumulation zone of the Aug-one Glacier, and obvious ablation phenomena were observed during the ablation period (between June and September). The measured meteorological quantities are presented in Table 3, which lists the sensors of the AWS.

To obtain reliable turbulent data, EC system measurements were made adjacent to the AWS at a height of 4 m beginning in October 2017. This system includes a three-dimensional sonic anemometer (CSAT3B, Campbell Scientific Inc.) and an open path CO$_2$ and H$_2$O gas analyzer (LI-7500RS, LI-COR). All raw data are recorded at 10 Hz, including three-dimensional winds, CO$_2$–H$_2$O concentrations and virtual temperature.

**Standard Fog Collectors**

To harvest the water contained in fog, five identical standard fog collectors were installed at Hulu-1 to Hulu-5 in July 2014. The collectors were used to identify the maximum fog water yield region for the fog collection process and to evaluate the effectiveness of fog water collection. The analysis indicated that in terms of both the quality and magnitude of yield, fog is a viable source.
of water and can be successfully used to supplement water supplies in mountainous regions.

Open-Top Chamber

To determine whether climate warming affects the moisture and temperature of soil in the shrub zone, a warming simulation experiment was begun in September 2016. The warming treatment was conducted using International Tundra Experiment hexagonal open-top chambers (OTCs). Three *P. fruticosa* shrub plots (80, 40, and 0% shrub coverage) were selected as experimental subjects. There were three warming OTCs and one control sample in each plot, and a total of nine OTCs were fixed. An air temperature and humidity sensor was installed within 60 cm of each OTC to measure the temperature and relative humidity. The ECH2O STE sensors (Decagon) were used to measure the soil temperature, moisture, and electrical conductivity in six soil layers (at depths of 0, 5, 20, 40, 60, 80, and 120 cm). Soil heat flux was observed at the surface and in the 20-cm section with the HFP01SC soil heat flux plate (Hukseflux). Soil water potential was observed from pF-meter sensors (GeoPrecision) at soil depths of 5, 20, and 40 cm.

Flight Campaigns

Airborne and satellite remote sensing products were quantitatively validated using simultaneous in situ observations with a particular focus on upscaling point-scale and footprint-scale observations to the pixel scale. Two flight campaigns were performed in the Hulu catchment. A Leica ALS70 airborne laser scanner and RCD30 camera carried by the Harbin Y-12 aircraft were used in a LiDAR airborne optical remote sensing experiment from July to August 2012 (Li et al., 2013). The airborne LiDAR-DEM and DSM data production of the Hulu catchment were obtained through parameter calibration, the automatic classification of point cloud density, and manual editing. The L-band, K-band, and Ka-band radiometers were flown with manned and unmanned missions to develop more reliable remote sensing methods for deriving soil moisture (including surface soil freeze–thaw status), snow depth, and SWE data.

Data Management and Policy

Data Transmission

The data transmission of the CHOICE involves the integrated use of ZigBee network technology and mobile Internet technology for the implementation of the remote transmission of monitoring data. The data center adopts heterogeneous large-data storage and retrieval technology based on middleware, which guarantees the comprehensive storage and retrieval of all types of field observation elements. This solves the problem of obtaining continuous high-precision acquisition data for monitoring data in a low-temperature environment.

Data Management

All observed data are automatically controlled to determine unrealistic outliers, constant values, and extreme jumps. All values were carefully inspected for erroneous data by visually examining each variable record. Additional manual quality control is required for individual observations as required. Meanwhile, a series of quality control measures were undertaken during and after field observations, data processing, data set generation, and data release.

The CHOICE data-sharing platform is a generic term for the meteorological, hydrological, ecological, and cryospheric element data of the Hulu catchment and Aug-one Glacier. To ensure the application of hydrological scientific research in the Hulu catchment, we divided the CHOICE data into three levels of data: raw, quality controlled, and filled. There are six categories of data: meteorology, hydrology, cryosphere, ecology, soil, and telemetry data.

Data Sharing

The CHOICE has built a data-sharing platform based on the entire flagship observation network (Fig. 1b). The CHOICE data are mainly shared through our website (http://hsy.casnw.net/), which contains data sheets of all our data observed from the CHOICE. Its data-sharing policy includes the following regulations. The first is total sharing, which means that there are no many constraints on these data. Second, there is data-restricted sharing, which means that there is a protection date after which the data can undergo total sharing. Finally, protocol sharing is applied to most data sets. This means that data applicants have to sign an agreement with their owner to use their data. Meanwhile, the data sets of precipitation, evaporation, discharge, air temperature, soil temperature, radiation, frozen soil depth, daily groundwater table depth, and temperature are available from the WestDC database (http://westdc.westgis.ac.cn/). This work data available from the Dryad Digital Repository (Han et al., 2018).

In recent years, a series of studies have been published using the CHOICE sharing platform data, and a number of researchers have used the CHOICE data for studies of alpine meteorology, cryospheric hydrology, groundwater, soils, and isotopes (Evans et al., 2015; Chen et al., 2015; Li et al., 2014; Yang et al., 2014a, 2016; Liu and Chen, 2016; Lin et al., 2017; Ma et al., 2017). The above review indicates that the CHOICE has become a fine platform for cryospheric hydrology studies in northwest China.

New Insights and Novel Scientific Findings

Elevation of Maximum Precipitation

According to the six AWS of the CHOICE obtained throughout the Hulu catchment and peripheral precipitation data from five China Meteorological Administration stations (Zhangye, Minle, Sunan, Qilian, and Yeniugou), two or more yearly EMPs exist in the northern Qilian Mountains. The maximum annual average precipitation is 790 mm in Hulu catchment. It was found that EMPs in Hulu catchment lie in seven-eighths of the elevation of the peak on the annual scale and to be insignificant during winter. Nevertheless, the presence of several parallel and sufficiently high mountains normal to the prevailing wind direction (westerlies) could cause
more EMPs. Special kinds of land cover, such as coniferous forest and glacier, have certain cold and wet island effects on the formation of the EMP. With three main circulations originating from different directions and topographic relief effect results in a complex precipitation distribution in the study area (Chen et al., 2018a).

**Relationship Between the Freeze–Thaw Process and Baseflow**

The freeze–thaw process of soils exerts significant influences on global climate change and plays an important role in the hydrological cycles in alpine region. Recent studies showed that the increasing precipitation was the most critical factor for increasing baseflow in warm season (from May to September), while the degradation of frozen soil was another closely related factor inducing the increasing of baseflow in the cold season (from October to April) (Evans et al., 2015; Liljedahl et al., 2016; Qin et al., 2016). It also can impact regional and local hydrology by increasing surface and subsurface connectivity (Connon et al., 2014; Walvoord and Kurylyk, 2016; Ma et al., 2017). The LST and freeze–thaw processes directly affect the soil water movement, land surface hydrological processes, and ecological environments. In addition, varied thermal states of the frozen soil differ in reducing the soil infiltration, which affects the effects of the infiltration of rain and snow meltwater. Meanwhile, snow cover or atmospheric energy exchange could indirectly affect the special hydrological characteristics of permafrost and the water balance; they jointly regulate baseflow and land surface hydrological cycle (Qin et al., 2017).

**A Diminished Accumulation Zone on a Glacier**

A diminished accumulation zone will result in a reduction in the transport and expansion of the glaciers, and then the glaciers will have to retreat to limit themselves to reduce ablation. In recent years, with increases in temperature and precipitation, the melting of a few days every summer is sufficient to eradicate all the winter snowpack that formed in the accumulation zone. Meanwhile, an increase in heavy rainfall events during summer will accelerate the ablation of glaciers (Tian et al., 2014). Many small valley glaciers presently have a very small accumulation–area ratio. This is a symptom of a glacier that cannot survive. As a result, many small valley glaciers have quickly disappeared in the Qilian Mountains (Shi, 2001).

From 1956 to 2010, the total surface area of the glacier in the Qilian Mountains decreased by 20.88%, and the absolute area loss of glaciers between 4350 and 5100 m asl constituted the main body of loss (Sun et al., 2018). In the area of 98°E of the Qilian Mountains, during the most intense period of summer ablation, we take pictures by regular and unmanned aerial vehicle photography on the Oct-one and the Aug-one glacier in the central Qilian Mountains, as shown in Fig. 7a and 7b, respectively. There is no accumulation zone on these two glaciers, and the current equilibrium line elevation (ELE) has exceeded or approached the top of the glacier. The ELE of the Aug-one Glacier was 4680 m asl in 2016, which is close to the top of the glacier (i.e., 4827 m asl). According to the first and second glacier catalog data of China, glaciers with elevations below 4000 m asl in the Qilian Mountains have completely disappeared in the past 50 yr (Sun et al., 2018). If the climate becomes ~2°C warmer in the coming years, the ELE might rise by as much as 300 m, reaching elevations of >5000 m asl, meaning that there will hardly be any accumulation zones left on small valley glaciers and that they might disappear by the middle of this century (Chen et al., 2018b).

**Cryosphere Basin Hydrological Model**

Based on 10-yr observations in the western cold regions of China, especially those obtained in the Upper Hei River basin (UHR), a new CBHM was created to evaluate the effects of cryospheric changes on stream flow from the UHR (Chen et al., 2018b). The CBHM was derived from a distributed runoff model for the inland river mountainous basins of northwest China (Chen et al., 2003; Version 1) and its updated version, a distributed water–heat coupled (DWHC) model for mountainous watershed of an inland river basin in northwest China (Chen et al., 2008). In Version 1, glacier and snowmelt runoff was estimated using the simple degree-day method, but permafrost hydrology was omitted. Based on the observations of water and heat transfer and coupled processes in frozen soil from 2005 to 2007 at the Yeniugou station in the UHR and using the mechanisms from CoupModel (Jansson and Karlberg, 2001), version 1 was updated as the DWHC model. To improve our knowledge of alpine hydrology in the western cold regions of China, the CHOICE was established in the UHR (Chen et al., 2014). The CHOICE includes dense meteorological measurements from 2980 to 4800 m asl; these include meteorology, cryospheric element, SVAT observation system, and runoff observations. As a result, some parameters and empirical equations of alpine hydrology were acquired. Based on the observation and research results in the Hulu catchment and other regions in the western cold regions of China, the DWHC model was updated as the CBHM.

**Past and Future Runoff Trends of Mountain Cryosphere in China**

Based on our observation data and other data, the past runoff trends of mountain cryosphere in China and future trend by CBHM was documented. In the past 50 yr, river runoff has generally shown an increasing trend as a result of increased rainfall, snowfall, and glacial runoff in the cold regions of western China. Because the total glacier decreased by ~18% in area and 28% in volume in western China, glacial runoff increased from 517.8 × 10^8 m^3 to 794.7 × 10^8 m^3 from the 1960s to the 2000s (Shi, 2001; Xie et al., 2006). Permafrost degradation has mainly increased infiltration and enlarged the groundwater reservoir. This could lead to an increased winter flow in western China. Although the extent of snow cover has decreased slightly over the past 50 yr, snowmelt has shown an increasing trend in most watersheds in the cold regions of western China as a result of the increased snowfall (Wang and Li, 2006). Along with increasing air temperature, glacial runoff will decrease in the near future, and the rate of this decrease is inversely proportional to the glacial size. According to different receptive concentration pathway (RCP) scenarios, glacial runoff will decrease 60 to 70% and 80 to 90%, compared with their average values in the southern and southeastern
Tibet Plateau and western Qilian Mountains, respectively, between 1971 and 2010 under RCP2.6 and RCP 4.5 by the 2090s. Most of the small glaciers will have disappeared, leading to glacial runoff started to decrease. Moreover, snowmelt will reduce by 2030 in most regions of western China except the northern Tien Mountains. However, because of precipitation in western China increasing until the 2090s, river runoff will increase in most watersheds compared with 1971 to 2010 under both RCP2.6 and RCP4.5, especially in watersheds with lower glacial area ratios. (Chen et al., 2018c). As a result, when the global air temperature rises by ~2.0~C, river runoff will increase and reach a maximum after 30 to 40 yr then decrease to similar volumes as today. Therefore, the runoff of endorheic basins will depend only on precipitation once the glacial runoff no longer exists.

**Future Perspectives**

As a microcosm of the Earth system, the catchment is a unique unit for the study of cryospheric hydrological system science (Cheng and Li, 2015). The cryosphere, meteorology, hydrology, and ecosystem within a catchment must be considered as a whole. Determining the best way to monitor and model the cryospheric hydrological processes of such complex water systems remains a considerable challenge. In addition, because of the strong vertical elevation gradients and complex topography and exposure to solar radiation, mountain hydrologies have a high degree of heterogeneity, which often become uncertainties when they represent the transitional zone of the hydrology cycle. In many mountain areas, observation networks are inadequate for capturing the heterogeneity and variability in important processes and thus strongly hinder our understanding of high-elevation regions (Viviroli et al., 2011).

In view of these challenges and uncertainties, we established the CHOICE as a unique high Alpine and vertical landscape zones research catchment with available time series of 9 yr of glaciological and hydrometeorological observations. The CHOICE aim is to understand complex catchment systems from the perspective of an entire catchment. In fact, long-term cryospheric and
Further build on the available CHOICE database with new and continuous monitoring of precipitation changes on the northern slope of the Qilian Mountains for continued study of the spatial-temporal distribution of precipitation; (ii) promote the feedback mechanisms of glaciers, snow, and frozen soil on climate change in the Alpine region along with the observation of sublimation of snow and ice and estimation of a parameterization method; (iii) assess the CBHM parameterization schemes in arid endorheic basins and forecast runoff and water resources in mountainous basins; and (iv) further build on the available CHOICE database with new and future data.

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