to be most affected by climate change are in developing nations, where availability of rainfall data is not as widespread as it is in the United States. This methodology, coupled with GCM predictions, could be used to evaluate precipitation trends in areas most vulnerable to climate change impacts. As computing power grows and our understanding of the climate is further refined, the use of regional atmospheric models to recognize trends and predict future behavior will be extremely useful in anticipating the effects of climate change.

Many avenues exist for further analysis using the reconstructed data generated by this study. Because WRF output is spatially distributed, the coupling of a hydrologic model to route historical precipitation through SDW would provide insights into historical streamflow. The reconstruction of a long-term streamflow record in SDW could yield validation of other streamflow datasets and insights into historical flooding in northern California. Another way to further the results of this study is the coupling of historical precipitation trends with future projections. This work could involve the execution of similar methodology over SDW in a future period using GCM future projection data as input to the WRF model and analysis of trends in future precipitation behavior. The historical trends found in the current study could be coupled with future trends to examine if the pattern of increased precipitation seen in this study continues, and to validate the trends seen in projections with more certain historical data.

References

Bougeault, P., and Lacarrere, P. (1989). “Parameterization of Orography-Induced Turbulence in a Mesobeta--Scale Model.” *Monthly Weather Review*, 117(8), 1872–1890.

Chou, M., and Suarez, M. J. (1999). *A Solar Radiation Parameterization for Atmospheric Studies*.

Compo, G. P., Whitaker, J. S., Sardeshmukh, P. D., Matsui, N., Allan, R. J., Yin, X., Gleason, B. E., Vose, R. S., Rutledge, G., Bessemoulin, P., Brönnimann, S., Brunet, M., Crouthamel, R. I., Grant, A. N., Groisman, P. Y., Jones, P. D., Kruk, M. C., Kruger, A. C., Marshall, G. J., Maugeri, M., Mok, H. Y., Nordli, Ø., Ross, T. F., Trigo, R. M., Wang, X. L., Woodruff, S. D., and Worley, S. J. (2011). “The Twentieth Century Reanalysis Project.” *Quarterly Journal of the Royal Meteorological Society*, 137(654), 1–28.

Daly, C., Halbleib, M., Smith, J. I., Gibson, W. P., Doggett, M. K., Taylor, G. H., Curtis, J., and Pasteris, P. P. (2008). “Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States.” *International Journal of Climatology*, 28(15), 2031–2064.

Dore, M. H. I. (2005). “Climate change and changes in global precipitation patterns: What do we know?” *Environment International*, 31(8), 1167–1181.

Groisman, P. Y., Knight, R. W., Easterling, D. R., Karl, T. R., Hegerl, G. C., and Razuvaev, V. N. (2005). “Trends in Intense Precipitation in the Climate Record.” *Journal of Climate*, 18(9), 1326–1350.

Han, J., and Pan, H.-L. (2011). "Revision of Convection and Vertical Diffusion Schemes in the NCEP Global Forecast System." *Weather and Forecasting*, 26(4), 520–533.

Karl, T. R., and Knight, R. W. (1998). "Secular Trends of Precipitation Amount, Frequency, and Intensity in the United States." *Bulletin of the American Meteorological Society*, 79(2), 231–241.

Kiely, G. (1999). "Climate change in Ireland from precipitation and streamflow observations." *Advances in Water Resources*, 23(2), 141–151.

Kunkel, K. E., Karl, T. R., Brooks, H., Kossin, J., Lawrimore, J. H., Arndt, D., Bosart, L., Changnon, D., Cutter, S. L., Doesken, N., Emanuel, K., Groisman, P. Y., Katz, R. W., Knutson, T., O'Brien, J., Paciorek, C. J., Peterson, T. C., Redmond, K., Robinson, D., Trapp, J., Vose, R., Weaver, S., Wehner, M., Wolter, K., and Wuebbles, D. (2013). "Monitoring and Understanding Trends in Extreme Storms: State of Knowledge." *Bulletin of the American Meteorological Society*, 94(4), 499–514.

Lin, Y., and Colle, B. a. (2011). "A New Bulk Microphysical Scheme That Includes Riming Intensity and Temperature-Dependent Ice Characteristics." *Monthly Weather Review*, 139(3), 1013–1035.

Niu, G. Y., Yang, Z. L., Mitchell, K. E., Chen, F., Ek, M. B., Barlage, M., Kumar, A., Manning, K., Niyogi, D., Rosero, E., Tewari, M., and Xia, Y. (2011). "The community Noah land surface model with multiparameterization options (Noah-MP): 1. Model description and evaluation with local-scale measurements." *Journal of Geophysical Research Atmospheres*, 116(12), 1–19.

O'Gorman, P. A. (2015). "Precipitation Extremes Under Climate Change." *Current Climate Change Reports*, 1(2), 49–59.

Saidi, H., Ciampittiello, M., Dresti, C., and Ghiglieri, G. (2013). "The climatic characteristics of extreme precipitations for short-term intervals in the watershed of Lake Maggiore." *Theoretical and Applied Climatology*, 113(1–2), 1–15.

Schär, C., Ban, N., Fischer, E. M., Rajczak, J., Schmidli, J., Frei, C., Giorgi, F., Karl, T. R., Kendon, E. J., Tank, A. M. G. K., O'Gorman, P. A., Sillmann, J., Zhang, X., and Zwiers, F. W. (2016). "Percentile indices for assessing changes in heavy precipitation events." *Climatic Change*, Climatic Change, 137(1–2), 201–216.

Skamarock, W. C., Klemp, J. B., Dudhi, J., Gill, D. O., Barker, D. M., Duda, M. G., Huang, X.-Y., Wang, W., and Powers, J. G. (2008). "A Description of the Advanced Research WRF Version 3." *Technical Report*, (June), 113.

Trinh, T., Ishida, K., Fischer, I., Jang, S., Darama, Y., Nosacka, J., Brown, K., and Kavvas, M. L. (2016). "New Methodology to Develop Future Flood Frequency under Changing Climate by Means of Physically Based Numerical Atmospheric-Hydrologic Modeling." *Journal of Hydrologic Engineering*, 21(4), 4016001.

Zhu, Y., and Newell, R. E. (1998). "A Proposed Algorithm for Moisture Fluxes from Atmospheric Rivers." *Monthly Weather Review*, 126(3), 725–735.

Streamflow Pattern Variations Resulting from Future Climate Change in Middle Tianshan Mountains Region in China

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Abstract

In arid and semi-arid regions of North West china, glacier-melt, seasonal snowmelt and rainfall are the primary sources of flow in the rivers that originate from alpine areas. Spring and summer peak flow resulting from snowmelt and rainfall, respectively, are the main characteristics of streamflow pattern. Because of the damages caused by the spring and summer peak flow, a better understanding of the streamflow pattern variation under future climate warming is crucial. To analyze the variation of streamflow pattern under climate warming, the Kaidu River and the Manasi River watersheds in northern and southern slopes of Middle Tianshan Mountains, located in Xinjiang were selected as study areas. These watersheds receive water from water sources in different proportions. A modified hydrological model was forced with metrological data from CIMP5 data set and the streamflow in Kaidu and Manasi River watersheds were simulated. The results indicate that one-peak-flow pattern is projected to turn to the two-peak-flow pattern in the Manasi River watershed in the future. The two-peak flow pattern will continue in the Kaidu River watershed, but the dominant peak flow will shift from summer to spring in future. This study provides useful information for water resources managers to take different actions to reduce damages caused by spring and summer peak flow under future climate warming.

INTRODUCTION

Alpine area is the source of rivers in arid and semi-arid regions of China. Glacier melt water, seasonal snow melt water, rainfall, and groundwater are the main water sources for streamflow in alpine areas (Ji and Luo 2013; Xu et al. 2008; Yang and Cui 2005). The contributions of these water sources shape the seasonal distribution of annual streamflow (Zhang et al. 2016a) and influence the streamflow patterns. The changes in streamflow pattern such as spring peak flow and summer peak flow have implications for flood and water management (Forsee and Ahmad, 2011). Temperature and precipitation are two sensitive factors in influencing the contribution of different water sources to streamflow in alpine areas (Zhang et al. 2016a). Precipitation taking place as rainfall contributes to the streamflow directly; while that taking place as snowfall accumulates as snowpack (Zhang et al. 2014). Temperature influences the contributing time of glacier/snowpack-melt-water to streamflow (Kuusisto 1984; Kalra et al. 2013a). Under climate warming, a variation of temperature and precipitation may alter the pattern of streamflow (Dawadi and Ahmad 2012). In order to prevent the flood damages (Ahmad and Simonovic, 2001, 2006; Mosquera-Machado and Ahmad 2007) and better manage the water resources (Ahmad and Prashar 2010; Wu et al., 2013; Qaiser et al., 2011,2013; Dawadi and Ahmad 2013), understanding of the variation of streamflow pattern in the future is necessary. Several researchers have evaluated the changes in stream flow in response to climate variability (Pathak et al. 2016a and b; Tamaddun et al. 2016a and b; Sagarika et al. 2014, 2015a and b; Kalra et al. 2013 b and c).

Middle Tianshan Mountains (42° N to 44° 30′ N and 82° E to 86° 30′ E) is the origination location of some large rivers in Xinjiang. Two rivers originate from Middle Tianshan Mountains: the Kaidu River in southern slope and the Manasi River in northern slope (Figure1). Obstructed by the mountain, the flow of air moisture that forms precipitation in northern and southern slopes is different. The annual precipitation is about 450 mm in northern slope as the windward slope, while less than 200 mm in southern slope as the leeward slope (Zhao et al. 2011). Meanwhile, the annual glacier melt-water accounts for 14.1% in southern slope (Shi 2014) while that accounts for 34.6% in northern slope (Zhang et al. 2009). The contributions of different water sources to streamflow lead to different streamflow pattern in northern and southern slopes of Middle Tianshan Mountains. The Kaidu River have spring peak flow caused by seasonal snowmelt water and summer peak flow caused by heavy rainfall (Zhang et al. 2014; Zhang et al. 2016a), while the Manasi River only has summer peak flow caused by heavy rainfall and glacier-melt-water (Zhang et al. 2016a).

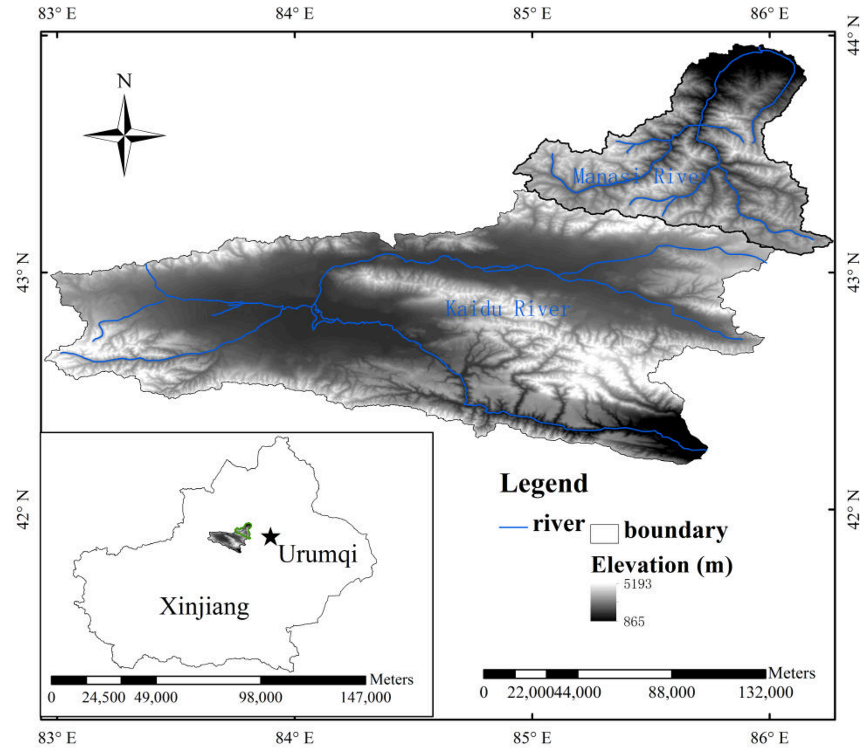

Figure 1. Location of the Kaidu River (lower) watershed and the Manasi River (upper) watershed.

In Middle Tianshan Mountains, the meteorologic and hydrologic stations are scarce with a short historical observation record in alpine regions. There is only one meteorological station – Bayinbuluk station (2458 m above the sea level) and one hydrological station – Dashankou station (1400 m above the sea level) with long historical data in the Kaidu River watershed; while one meteorological and hydrological station at Kensiwate (885 m above the sea level) with long historical data above the mountain pass in the Manasi River watershed. The shortage of data brings difficulties in studying hydrological process and streamflow pattern variation. Various hydrological models have been used to analyze the runoff process in Middle Tianshan Mountains. Recently, SRM and its different modified versions (Dou et al. 2011; Yu et al. 2013; Li et al. 2014), SWAT (Yu et al. 2011; Ji and Luo 2013), HVB-ETH (Yang et al. 2012), Digital filtering method (Li et al. 2012; Fan et al. 2013) and System dynamics model (Zhang et al. 2016a,b) have been used to simulate the streamflow in Middle Tianshan Mountains. However, these studies mostly focused on streamflow simulation, rarely considering the variation of streamflow pattern in the future in response to climate change. In order to analyze the variation of streamflow patterns in northern and southern slopes of Middle Tianshan Mountains in the future, a modified hydrological model was used to simulate the streamflow and to evaluate the streamflow pattern in the Kaidu River and Manasi River watersheds.

METHODOLOGY AND DATA

A modified SDHydro model (Zhang et al. 2016b) was used to simulate the runoff in both southern and northern slopes of Middle Tianshan Mountains. The model was developed using five tanks: snow storage, canopy interception storage, surface soil water storage, subsurface soil water storage and groundwater storage (Li and Simonovic 2002). The modifications include snowmelt rate estimation and water infiltration and percolation rate simulation (Zhang et al. 2016b). Using the modified SDHydro model, Zhang et al. (2016a & b) simulated the streamflow in the Kaidu and Manasi River watersheds and concluded that modified SDHydro model can simulate the streamflow reasonably well. In order to analyze the variation of streamflow pattern in the future, the same model with the same parameter set was used to project the streamflow in both watersheds.

Climatic data from Coupled Model Intercomparison Project Phase 5 (CMIP5) models were used to simulate the runoff in both watersheds. Correlation coefficients and slope coefficients between observed and different CMIP5 models' historical climatic data were used as criteria to assess CMIP5 models' applicability in the study area. CanESM and BNU-ESM were selected for this study according to the criteria combined with the data availability for downloading. Three scenarios (Representative Concentration Pathway 2.6 (RCP 2.6); 4.5 (RCP 4.5) and 8.5 (RCP 8.5)) for CanESM and BNU-ESM were used in this study to generate climatic data and estimate the changes in annual and seasonal runoffs in the Kaidu River and Manasi River watersheds in the future i.e., from 2006 to 2100. The spatial resolution of both models is 2.8125°×2.8125°. The future temperature and precipitation datasets in the Kaidu River and Manasi River watersheds were interpolated using the nearest-neighbor interpolation method. The future runoff in both watersheds was projected by using temperature and precipitation from CanESM and BNU-ESM as the inputs to the modified SDHydro model.

RESULTS AND DISCUSSION

Using the modified SDHydro model, the streamflow in the future has been simulated from 2006 to 2100. The projected annual runoff, spring runoff, and summer runoff are shown in Figure 2, Figure 3 and Figure 4, respectively to reflect the patterns of the streamflow.

The volume of the annual runoff in the Kaidu River was approximately three times greater than that in the Manasi River (Figure 2). The variation trend of the future annual runoff in both watersheds was analyzed using the Mann-Kendall method. The runoff have a significant increasing trend ($p<0.05$) under scenario RCP 2.6, RCP 4.5 and RCP 8.5 of CanESM in the Kaidu River watershed. The annual runoff in the Manasi River watershed have a significant increasing trend ($p<0.05$) only under scenario RCP 2.6, but no significant trends were detected under scenario RCP 4.5 and RCP 8.5 of CanESM. For BNU-ESM model, the runoff under all scenarios in the Kaidu River watershed have no significant trend. The annual runoff in the Manasi River watershed have a significant decreasing trend ($p < 0.05$) under scenario RCP 8.5, but no significant trends were detected under scenario RCP 2.6 and RCP 4.5.

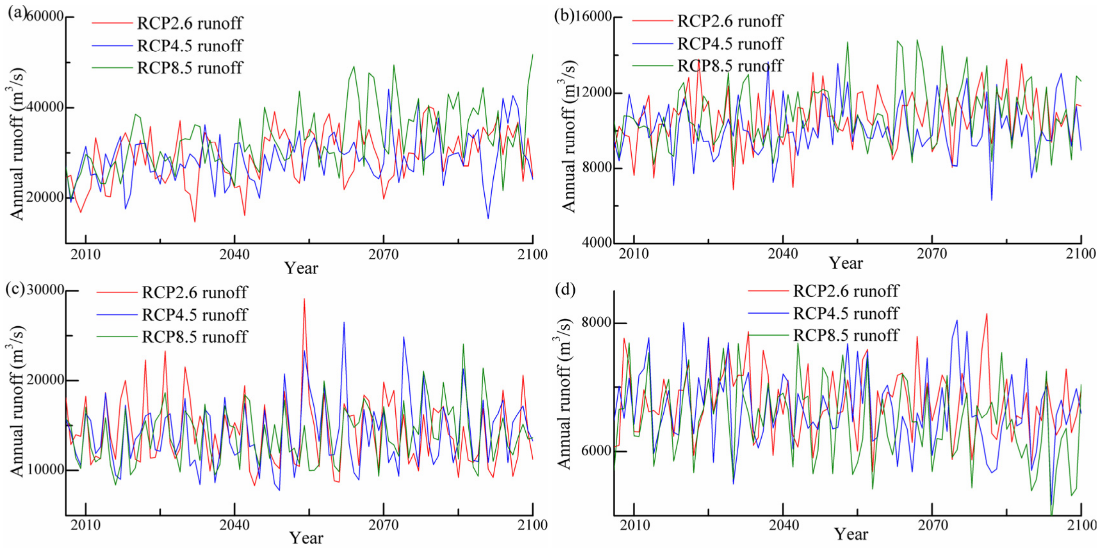

Figure 2. Variation of annual runoff in the Kaidu River under CanESM (a) and BNU-ESM (c) and in the Manasi River under CanESM (b) and BNU-ESM (d) in the future.

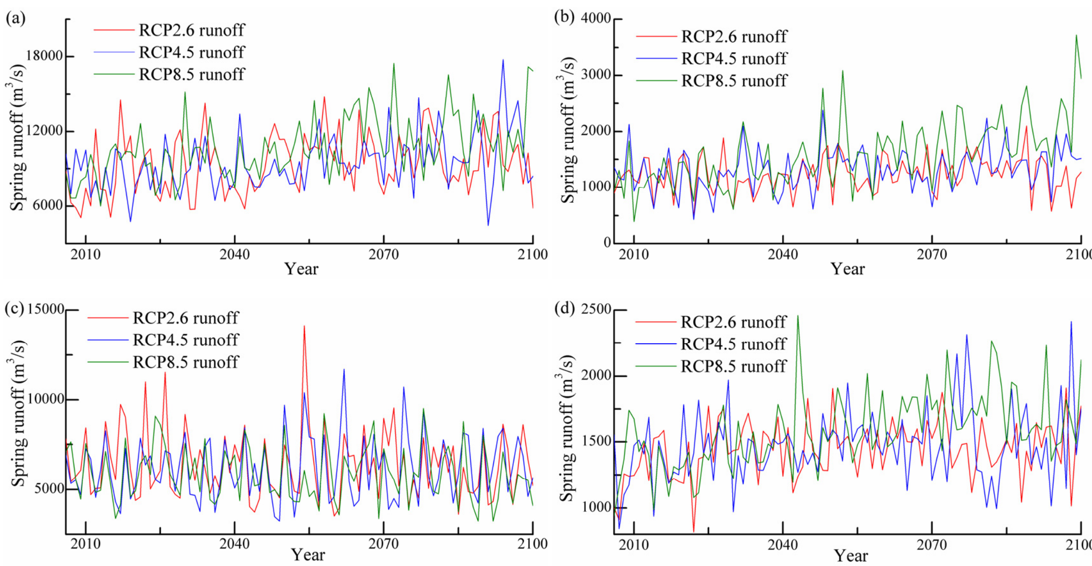

Figure 3. Variation of spring runoff (from March to May) in the Kaidu River under CanESM (a) and BNU-ESM (c) and in the Manasi River under CanESM (b) and BNU-ESM (d).

The volume of the spring runoff in the Kaidu River was about 5 times greater than that in the Manasi River (Figure. 3). The spring runoff accounted for about 42% of annual runoff in the Kaidu River watershed, but only about 27% in the Manasi River watershed. For CanESM model, spring runoff experienced a significant increasing trend ($p < 0.05$) in the Kaidu River watershed in the future for RCP 2.6, RCP 4.5 and RCP 8.5 scenarios. In the Manasi River watershed, a significant increasing trend was noted for spring runoff ($p < 0.05$) under scenario RCP 4.5 and

RCP 8.5, but no significant trend was noted under scenario RCP 2.6. For BNU-ESM model, no significant trends were detected in the Kaidu River under scenario RCP 2.6, RCP 4.5 and RCP 8.5. However, a significant increasing trend ($p<0.05$) was noted in the Manasi River under scenario RCP 2.6 and RCP 8.5, but there was no significant trend under scenario RCP 4.5.

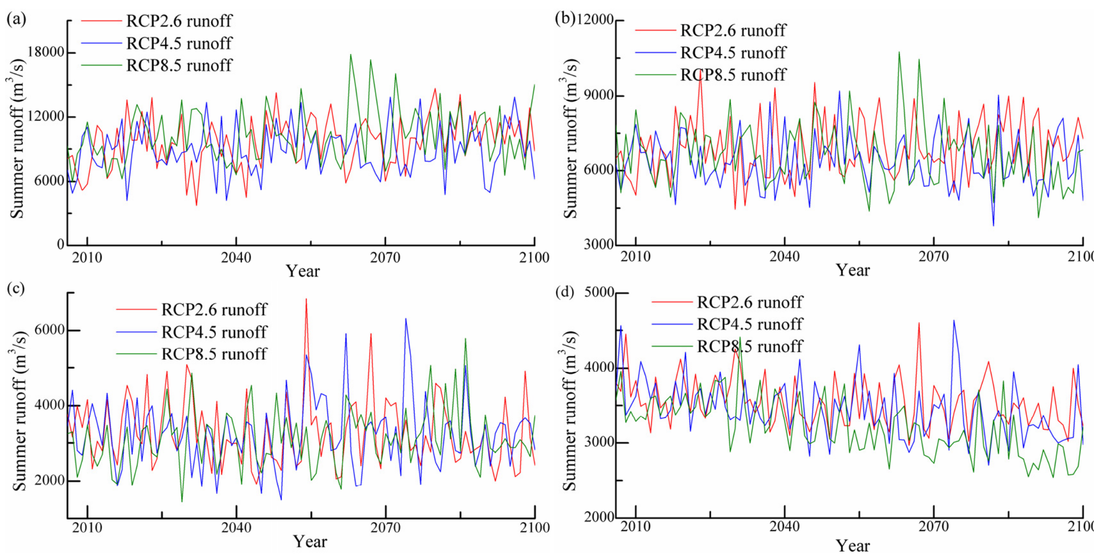

Figure 4. Variation of summer runoff (from June to August) in the Kaidu River under CanESM (a) and BNU-ESM (c) and in the Manasi River under CanESM (b) and BNU-ESM (d).

The volume of summer runoff in the Kaidu River was about 1.45 times greater than that in the Manasi River, as illustrated in Figure. 4. The summer runoff accounts for approximately 30% of annual runoff in the Kaidu River, while about 64% in the Manasi River. For CanESM model, summer runoff experienced a significant increasing trend ($p<0.05$) in the Kaidu River in the future for RCP 2.6, RCP 4.5 and RCP 8.5 scenarios. In the Manasi River, a significant increasing trend ($p<0.05$) was noted for summer runoff under RCP 2.6, but a significant decreasing trend was noted under RCP 4.5 and RCP 8.5 scenarios. For BNU-ESM model, summer runoff in the Kaidu River experienced a decreasing trend under RCP 2.6 and increasing trend under scenarios RCP 8.5. However, no significant trend was detected under scenario RCP 4.5. In the Manasi River, summer runoff had a significant decreasing trends ($p<0.05$) under scenarios of RCP 2.6, RCP 4.5 and RCP 8.5.

Variations of projected annual runoff, spring runoff and summer runoff under CanESM and BNU-ESM models in the future were different in the Kaidu River and the Manasi River. For Kaidu river, annual stream flow was increasing under all scenarios for CanESM model. However there were no trends for BNU-ESM model. Overall, no significant trends were detected in future annual runoff in Manasi River for both models. Spring runoff showed a significant increasing trend in the Kaidu River for all scenarios of CanESM model and no significant trends for BNU-ESM model. Spring runoff showed a significant increasing trend in the Manasi River for both models. The future summer runoff showed a significant increasing trend for Kaidu River for

CanESM model but no significant trends for BNU-ESM model. The trend in spring runoff is similar to that of the summer runoff in the Kaidu river for CanESM model. The future summer runoff showed a significant decreasing trend in the Manasi River for both models.

The changes of spring and summer runoff can better reflect the changes in spring and summer peak flow. In the Kaidu River watershed, increased spring runoff and summer runoff may cause serious damages if a flood happens in the future. The magnitude of spring runoff and summer runoff in the future indicated that the two-peak-flow pattern will continue in the Kaidu River watershed. However, the dominance of the summer peak flow will be replaced by the spring peak flow in the future. In the Manasi River watershed, annual runoff has no significant change, but spring runoff has increasing trend while summer runoff has decreasing trend. The change in the runoff distribution within a year indicates the one-peak-flow pattern of the runoff in the Manasi River watershed will shift to two-peak flow pattern in the future. Under climate warming, glacier shrinks the predominant position of glacier-melt-water and rainfall contributing to a runoff in the Manasi River will be replaced by seasonal snowmelt water and rainfall as that in the Kaidu River watershed.

CONCLUSION

Rivers in an alpine area receive water from different sources, i.e., glacier melt , seasonal snowmelt , rainfall, and groundwater. The different contribution rate of water sources influences the pattern of streamflow. Spring peak flow influenced by snowmelt water combined with summer peak flow determined by heavy rainfall is the main characters of streamflow pattern. Damages caused by the spring and summer peak flow made the research of the streamflow pattern variation crucial under climate warming. In order to analyze the variation of streamflow pattern, especially the variation of spring and summer peak flow in northern and southern slopes of Middle Tianshan Mountains in the future, a modified SDHydro model was selected to simulate the streamflow. The Kaidu River in southern slopes and the Manasi River in northern slope were chosen as the study area. Climatic datasets from CanESM and BNU-ESM of CMIP5 were used as the inputs of the modified SDHydro model.

Under climate warming in the future, the one-peak-flow pattern in northern slope watershed will turn into the two-peak-flow pattern while the two-peak-flow pattern will remain in southern slopes watershed. The dominant position of the summer peak flow will be replaced by the spring peak flow in the southern slope of Middle Tianshan Mountains. The changing intra-annual runoff pattern in northern and southern slopes of Middle Tianshan Mountains provides useful information to water resource managers for water allocation and management in the future.

Precipitation is the main contributor to streamflow. The intra-annual variation of precipitation greatly influences the streamflow pattern. However, interannual and intra-annual variations of precipitation are diverse under different CMIP5 models, which may primarily influence the variation of simulated streamflow. More CMIP5 models should be used in the analysis to better understand the influence of different CMIP5 models on streamflow.

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REFERENCES

Ahmad, S., & Simonovic, S. P. (2001). “Integration of heuristic knowledge with analytical tools for the selection of flood damage reduction measures”. Canadian Journal of Civil Engineering, 28(2), 208-221.

Ahmad, S., & Prashar, D., (2010). "Evaluating Municipal Water Conservation Policies Using a Dynamic Simulation Model." *Water Resources Management, 24*(13), 3371-3395.

Ahmad, S., Simonovic, S.P., (2006). "An intelligent decision support system for management of floods." *Water Resources Management, 20* (3), 391-410.

Carrier, C., Kalra, A., & Ahmad, S. (2013). “Using Paleo Reconstructions to Improve Streamflow Forecast Lead Time in the Western United States.” *Journal of the American Water Resources Association*, 49(6), 1351–1366. doi:10.1111/jawr.12088.

Dawadi, S., & Ahmad, S. (2012). “Changing climatic conditions in the Colorado River Basin: Implications for water resources management.” *Journal of Hydrology,* 430-431, 127-141. doi:10.1016/j.jhydrol.2012.02.010.

Dawadi, S., & Ahmad, S. (2013). “Evaluating the impact of demand-side management on water resources under changing climatic conditions and increasing population.” *Journal of Environmental Management*, 114, 261–75. doi:10.1016/j.jenvman.2012.10.015.

Forsee, W., and Ahmad, S. (2011). “Evaluating urban stormwater infrastructure design in response to projected climate change.” ASCE J. Hydrologic Eng. 16, 865–873. doi:10.1061/(ASCE)HE.1943-5584.0000383.

Dou, Y., Chen, X., Bao, A., & Li, L. (2011). “The simulation of snowmelt runoff in the ungauged Kaidu River Basin of Tianshan Mountains, China.” *Environmental Earth Sciences*, 62(5):1039–1045. doi:10.1007/s12665-010-0592-5.

Fan, Y., Chen, Y., & Liu, Y. (2013). “Variation of baseflows in the headstreams of the Tarim River Basin during 1960–2007.” *Journal of Hydrology*, 487: 98-108.

Ji, X., Luo, Y. (2013). “The influence of precipitation and temperature input schemes on hydrological simulations of a snow and glacier melt dominated basin in Northwest China.” *Hydrology and Earth System Sciences Discussions*, 10(1): 807-853. doi:10.5194/hessd-10-807-2013.

Kalra, A., Ahmad, S., & Nayak, A. (2013a). “Increasing streamflow forecast lead time for snowmelt-driven catchment based on large-scale climate patterns.” *Advances in Water Resources*, 53: 150-162. doi: 10.1016/j.advwatres.2012.11.003.

Kalra, A., Miller, W. P., Lamb, K. W., Ahmad, S., & Piechota, T. (2013b). “Using large-scale climatic patterns for improving long lead time streamflow forecasts for Gunnison and San Juan River Basins.” *Hydrological Processes*, 27(11), 1543–1559. doi:10.1002/hyp.9236.

Kalra, A., Ahmad, S., & Nayak, A. (2013c). “Increasing streamflow forecast lead time for snowmelt-driven catchment based on large-scale climate patterns.” *Advances in Water Resources*, 53, 150–162. doi:10.1016/j.advwatres.2012.11.003