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Hydrological Impacts of Climate Change on Streamflow of Dongliao River Watershed in Jilin Province, China

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Abstract: The impacts of future climate change on streamflow of the Dongliao River Watershed located in Jilin Province, China have been evaluated quantitatively by using a general circulation model (HadCM3) coupled with the Soil and Water Assessment Tool (SWAT) hydrological model. The model was calibrated and validated against the historical monitored data from 2005 to 2009. The streamflow was estimated by downscaling HadCM3 outputs to the daily mean temperature and precipitation series, derived for three 30-year time slices, 2020s, 2050s and 2080s. Results suggest that daily mean temperature increases with a changing rate of 0.435℃ per decade, and precipitation decreases with a changing rate of 0.761 mm per decade. Compared with other seasons, the precipitation in summer shows significant downward trend, while a significant upward trend in autumn. The annual streamflow demonstrates a general downward trend with a decreasing rate of 0.405 m^3/s per decade. The streamflow shows significant downward and upward trends in summer and in autumn, respectively. The decreasing rate of streamflow in summer reaches 1.97 m^3/s per decade, which contributes primarily to the decrease of streamflow. The results of this work would be of great benifit to the design of economic and social development planning in the study area.

Keywords: streamflow; climate change; Soil and Water Assessment Tool (SWAT); statistical downscaling; Dongliao River

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1 Introduction

Climate change is anticipated to have threatening consequences on environment and water resources both at the global and local levels. It is envisaged that climate change has far reaching impacts on local and regional hydrological regimes, which will in turn affect ecological, social and economical systems. For example, climate change will affect the hydrologic cycle, further exert impacts on the magnitude and timing of runoff, the frequency and intensity of floods and droughts, and the quality and quantity of water resources. Also climate change has implications in a variety of sections including water supply system, power generation, sediment transport and deposition, and ecosystem conservation (Jiang, 2005).

For modeling hydrological response to climate change, two tasks need implementing: the generation of future climate change scenario and the establishment of hydrologic model. The General Circulation Models (GCMs) are currently considered to be the most sophisticated and well developed models for investigating the physical and dynamic processes of the Earth′s surface-atmosphere system, which have been widely applied in the stu-

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dies of global climate change (Dibike and Coulibaly, 2005). However, the GCMs are inherently unable to predict regional climate scenarios due to its coarse resolution (Wigley *et al*., 1990; Risbey and Stone, 1996). Moreover, they were not designed for climate change impact studies and did not provide a direct estimation of hydrological responses to climate change (Dibike and Coulibaly, 2005). Therefore, downscaling hydrologic variables from macro-scale to micro-scale both in space and time have become an important research topic of hydrology. Compared with dynamical downscaling, statistical downscaling is computationally inexpensive and can easily be applied with any GCM output and adopted to local scale. Therefore, this method was widely used by many researchers worldwide (Xu, 1999b; Wilby *et al*., 2002; Wood *et al*., 2004). Numerous studies based on statistical methods for exploring impact of climate change at the watershed scale were summarized (Jha *et al*., 2004).

The downscaled GCMs can be coupled with hydrological models to evaluate the regional effects of global climate change. Numerous hydrological modeling approaches have been applied to study the hydrological impacts of climate change caused by global warming (Xu, 1999a). The Soil and Water Assessment Tool (SWAT) hydrological model, as a tool to investigate climate change effects, includes approaches describing how CO_2 concentration, precipitation, temperature and humidity affect plant growth, evapotranspiration, snow and runoff generation (Arnold and Fohrer, 2005; Neitsch *et al*., 2005; Gassman *et al*., 2007). Climate, land use, soil, topography and geological variations can be taken into account in simulation process. The SWAT model is one of the most well recognized process-based models and many successful applications have been reported in China, such as hydrologic assessments (Chen, 2009), comparisons with other models or techniques (Gao *et al*., 2008), calibration and/or sensitivity analysis (Hu *et al*., 2007), pollutant assessments (Fan *et al*., 2008), land use and climate change impacts (Qin *et al*., 2009; Zhao and Xu, 2009).

As the source area of the Liaohe River, the water quality and water resources in the Dongliao River have been deteriorated seriously due to natural effects and many irrational human activities, which posed a great threat to the ecological security and socio-economic sustainable development of the Dongliao River Watershed in Jilin Province, China in recent years. Therefore, evaluation of water resources in light of future climate change is very important for sustainable planning and management of the resource. Therefore, taking the SWAT model as a simulation tool, this paper intends to predict the response of the streamflow to the future climate change in the Dongliao River based on future climate scenarios generated by downscaled GCM output data. The results of the study are expected to provide a theoretical basis for the local water management authorities to make scientific and rational control measures and response plans in the study area.

2 Material and Methods

2.1 Study area

The Dongliao River in Jilin Province, taking as the study area of this paper, is a primary branch of the upper reaches of the Liaohe River. It is originated in the Sahaling Mountain in the Liaoyuan City, Jilin Province, China. It mainly flows through Liaoyuan City, Dongliao County, Lishu County, Gongzhuling City, Shuangliao City, with a total length of 321 km and watershed area of 10 136 km^2 (Sun, 2011).

The climate change in the Dongliao River Watershed of Jilin Province is controlled by Pacific low-pressure and Siberian high-pressure. The annual average precipitation decreases from 700 mm in the upstream to 450 mm in the downstream. And the temporal distribution of precipitation is not uniform, the amount from June to September accounts for 75% of annual precipitation, and 50% from July to August. The annual change of precipitation in the east is more significant than that in the west. The precipitation at wet period is about two to four times more than that at dry period. The runoff depth decreases from 150 mm in the upstream to 25 mm in the downstream.

The distribution of surface runoff in the study area is corresponsive to the precipitation. The average temperature goes below zero in November and the runoff disappears since the rain becomes snow. The river is recharged by groundwater besides the slow flow, while there is even no flow recharge at dry period. The ice-frozen period in a year reaches five months. And the streamflow in flood season (from June to September) accounts for 80% of annual streamflow. The average sediment concentration of the Dongliao River is about 5.00 kg/m^3. The location of the study area is showed in Fig. 1.

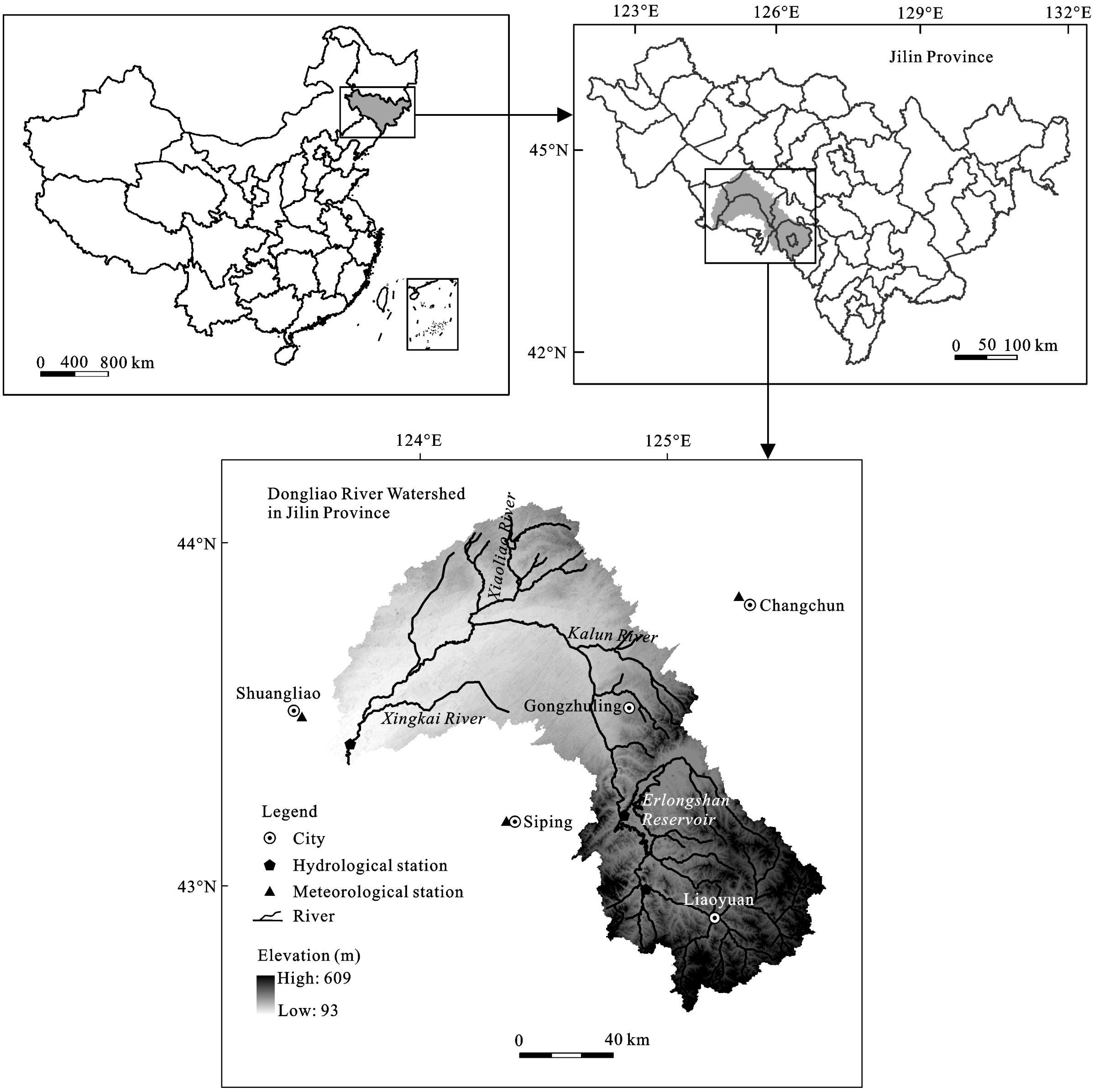

Fig. 1 Location of Dongliao River Watershed in Jilin Province

2.2 Data sources and processing

In order to generate future climate change scenarios, three types of daily data were collected for hydrologic modeling and statistical downscaling: 1) observed station data; 2) the US National Centers for Environmental Prediction (NCEP) reanalysis data; and 3) HadCM3 output.

2.2.1 Station data

Daily maximum (T_{max}) and minimum (T_{min}) temperature and precipitation (*PRCP*) data from stations in the study area were collected from China Meteorological Data Sharing Service System. The reference input parameters used in the SWAT model, such as topography, landscape, soil and flow data were obtained from Li (2011).

2.2.2 NCEP reanalysis data and GCM outputs

NCEP reanalysis data were used to develop the downscaling model, and the GCM (HadCM3) scenario outputs were adopted to project future climate changes. The reanalysis data were interpolated to fit the grid size of the HadCM3 output and to ensure the consistency of the downscaling model in projections. There were 26 large scale weather factors of the reanalysis and GCM data, from which the data on the grid closest to the watershed were selected. The values of factors were normalized by respective means and standard deviations. NCEP reanalysis data and GCM outputs data on the study area are available from the Canadian Climate Impacts Scenarios (CCIS) website (http://www.cics.uvic.ca/scenarios/index.cgi).

2.3 Climate change scenarios generation method and SWAT model

2.3.1 Statistical downscaling method

In this study, a GCM of HadCM3 (The Hadley Centre's coupled ocean/atmosphere climate model) (Collins *et al*., 2001) was used to establish climate change scenarios. Downscaling of the GCM output to the study area was implemented by using the statistical downscaling model (SDSM) (Wilby *et al*., 2002). Statistical downscaling (SDS) method is based on the view that regional climate is conditioned by two factors, the large scale climate state (atmospheric circulation factors), and regional/local climate features. From this perspective, regional or local climate information is derived by first determining a statistical model which relates large scale climate variables (or ′predictors′) to regional and local variables (or ′predictors′). Then the large scale output of a global climate model (GCM) simulation is fed into this statistical model to estimate the corresponding local and regional climate characteristics. The coupling of GCM and hydrological model can be used to estimate the impacts of climate change on water resources (Zhang *et al*., 2011).

Firstly, the observed daily maximum and minimum temperature and precipitation were chosen as predictands. According to the correlation analysis and scatter diagram of predictand and the large scale climate variables in NCEP reanalysis data (e.g. surface pressure and atmospheric temperature), the suitable predictors for each predictand were determined. Secondly, the SDSM 3.1 was used to construct the statistical relationship between predictands and predictors. This correlation is calibrated and validated against the historical observations monitored during 1961–1975 and 1976–1990, respectively. And then these relationships were applied to the GCM simulation in order to obtain the change in the local scale variables of interest.

2.3.2 SWAT model

SWAT model is a medium-large scale river basin model that was developed to predict the impact of land management practices, such as land use and cover changes, reservoir management, groundwater withdrawals, and water transfers on sediment, water, and agricultural chemical yields in complex watersheds with varying soils, land-use and management conditions over long periods of time (Arnold *et al*., 1998; Neitsch *et al*., 2005). The version AvSWAT2005 was used in this study, which uses a GIS interface and readily available input data such as Digital Elevation Model (DEM), climate, soil and land-use data.

The simulated domain was discretized into multiple sub-watersheds, which were then divided into units of unique soil/land use characteristics called hydrological response units (HRUs). The classification of the study area was represented by 26 subbasins and 357 HRUs.

In SWAT model, surface runoff volume is estimated by using a modified version of the Soil Conservation Service (SCS) Curve Number (CN) method. For evapotranspiration estimation, three options are available in SWAT, e.g., Penman-Monteith, Priestley-Taylor, and Hargreaves methods. A kinematic storage model is used to predict lateral flow, whereas return flow is simulated by creating a shallow aquifer. The Variable Storage and Muskingum methods are employed for channel flood routing. Sediment yield is calculated with the Modified Universal Soil Loss Equation (MUSLE) (Arnold *et al*., 1998).

2.3.3 SWAT model calibration and validation

The application of the model first involved the analysis of parameter sensitivity, which was for model calibration (Muleta and Nicklow, 2005). LH-OAT (Latin Hypercube One-factor-At-a-Time) analysis module and SCE-UA (Shuffled Complex Evolution) auto calibration module have been added to SWAT2005, which enables SWAT2005 have an autocalibration-sensitivity analysis procedure. The calibration was carried out combining with auto and manual calibration using the observed flow data from January 2005 to December 2007. Model validation is a process of performing the simulation using data collected from January 2008 to December 2009, without modifying any parameter that have been adjusted during calibration. For the streamflow simulation, calibration and validation were performed for monthly time step using the observations from the Wangben gauging station at the watershed outlet.

The model performance was evaluated by using goodness-of-fit statistics, the coefficient of determination (R^2) and Nash-Sutcliffe model efficiency (E_{NS}) (Nasha and Sutcliffea, 1970).

Surface runoff was calibrated until the following three conditions are satisfied, i.e. the discrepancy between the measured average and simulated values is less than 15%, monthly coefficient of determination is greater than 0.6 and Nash-Sutcliffe model efficiency is greater than 0.5 (Santhi *et al*., 2001). Monthly E_{NS} greater than 0.75, between 0.65 and 0.75, between 0.5 and 0.65 represent the goodness-of-fit is excellent, good and satisfactory, respectively (Moriasi *et al*., 2007).

3 Results and Analyses

3.1 Generation of climate change scenarios

In this study, the method used for construction of climate change scenarios is statistical downscaling model SDSM3.1, which downscaled the GCM output to generate future climate scenario. The calibration and validation results of SDSM were listed in Table 1. The generated climate sequences were derived for three 30-year time slices: 2020s (2010–2039), 2050s (2040–2069) and 2080s (2070–2099). The changing rate of each period was analyzed by comparing with the baseline data at the period of 1961–1990, which was illustrated in Fig. 2.

Explained variance (*E*) indicates the degree of correlation between predictands and predictors, and standard error (*S.E.*) represents the sensitivity of predictands to predictors. As shown in Table 1, 75.2% and 76.8% of the variance in maximum and minimum air temperature could be explained by the downscaling model, whereas only 15.7% of the variance in daily precipitation could be explained. The standard errors for T_{max}, T_{min} and daily precipitation were 0.012℃, 0.031℃ and 0.040 mm, respectively at the calibration period. The model results during the validation period demonstrate a good agreement between the observed and simulated mean daily maximum and minimum temperature, and the standard errors for T_{max}, T_{min} and daily precipitation, 0.104℃, 0.137℃ and 0.079 mm, are obtained. We can conclude that the statistical relationship established with SDSM is suitable for the generation of future climate change scenarios.

Figure 2 illustrates the future climate change scenarios generated by downscaling the GCM output using SDSM. It can be seen that there is a general increasing trend for mean temperature at the three future periods, especially in the summer (Fig. 2a). Compared with the baseline data from 1961 to 1990, the temperature would increase with an average of 1.17℃, 2.44℃ and 4.75℃ in the 2020s, 2050s and 2080s, respectively. As shown in Fig. 2b, the daily average precipitation showed an increasing trend in the most months, especially in September, and sharp decrease in July. Compared with that at the period of 1961–1990, the daily precipitation would slightly decrease with an average of 0.08 mm, 0.12 mm and 0.32 mm in 2020s, 2050s, and 2080s.

Table 1 Model evaluation statistics for calibration (1961–1975) and validation (1976–1990) period

Predictand	Calibration		Validation
	E (%)	*S.E.*	*S.E.*
T_{max}	75.2	0.012℃	0.104℃
T_{min}	76.8	0.031℃	0.137℃
PRCP	15.7	0.040 mm	0.079 mm

Notes: T_{max} and T_{min} are maximum and minimum of temperature, respectively; *PRCP* is daily precipitation; *E* is explained variance; *S.E.* is standard error

3.2 Characteristics analysis for future climate change

The characteristics of future climate change were further

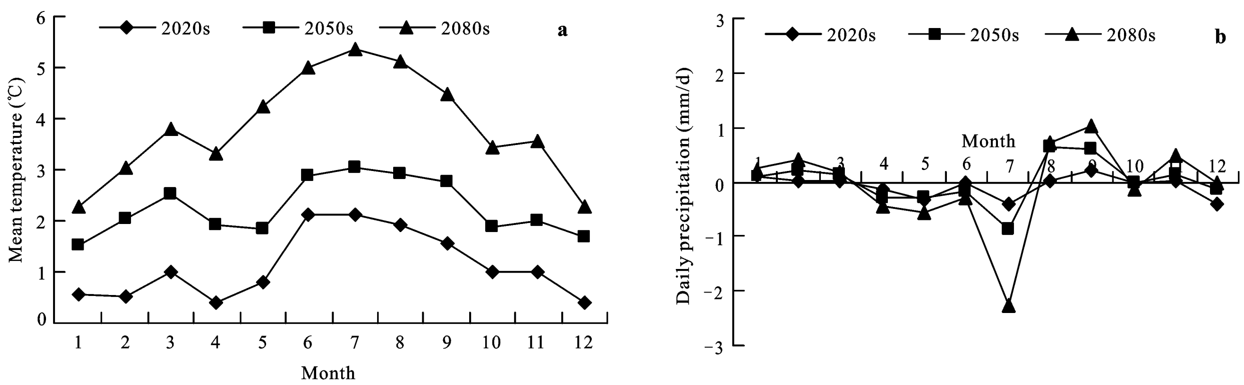

Fig. 2 Changes in mean temperature (a) and daily precipitation (b) in 2020s, 2050s and 2080s

analyzed by using the linear regression and Mann-Kendall (M-K) trend analysis methods (Kumar *et al.*, 2009).

Table 2 summarized the results of the regression slope b, the Z_c values obtained from M-K test methods and Kendall slope β value. It can be seen that the warming trends of annual average and seasonal daily temperature were all significant at 0.05 level, and β values were all positive, representing an obvious upward trend. The increase magnitude of the four seasons shows a similar behavior. Annual precipitation showed a slightly decreasing trend but not significant at 95% confidence level. For the seasonal change, precipitation showed significantly decrease in summer, while a significantly increasing trend in autumn and winter. Changes of precipitation and temperature in summer contribute primarily to the decrease in annual precipitation and increase of temperature, respectively. So the significant changes of the precipitation and temperature in the future may occur in summer.

3.3 Hydrological response of streamflow to climate change

3.3.1 SWAT model calibration and validation

Parameter sensitivity analysis was performed before the calibration and validation of the SWAT model. And then calibration was carried out by trial and error method, manually adjusting the relevant parameters from the observed streamflow data. The model calibration and validation were performed on a monthly basis from January 2005 to December 2007 and from January 2008 to December 2009, respectively. As is shown in Fig. 3, we can observe that at the most of the periods, there is a very good agreement between the simulated and observed streamflows. E_{NS} and R^2 values are 0.781 and 0.803 for calibration, and 0.715 and 0.776 for validation, respectively. The relative errors for observed and simulated streamflow were both within the evaluation criteria range.

Table 2 Results of trend test for series of daily mean temperature and precipitation

	Mean temperature				Precipitation			
	b (℃/10yr)	Z_c	H_0	β	b (mm/10yr)	Z_c	H_0	β
Annual	0.435	9.98*	Reject	0.059	–0.761	–0.146	Accept	–0.076
Spring	0.368	5.43*	Reject	0.050	1.227	1.331	Accept	0.115
Summer	0.525	9.19*	Reject	0.067	–8.894	–2.170*	Reject	–0.830
Autumn	0.443	9.07*	Reject	0.057	6.061	4.412*	Reject	0.594
Winter	0.406	7.93*	Reject	0.055	0.575	4.457*	Reject	0.057

Note: * Significant at 0.05 level

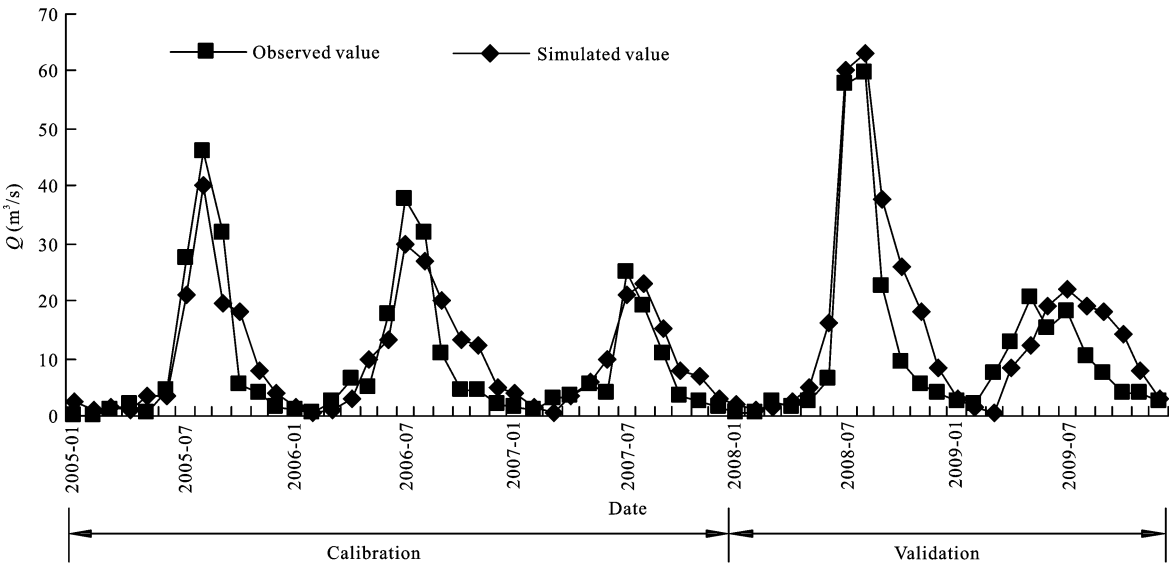

Fig. 3 Observed and simulated monthly streamflow (Q) at calibration and validation periods

3.3.2 *Impact of climate change on streamflow*

The relative changes of the predicted streamflow compared with that at the period of 1961–1990 are illustrated in Fig. 4. It can be seen that there is significant decrease from April to July during the three predicted periods, while a substantial streamflow increase in September was observed. Combining Fig. 2 and Fig. 4, we can observe that the changing trend of streamflow and precipitation in the future show similar behavior in corresponding seasons, whereas with the largest response in July, August and September. The relatively less precipitation and higher temperature may contribute to the greatest reduction of streamflow in July. From December to March, the increase of temperature may cause the increase of spring snowmelt, which corresponds to the increase of streamflow in winter. In autumn, the streamflow showed an upward trend due to the increase of precipitation, and the higher temperature made the extent of increase is smaller than that of decrease in summer. So the streamflow in the study area showed a holistic decrease, with an average of 0.18 m^3/s, 0.36 m^3/s, and 0.65 m^3/s in the 2020s, 2050s and 2080s compared with the baseline data at the period of 1961–1990. The reduction of streamflow may worsen the water shortage of the study area.

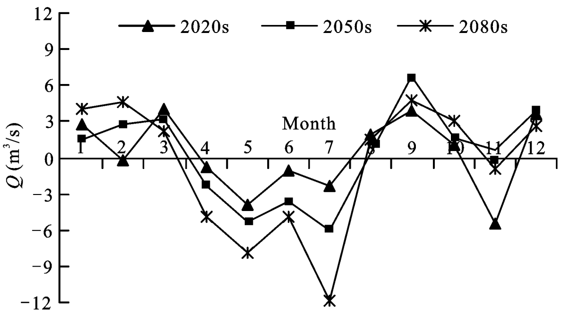

Fig. 4 Streamflow (Q) changes predicted by SDSM method in 2020s, 2050s and 2080s

3.3.3 *Characteristics of future streamflow changes*

According to the M-K statistics Z_c in Table 3, streamflow presents a significant downward trend in summer ($\beta < 0$) with a changing rate of –1.97 m^3/s per decade, and a upward trend in autumn ($\beta > 0$) with a changing rate of 0.868 m^3/s per decade at 0.05 level. However, the streamflow changes in other seasons are less obvious. The streamfow decrease in summer is the most important contribution to the annual streamflow change.

Table 3 Results of trend test for streamflow

	b ((m³/s)/10yr)	Z_c	H_0	β
Annual	–0.405	–0.575	Accept	–0.046
Spring	–0.703	–0.857	Accept	–0.027
Summer	–1.970	–2.007*	Reject	–0.354
Autumn	0.868	1.983*	Reject	0.137
Winter	0.115	1.167	Accept	0.119

Note: * Significant at 0.05 level

4 Conclusions

The impacts of climate change on the streamflow has been addressed and analyzed in this study. Future climate change scenarios have been derived by SDSM3.1 which was used to downscale the GCM (HadCM3) outputs. The monthly streamflows are simulated and analyzed by coupling with GCM output and a physically process-based, distributed hydrologic model (SWAT).

The SWAT model was successfully calibrated and validated in the Dongliao River Watershed located in Jilin Province. The statistical evaluations for streamflow showed that the E_{NS} and R^2 values were 0.715 and 0.776 in validation, which reveal that the performance and feasibility of the SWAT model for prediction of streamflow in the study area are soundly guaranteed. The SDSM, calibrated and validated using the NCEP reanalysis data sets and observed data, can well downscale GCM (HadCM3) output to generate climate change from 2010 to 2099. The projected daily temperature shows a significant increase trend, while annual precipitation shows a slightly decreasing trend. A substantial decrease of precipitation in summer may make the largest contribution to the decrease in annual precipitation. The hydrologic impact analysis made with the downscaled precipitation and temperature time series as input to the SWAT model suggest an overall decreasing trend in annual streamflow, with a decreasing rate of 0.405 m^3/s per decade, except for a significant upward trend in autumn. The decreasing rate of streamflow in summer is up to a value of 1.97 m^3/s per decade, which may primarily contribute to the decrease of streamflow in this region.

The SWAT model produced good simulation results, and the calibrated model can be used for further analysis of the impacts of climate change and other different management scenarios on streamflow in the study area. The results of this study will provide a theoretical basis for local water management authorities to make scientific and rational control measures and response plans, and also will be of great benefit to the design of social and economic development planning in the study area.

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