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Original Research Paper

Study on Snowmelt Runoff Under Climate Change Effect in Tianshan Mountain in China

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ABSTRACT

A major proportion of discharge in the Juntanghu river basin is contributed by its glacier-fed river and snow catchments situated in northern mid-slope of Tianshan Mountain, Northwest China. The Mann-Kendall trend test based on the 50 years data (1961 to 2011) were used for analysis of the climate change trends and the application of the SWAT model under different climate change scenarios show that watershed hydrological cycle would alter under different climatic scenarios. This suggests that the reservoirs will be necessary for large flow storage to meet the need of the flood control, water supply, etc.

INTRODUCTION

Snow accumulation and ablation processes dominate the surface water cycle over much of the global land area poleward of about 40° latitude, particularly in the continental interiors (Adam et al. 2009). Xinjiang is the most far northwest region in China which is located in interior of Eurasia, the snowmelt process is complicated due to hydrology distribution and extreme climatic condition. Tianshan mountain belt is the global hydrologic system and climate changed hot-area. Hence, understanding snowmelt processes is important to water resource management not only in Xinjiang but also globally. A recent research indicated that a small-scale natural climate fluctuation had a large influence on glaciers over past 1,00,000 years. The research show that hydrological regimes of glacier-melt and snow-melt driven watersheds will be impacted by a warming climate (Barnett et al. 2005, Immerzeel et al. 2010, Schaefer et al. 2006). According to the survey, we find that the global average temperature will be warming 1.1~6.4°C in 21 century (Qingwei et al. 2004). It is know that the effect of global climate change will also be on hydrologic system and on mountain snow and glacier melt, which can affect timing and amount of runoff in mountainous watersheds. The climate change on global scale will not only affect the global hydrological system but trigger water resource redistribution which has great effects on the human society or environment accordingly. The research on the climate change and hydrology in high mountain region is important owing to sensitive hydrology process in circumpolar latitude and high altitude localities. The global climate change has caused spring flood from ice-melt water in recent decades, and the flood from northern slope of Tianshan mountain has caused damages such as traffic stop, property collapse and casualties, etc. (Sufen & Guowei 2003, Tian et al. 2011). In the last decade, mountain-front stream discharge has increased by 10% (Chen et al. 2008, Shi & Zhang 1995). The low water use efficiency and water shortage make people in Xinjiang very thirsty, therefore, comprehensive research on the northern slope of Tianshan mountain snowmelt runoff and accurate stream flow simulation and forecast of great importance to water resource management and develop water resource reasonably (Abudu et al. 2010) and also can provide a basis for forecast of water resources availability while minimizing the risk from disaster caused by spring rapid snowmelt and glacier melt. However, current studies show that there are few and not a clear assessments of impact of climate change on water resources in China (Piao et al. 2010).

The uncertainty of the high mountain runoff will greatly increase owing to the cold highland area terrain is so complex that the solar radiation differs on each elevation together with refreeze phenomenon.

Many researchers used these models to suit hydrologic conditions and simulate the daily stream flows in glacier-fed and snow-catchments (Sorman et al. 2009, Verdhen & Prasad 1993, WMO 1986). They are data-intensive or/and complicated. Few snowmelt models can process varied hydrologic conditions in general (Tekeli et al. 2005). Many researchers using the MIKE-SHE, snowmelt runoff model (SRM) integrated with remote-sensing snow cover products to simulate the daily discharges and to study the climate change impact on these discharges in research area. The SRM has been used by various agencies, institutes and universities in more than 100 basins at various elevations (Martinec et al. 2008). However, there has been little research on watershed hydrological cycle under different climate change scenarios simulated by using soil and water assessment tools (SWAT). Similarly with SRM model (degree-day methods), the soil and water assessment tools (SWAT) have been most widely used both in simulation and forecast, and do not need snow covered area (SCA) data which is required by SRM. SWAT was developed by Dr. Jeff Arnold in 1998 for the United States Department of Agriculture (USDA), Agricultural Research Service (ARS) and has been widely used in water and land resource management to predict the impact of water, sediment and fertilizer in large scale watershed (Bingner 1996, Chow et al. 1998, Chu & Shirmohammadi 2004, Gitau et al. 2002, Rosenthal et al. 1995, Sophocleous et al. 1999, Spruill et al. 2000, Van Liew & Garbrecht 2003, Weber & Möller 2001).

The Jutanghu watershed of northern slope of Tianshan Mountain, Xinjiang, China was selected as typical research area. Temperature and precipitation annual average data were taken from 10 weather stations of northern slope of Tianshan mountain to simulate the relationship between snowpack, meteorology and runoff.

REGIONAL SETTING

Juntanghu River basin was chosen as the study area. The distance from the source of Juntanghu River to the Hongshan Reservoir is 60km, the Hongshan Reservoir catchment area is about 861km^2 and the total watershed area is 1218km^2 (Fig. 1). The average elevation of the basin is 1503m and the mean annual runoff is 3273×10^4 m^3. The snow cover in the Tianshan mountains accounts for 55% of total area in winter and about 5% in summer (Dou et al. 2010). The snow melt runoff produces about 40.3% of the total stream of river in Xinjiang. But, the contribution of snowmelt to runoff varies with interactions between climatic factors and environmental factors (Li & Simonovic 2002). The snow cover start emerging at the mid of September and the peak of the snow cover will reach in January of the next year. The thick-

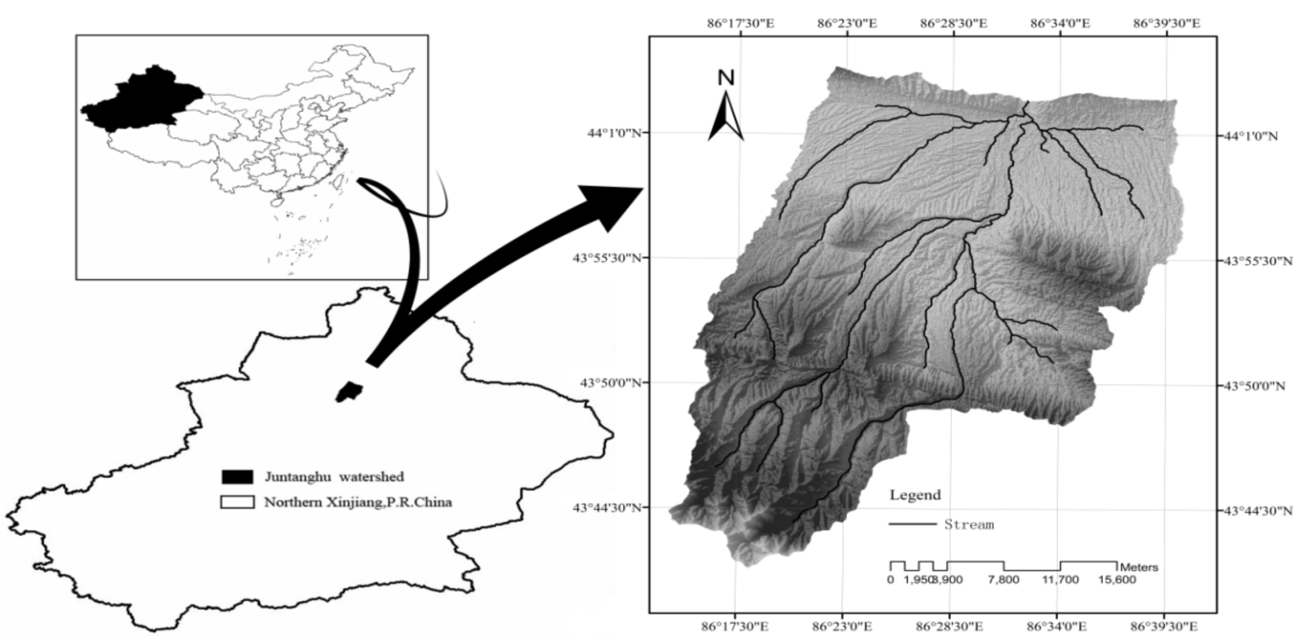

Fig. 1: The Juntanghu watershed of northern slope of Tianshan mountain, Xinjiang, Hutubi county, China.

Table 1: Source of input data for research area (Northern mid-slope of Tianshan mountain, Juntanghu watershed)

Data	Sources
Soil	http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/ (FAO-1:1,000,000)
Land use	http://westdc.westgis.ac.cn/data/f1aaacad-9f42-474e-8aa4-d37f37d6482f (WESTDC—1:10,0000)
Topography	http://asterweb.jpl.nasa.gov/gdem.asp (DEM-30m)
Weather data	http://www.climate.xj.cn/gx/dsQuery.do?id=5&pid=-1 (temperature, solarradiatio-n,pricipitation,wind,etc.)
Stream data	Hongshan Reservior (Daily stream data at hongshan guage station)

ness of snow pack can reach from 20cm to 30cm. The temperature is identified as a critical factor that may influence hydrological process in Juntanghu watershed of its contributions to snowmelt, surface soil frost and thaw, and evaporation (Anderson 1973, Li & Simonovic 2002, Tanasienko & Chumbaev 2008). The snow melt will happen when the air temperature rise again in February and can reach its maximum proportion in March. The snowmelt flood occurring in this area became more frequent in recent years and it is imperative to better understand the snowmelt process for better agriculture practices and flood control.

MATERIALS AND METHODS

Data

The source of input data (such as soil, topography, land cover data, weather data and stream data) for analysis in this paper were accessed from different sources (Table 1). Daily temperature and precipitation data were obtained for the Juntanghu watershed from 1992 to 2010, and monthly temperature and precipitation data of northern slope of Tianshan mountain from 1961 to 2009. The daily inflow series data were obtained for the Hongshan reservoir- from 2000 to 2010. All the data such as soil, land use and DEM inputted into module were all formatted as WGS_1984_UTM_Zone_45N project.

Methods

The Mann-Kendall test: The Mann-Kendall monotonic trend test (Yue et al. 2002) was used in this study. Hipel & McLeod (1994) and McLeod et al. (1991) have managed Mann-Kendall trend test in all kinds of the circumstance data analysis. The M-K trend test made a great development due to its several advantages (Hamed & Ramachandra Rao 1998, Yue et al. 2002).

The SWAT model: In order to predict the relationship between snowmelt flood and climate change in high cold mountain, the SWAT model was selected in this research. SWAT is a physically-based continuous distributed model that operates on a daily time step in an ungauged watershed. The watershed discretization in the SWAT model is operated from a given digital elevation model (DEM) to a number of sub-basins. Within each sub-basin, the hydrologic response units (HRUs), which consist of similar land use and soil type combinations, are the basic modelling units. The watershed delineation module of ArcView SWAT (AVSWAT) is based on the elementary raster functions provided by ArcView and its spatial analyst extension (Di Luzio et al. 2004). Due to the extensive use in the water resource management and flood forecast, the SWAT model has been applied more extensively in recent years in China.

Water balance is the key and driving force for everything that occurs in the watershed no matter what problems are studied using SWAT. To accurately predict the movement of water, pesticides, sediments and nutrients, the hydrological cycle simulated by SWAT should conform to the observation in watersheds. In SWAT, hydrological simulation can be grouped into two major divisions. The land phase of the hydrological cycle and the water routing phase of the hydrological cycle; the first one controls the amount of water, sediment, pesticides and nutrient loadings to the main channel in each sub-basin.

There are lots of methods which can be used for analysis of the interaction between climate and runoff (Singh & Bengtsson 2004). The hydrological model and the hydrologic statistics are the common methods in recent years. The latter methods not only demand full and accurate data but also assume the relationship between climate, precipitation and runoff, and remain unchanged in the future. It is a good choice for us to analyse data using hydrological model that match the data missing in area.

RESULT ANALYSIS

Hydrological Feature Statistics Using Mann-Kendall Trend Test

The Mann-Kendall (MK) statistical test showed a significant increasing trend in the mean annual temperature (MAT) in the northern slope of middle Tianshan mountains during 1961-2011 ($P < 0.001$), with a rate of 0.40°C/decade, and indicated step change points in 1995 ($P < 0.01$). The rising rate is consistent with the temperature of the northwestern China (0.34°C/decade) (Li et al. 2012), and is much higher than the average of the entire globe (0.13°C/decade) (Brohan

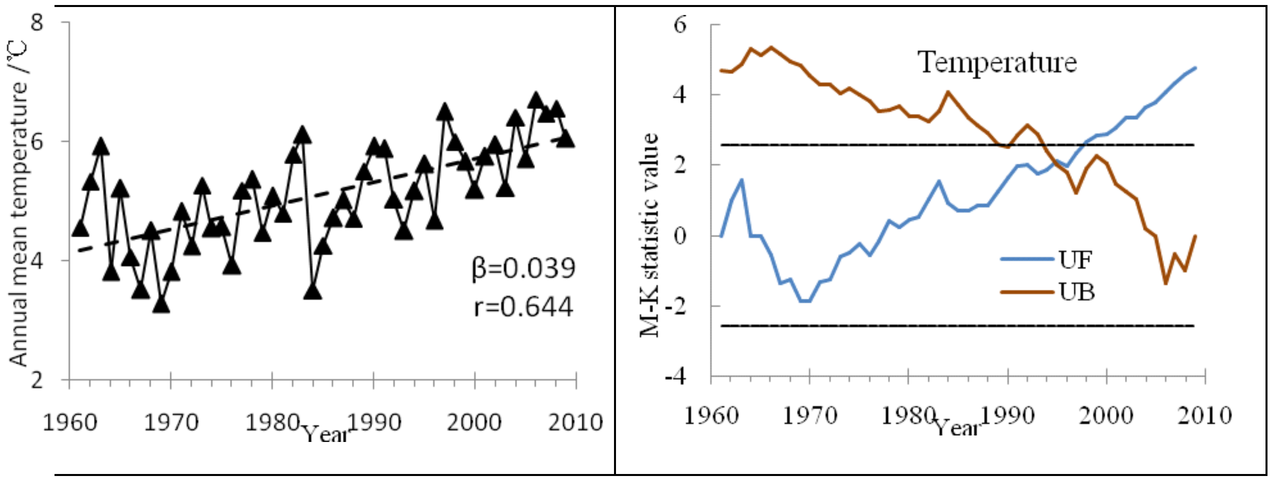

Fig. 2: Variation by Mann-Kendall test in the mean annual temperature during the period from 1961 to 2009 in northern mid-slope of Tianshan mountain.

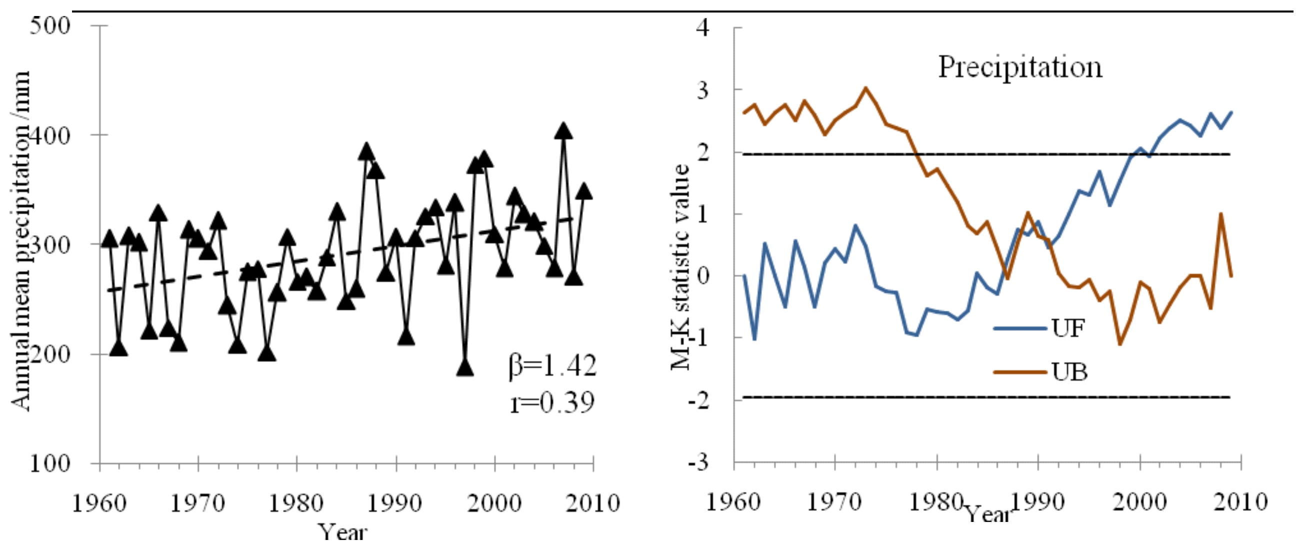

Fig. 3: Variation by Mann-Kendall test in the mean annual precipitation during the period from 1961 to 2009 in northern mid-slope of Tianshan mountain.

et al. 2006, Solomon 2007) and the average of China (0.25°C/decade) (Ren et al. 2005). Among the mountain and oasis landscapes, the oasis has the highest increasing rate, which is 0.42°C per decade; the mountain has the lowest, with a rate of 0.21°C per decade. This is because of the widespread snow and glacier, vegetation diversity, and high ecosystem stability in the mountain area that have a certain buffer action on the global climate change (Li et al. 2012). From various seasons, the increasing rate is highest in summer and latest one is in spring. Coefficient of variation (CV) is the measured variation statistics of observed value and variation degree of the variable (i.e., temperature and precipitation) in time-series. In northern mid-slope of Tianshan mountain, the temperature is of moderate variability and CV is 0.168. The CV of temperature in each season is not high, ranging from 0.073 to 0.246, which belongs to moderate variability. The CV of temperature is the smallest in summer which belongs to weak variability, while the largest one is in autumn which belongs to moderate variability (Fig. 2).

During the past 50 years, the average increasing rate of precipitation in northern mid-slope of Tianshan mountain was 15.38 mm per decade and indicated that step change points in 1991 ($P < 0.05$). The increasing rate of precipitation on the mountains is the fastest, the rising rate of 21.10mm per decade, and the slowest one is oasis area, only 12.17 mm per decade. From various seasons, the rising rate is highest in winter and lowest one is in autumn. In northern mid-slope of Tianshan mountain, the precipitation is of moderate vari-

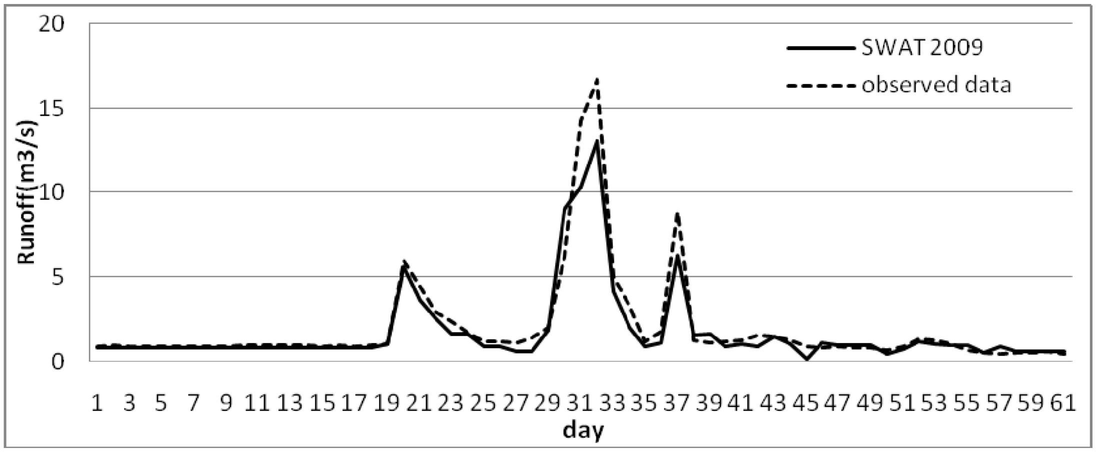

Fig. 4: Measured (observed) and simulated runoff during calibration period using SWAT 2009 model at the Juntanghu watershed, Xinjiang, China. The x-axis is a continuous days from the first snowmelt day to the end of snowmelt period (from 20th February to 20th April, 2000).

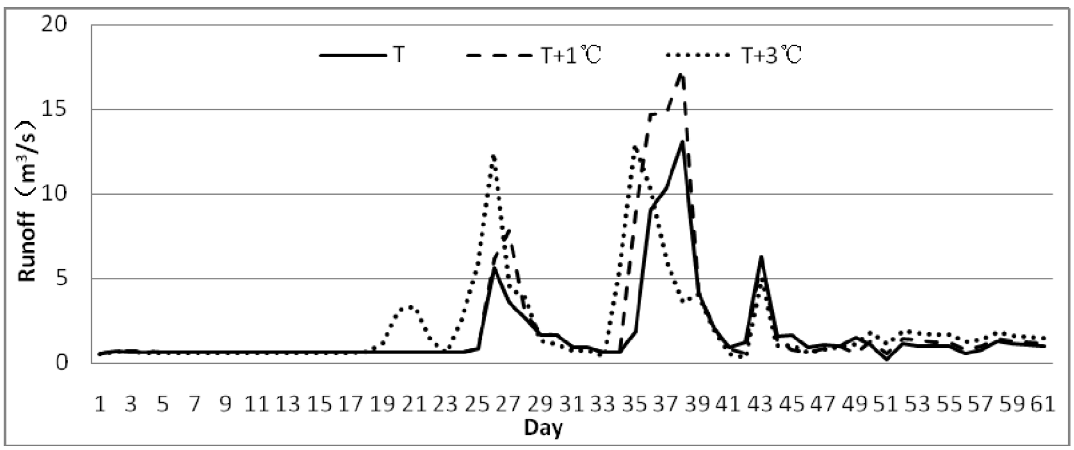

Fig.5: The sensitive analysis of temperature and snowmelt runoff. The x-axis is a continuous days from the first snowmelt day to the end of snowmelt period (from 20th, February to 20th, April, 2000).

ability and CV is 0.178. The CV of precipitation in each season is not high, ranging from 0.221 to 0.443, which belongs to moderate variability. The CV of precipitation is the smallest in summer while the largest one is in winter (Fig. 3).

Simulation by Using SWAT Model

In this study, the Juntanghu watershed was divided into 33 sub-basins. The SWAT model was calibrated and validated based on the observed inflow series at the Hongshan reservoir station. Data from 1995 to 2000 were used to warming up the model, the data from 2000 to 2005 were used for calibration, and data from 2006 to 2010 were used for validation. We extract one spring snowmelt period (from February 20th to April 20th) from the ten years results that we can master the change with the runoff when replace the different parameters.

In the calibration period, the NS efficiency coefficient for the SWAT model is 0.61, and the correlation coefficient R^2 is 0.630. In the model validation period, the NS efficiency coefficient of the original SWAT model is 0.75, the correlation coefficient R^2 is 0.769. From Fig. 4, we find that the surface runoff in winter is rare when compared with surface runoff in spring snowmelt stage from February 20 to April 20. We draw a conclusion that the snowmelt area can not enlarge due to the low temperature of winter. The snowmelt water will make a great influence on the hydrological surface in spring snowmelt stage, and this influence will take an important core of regulation in Juntanghu river basin.

Climate Change Scenarios

After calibration and validation of the model, we find the surface runoff can be influenced both by temperature and the precipitation, but which factor will have more influence

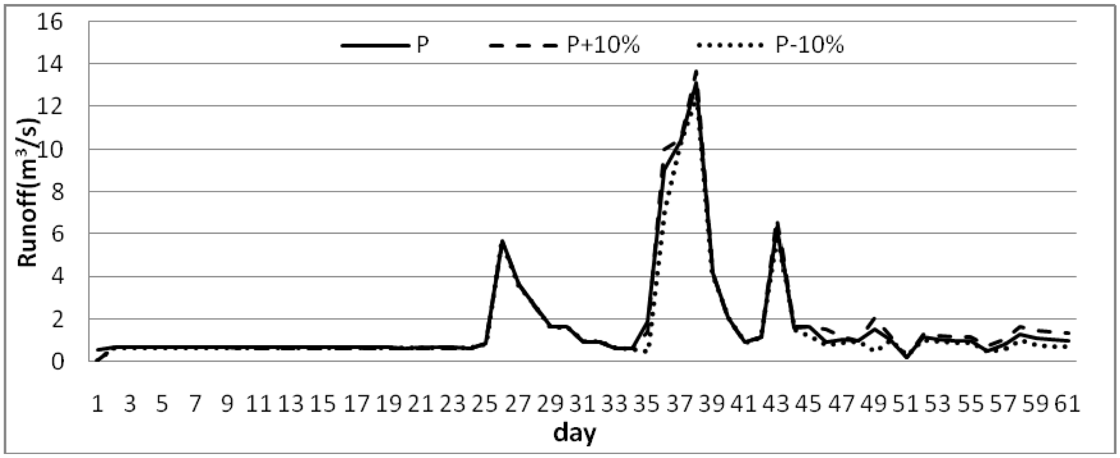

Fig. 6: The sensitive analysis of precipitation and snowmelt runoff. The x-axis is a continuous days from the first snowmelt day to the end of snowmelt period (from 20th February to 20th April, 2000).

on the runoff? In order to clarity this question, the scenario analysis was selected to make simulation and evaluation. The different future climate scenarios for precipitation and mean temperature were used to estimate the relative stream flow in the future for water resource management. The scenarios are described as follows:

A. An increase in mean temperature: In order to validate the snowmelt runoff contribution from temperature change, from Fig. 2 we found that the annual average temperature of the research area is always rising after the years 1996, therefore, we manually kept rising the temperature value in simulation day (temperature + 1e and temperature + 3e) and keep other parameter constant. The SWAT 2009 was used for simulate the snowmelt runoff changed condition.

B. An increase in precipitation: Due to the uncertainly of precipitation, the precipitation's setting is different from temperature (precipitation + 15% and precipitation - 15%).

The impact of temperature variability on Juntanghu river runoff: The mean temperature of the Juntanghu catchment was assumed to rise up to 1°C and 3°C, keeping the other variables constant, particularly precipitation. The daily discharges for the Juntanghu River simulated under these scenarios are presented in Fig. 5. The results obtained show that a 1°C rise in temperature will result in an increase of 7.78 m^3/s greater than 3.62 m^3/S which is simulated by T on day 27th February. In additional, the snowmelt phenomenon seems to be earlier on the 34th day and reach its flood peak (17.37m^3/s) on the 38th day which increased by 4.27 m^3/s when compared with the result simulated by T. A 3°C rise of temperature will force the mean discharge to increase and earlier nearly 7days (advance from 25th to 18th) and reach its flood level (12.393 m^3/s) when compared with the runoff (4.27m^3/s) simulated by T. The snowmelt phenomenon seems to be tiny earlier on the 33th day at a 3°C rise of temperature. In short, the peak value and runoff hydrograph have great changes during the spring snowmelt period when compared with other stage in whole year. It can also be seen that if the higher temperature arise, earlier the snowmelt phenomenon occur correspondingly. The great change will happen to runoff when temperature changed substantially. However, these results may be specific to this particular local area because the watershed response to the climate warming (rise in temperature) may not the same in other watersheds as explained by Null et al. (2010) and Young (2009) that the river runoff decreases with increasing temperature scenario.

The impact of precipitation variability on Juntanghu river runoff: When the precipitation of the Juntanghu catchment was assumed to change the value of precipitation (P+10% and P-10%) keeping other parameters constant (Fig. 6), the snowmelt runoff during preliminary to interim stage has less influence facing with changed precipitation. The simulation value has underestimate by 1.02 m^3/s (observed data 1.5 m^3/s V/s simulation value 0.48 m^3/s), at the same time, the rise in precipitation on the 26th also resulted in tiny increase in the runoff. The precipitation influence the snowmelt in later snowmelt period only. Above all, the snowmelt runoff in Juntanghu watershed seems to be more sensitive with temperature. The result suggests that the Juntanghu River runoff is greatly influenced by the snow and glacier cover melt caused by the temperature and not the catchment precipitation. The above theory is also confirmed by Archer (2003). This is the area that is considered to add an increasing amount of precipitation in the future and no significant increase in the average temperatures (Tahir et al. 2011). Mann-Kendall test showed the mean annual precipitation and temperature during the period from 1961 to 2009 in northern mid-slope of Tianshan mountain has rising trend, so the research area is considered to receive an increasing amount of precipitation in the future. The mean temperature has no significant increase, all this may be resulting in an extended snow cover area and this area will produce a large amount of runoff on melting if the mean temperature rise is too rapid in the future.

CONCLUSIONS

This research concludes that the soil and water assessment tools (SWAT) based on a degree day factor can efficiently simulate the glacier-fed and snow-watershed of northern slope of Tianshan Mountain, Xinjiang, China. The Mann-Kendall trend test analysis was selected to analyse the annual average precipitation and temperature from 1986 to 2011 of ten weather stations of northern slope of Tianshan mountain. We found that the annual average temperature and precipitation have been raised obviously in past ten years. The residual mass curve was used to validate the Mann-Kendall trend test and wavelet analysis in order to enhance reliability and find out the synchronism between them. Moreover, the SWAT model was selected to analyse the most sensitive parameter related to snowmelt runoff. The analysis of the climate change impact indicated that the research area's hydrological system will alter under different climatic change scenarios. The results show that increasing temperature will not only increase the volume of stream flow but also can make the snowmelt period ahead of time. Also the result produced form Juntanghu watershed can extend to overall area of northern mid-slope of Tianshan Mountain, Northwest China. The availability of the snowmelt runoff will change accordingly with the average temperature rise in spring. The research analysis also suggests that new or present reservoirs (such as Hongshan reservoirs, etc.) are needed for large flow storage in order to meet the increasing needs for flood control, water supply, etc. The climate scenarios analysis using by SWAT model was used in this study in order to provide useful information to manage water cycle and meet the country's future need.

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