Study on impacts of climate change on water resources in Songhua River Basin

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Abstract Climate change intensively impacts the hydrological circulation mainly through global warming, changes of precipitation and global atmospheric circulation. However, climate change induces frequenter meteorological and hydrologic extreme events and larger changes of mean annual runoff, quantity and distribution of water resources in a basin. Meanwhile, it results in the changes of climate response mechanisms of agricultural, industrial and domestic water demand. Therefore, climate change may aggravate the water problems and crisis in many basins. This paper quantificationally analyses the impacts of climate change on mean annual runoff, quantity and distribution of water resources and water demand in Songhua River Basin, a large-scale basin in Northeast of China. A physics-based, distributed hydrological model, WEP-L, which couples simulations of natural hydrological processes and water use processes, is developed for the purpose. Hypothetical climate change scenarios are created with the trends of precipitation and temperature data of 21 years (1980~2000). Based on the statistical relation between meteorological elements and each kind of water demands, conditions of water use under each climate change scenarios are estimated. After the WEP-L model verified by comparing simulated and observed discharges of 21years (1980~2000) at main stations, continuous simulation results of 21 years and model results under each scenario are compared for quantificationally analyzing the impacts on water resources in the basin.

Keywords climate change; water resource; water demand; Songhua River Basin

INTRODUCTION AND BACKROUND

Impacts of climate change on hydrological cycle and water resources

Because the hydrosphere is one of the important parts of the climatic system, climate change which mainly results from global warming will significantly affect the condition of hydrological cycle, which will lead to the change of water resource. There are a lot of direct evidences of global warming existing, which include that in the past 100 years, global temperature has raised 1℃, that the global even sea level has been rising during the recent 100 years, and that the area of snow is decreasing. Although, there are so many debates on the impacts of climate change on global hydrological circulation, the impacts of it on the regional hydrological circulation are very significant, for instance, the precipitation of some regional places including the east of Northern and Southern America, the north of Europe and the middle and the north of Asia have been increasing, in contrast, the precipitation of some places where are located at Sahara, Mediterranean Sea, the south of Africa and the south of Asia have been decreasing. Additionally, since climate change, the fluctuation of extreme events of climate and weather, which can be definited as that the events of weather or climate strongly departure their normal states, such as, draught, inundation, extremely high and low temperature, have had a significant current of augmenter. As one of extreme events, draught widely exists, especially in the Northeast of China, Far East of Russia and Africa.

Studies on impacts of climate change on hydrological circulation and water resources have been getting great developments during the past 20 years since the emergence of distributed watershed hydrological models; because that distributed hydrological model is based on the dynamic mechanism of hydrological circulation and this kind of model can simulate the temporal and special variability of one watershed. Kite (1999) applied distributed hydrological model which coupled with the regional climate model to study the response of climate change on runoff. Michael A.R (2006) researched the impact of climate change on water resources of Pan-Arctic region in Canada, and according to the research, the water resources of this region very sense to the climate change. Mark D. T (2009) applied eco-hydrological model combined a simple relation between rain and unsatisfied evaporative demand to study the climate change effects on watershed hydrology in the US Midwest, and based on his study, the effects in this region is very significant.

Generally speaking, the impacts of climate change on hydrological circulation and water resources, to some extent, and to some regions, are very great, even fatal in some regions. The distributed hydrological model is of very importance to the study on impacts of climate change on the hydrological circulation and water resources of one region, based on the advantages of distributed hydrological model as said upwards. Thus, a distributed hydrological model for large basins, WEP-L, is developed and applied for research of hydrological circulation and assessment of water resources in Songhua River Basins in this study.

Impacts of climate change on water demand

Climate change, such as temperature change, precipitation change and so on, to some extent influences the water demand of agriculture, industry and domestic needs. Generally speaking, the water demand includes social economic water demand, which can be divided into agricultural, industrial and domestic water demand, and ecological water demand. Climate change mainly including the variety of temperature and precipitation influence the water demand of those different styles, for instance, the increased temperature will results to the augment of agricultural water demand, since increased temperature lead to more evaporation. In this study, based on former people’s studies of impacts of climate change on water demand, the integrated method of estimating the impacts of climate change on water demand will be laid out.

WEP-L MODEL AND CLIMATE CHANGE

Distributed Hydrological Model WEP-L

The WEP-L model, which based on water and energy transfer processes (WEP) model that was developed by combing the merits of PBSD models and SVAT models, has been successfully applied in several watersheds in China under diversity climate and geographic conditions. The main advantages of the WEP model are that as follow state: (1) coupling models of hydrology and energy transfer, (2) taking the diversity of land use in each calculation unit into account, (3) incorporation of various generation theory of runoff. The WEP-L model inherits these advantages of WEP, and improves in follow aspects to make the model more applicable to large basins: (1) using the contour bands inside small subwatersheds, rather than grid of cells, as the computation units, (2) further dividing the soil vegetation land use group into three groups of soil vegetation, irrigated farm land and unirrigated farm land, (3) applying a snow melt model based on the temperature-index approach.

The vertical structure of WEP-L within a contour band which also is the calculational unit of the model includes, from top to bottom, interception layer, depression layer, top soil layer, medial soil layer, bottom soil layer, unconfined aquifer, aquitard and confined aquifer. On the horizontal direction, the land use is divided into five groups within a calculational unit: Soli-Vegetation group which consisting of bare soil land, tall vegetation and short vegetation; Non-irrigated Farmland group; Irrigated Farmland group; Water Body group and Imperious Area group which including imperious urban cover, urban canopy and rocky mountain. The basic simulative processes of the model shows as Tab.1

Tab 1 Basic Simulative Processes of WEP-L Model

Hydrology Elements	Simulation process
Evaporation	Penman Model and Penman-Monteith Model
Infiltration	Green-Ampt Equation; Richards model (in unsaturated soil area)
Surface Runoff	Horton Model and Richard Equation
Subsurface runoff	Green-Ampt Equation
Groundwater flow	BOUSINESSQ Equation and Darcy Law
River flow	Kinematic Wave Method or the Dynamic Wave Method
Over land flow	Kinematic Wave Method
Snow	Temperature-index Approach

Climate Change Scenes

There are two methods to set climate change scene in a general way. The first one is increment scene method, which means that based on the probable change of climate, artificially set the climate change scenes, such as properly increasing the temperature, precipitation, or both; the second one is the climate change scenes based on the GCM (Global Climate Model). The latter method has many virtues in predicting, but it also has many uncertainty including amount of dioxide emited in future, the response of the climate system and the diversity of nature (Yangwen Jia, 2008). Especially in some regional the results from different GCM vary greatly and indeed are conflicting in the precipitation prediction, even though adapt the same dioxide scene. Thus, the first scene method will be applied to the study, and eight scenes of precipitation and temperature are adapted to the model.

THE STUDY CASE

Introduction to the Songhua river basin

Songhua River basin located in Northeastern China where there are many important bases of truck agriculture of China. The Songhua River is an anabranch of Heilong River which is as Borderline River between China and Russia. Map of the Songhua River basin is shown in Fig.1. The area of the basin is 56.12 km^2. There are two headstreams of the Songhua River: one headstream is the Nen River which is running from Daxingan Mountain located in northwest of the basin, and whose length is 1370 km; the another one is the Ersong River which is derived from Changbai Mountain located in the southeast of the basin, and its length is 905 km. The Nen River and

Ersong River converge together to Songhua River at Sanchakou; the riverway after Sanchakou is the trunk of the river, and its length is 939 km.

Fig. 1 Basic information of Songhua River Basin.

Data and analysis

Tab.2 shows a list of the collected basic data on which the WEP-L input data are based. The data include five classifications as follow: (1) hydro-meteorology; (2) land cover information; (3) DEM, soil and hydrogeology; (4) river networks, river sections and hydraulic structures; and (5) water use and social-economy information. The meteorology data of key national meteorological stations with items of rain/snow, wind speed, air temperature, sunshine hour and humidity are obtained from the National Climate Bureau of China (NCBC). Most of the daily rain/snow data and the monthly runoff data are achieved from the Songhua River & Liao River Water Conservancy Commission (SLRWCC). Land cover information of two periods (1990s, 2000s) is gained from Department of Geography, Chinese Academy of Science (DG, CAS).

Tab 2 List of collected basic data on which the model input based.

Classification	Item	Content
Meteorological and hydrology	Daily rain/snow	Data of 534 rain station, and 103 meteorological stations from 1956 to 2000
	Daily meteorological data	Daily data of 103 meteorological station from 1956 to 2000 (wind speed, air temperature, sunshine hour, humidity)
	Monthly runoff	Data of 10 hydrologic stations from 1956 to 2000
Land Use	Deduced land use	1:100,000 map in 1990 and 2000
Vegetation	Crop patterns	Information of 3rd level WRA districts of the Songhua River in 1980,1990 and 2000
Topography, soil,	Topography	USGS GTOPO30 (1 km by 1 km)

river and geohydrology	River network	River network map
	Soil	Soil classification maps of China
	Geohydrology	Distribution of lithology, Thickness of Aquifers and Parameters of geohydrology
Water use	Reservoir operation	Reservoir operation information of 75 reservoirs
	Water use in irrigation areas	Water use data in 5 irrigation area
	Water use in administrative areas	Monthly water use data at the county level from 1956 to 2000
Social economy	GDP	GDP of 133 overlapped areas of prefectures and the 3rd level WRA districts in 1980, 1985, 1990, 1995, 2000
	Population	Population of 133 overlapped areas of prefectures and the 3rd level WRA districts in 1980, 1985, 1990, 1995, 2000

Data preparation and input

Before running the WEP-L model, there are still five steps to carry out: (1) river network generation, basin subdivision and coding; (2) treatment of river section and reservoir data; (3) disposal of land cover information; (4) Spatial and temporal interpolation of Hydro-meteorological data; (5) Spatial and temporal interpolations of social and economic data. Considering the limits of length of this paper, particular former 4 steps will not be indicated, and this inference (Yangwen Jia, 2006) expound these steps detailedly, but the fifth steps will be recounted as follow.

Water demand and response to the climate

The water demand data including agricultural, industrial and domestic water demand were achieved by Chinese official reports which named as *Integrate Plan of China Water Resources* and C*hina Water Resources Bulletin*. Besides these official reports, these are also some particular water demand data are gained from the Songhua River & Liao River Water Conservancy Commission (SLRWCC). The water demand data display in the Tab.2. According to the spatial and temporal interpolation methods which have comparative rationality, the water demand data we collect are applied to the WEP-L model to simulate the “dualistic hydrological circulation” which means naturally hydrological circulation coupling with artificial one.

Climate change impacts water demand of this basin. According to the study in North China (Yu Xuan, 2009), the responses of the water demand to climate change show in the Tab.3, for instance, when the temperature increase 1□, the industrial water demand will raise 1.5%.

Tab 3 the linear relationship between variety water demand and climate change.

	Industrial water demand	Agricultural water demand	Domestic water demand	Ecological water demand
Temperature (+1□)	+1.5%	+6%	+1.2%	+6%
Precipitation (+1%)	No evident relationship	-1%	No evident relationship	-0.75%

Model parameter estimation

There are three categories of parameters in the WEP-L model including parameters of land surface and river channel system, parameters of vegetation and parameters of soil and aquifer. The detailed contents of every category parameter display in Tab.4. Most of parameters can be evaluated by observation and remote sensing data, and few of them will be obtained through calibration and remote sending.

Tab 4 the detailed contents of every category.

categories	contents
Land surface and river channel	Including maximum depression storage depth of land surface, permeability of riverbed material, impervious ratios of residential area and industrial area, and Manning roughness of overland and river channel
Vegetation	Including vegetation fraction, maximum interception depth, leaf area index (LAI), aerodynamic resistance, canopy resistance and root distribution parameters
Soil and aquifer	Including soil layer thickness, soil porosity, soil saturated hydraulic conductivity, soil suction at infiltration wetting front, soil moisture–suction relation curve, soil moisture–hydraulic conductivity relation curve, thickness and hydraulic conductivities of unconfined and confined aquifers, specific yield of unconfined aquifer, and storage coefficient of confined aquifer

Model verification

Through most of the parameter are achieved by observation and remote sense, but there are few of them are vitally sensitive to the results of model. Thus the few sensitive parameters will be verified to improve the model results. Continuous simulation of 21 years (1980-2000) with the time step of one day, and 10 years (1991-2000) of which is selected as calibration period, is completed by this study. The application of the basis of “try and error” performs the model’s calibration. Based on the sensibility of parameters, the calibration parameters include maximum depression storage depth of land surface, amendatory coefficient of depth of three soils, soil saturated hydraulic conductivity, permeability of riverbed material. The above-mentioned monthly runoff data of hydrologic stations are the basis of calibration. The calibration and verification criterions include: (1) minimizing the simulation error of annually averaged river runoff, (2) maximizing the Nash–Sutcliffe efficiency of discharges. After the model calibration, all parameter are saved constantly, continuous simulation of 21 years (1980-2000) are performed to verify the model by observed monthly discharge at 8 main gage stations in the basin. Verification results of simulated monthly discharges of 21 years at the 8 stations are shown in Tab.5. Monthly discharges of 21 years at representative stations of the basin are displayed in Fig.2. Despite some flaws, the verification results are comparatively encouraging, and the simulated discharge hydrographs comparatively match the observed ones.

Tab 5 Verification results of simulated monthly discharges of 21 years at 8 gauge stations.

Station Number	Station name	River name	Observed average discharge (billion m^3 yr^{-1})	simulated average discharge (billion m^3 yr^{-1})	Relative error (%)	Nash-Sucliffe efficiency
1	Ayanqian	Nen River	250.4	236	-5.80%	79.13%
2	Jiangqiao	Nen River	503.8	477.5	-5.20%	86.75%
3	Danan	Nen River	533.6	526.2	-1.40%	81.98%
4	Fengman Reservoir	Ersong River	278.3	270.9	-2.60%	84.08%
5	Fuyu	Ersong River	322	333.1	3.40%	78.37%
6	Haerbin	Songhua River	1007.6	968.2	-3.90%	79.89%

		(main river)				
7	Tonghe	Songhua River (main river)	1147.1	1081.9	-5.70%	77.66%
8	Jiamusi	Mudan River	1548.6	1450.4	-6.30%	78.87%

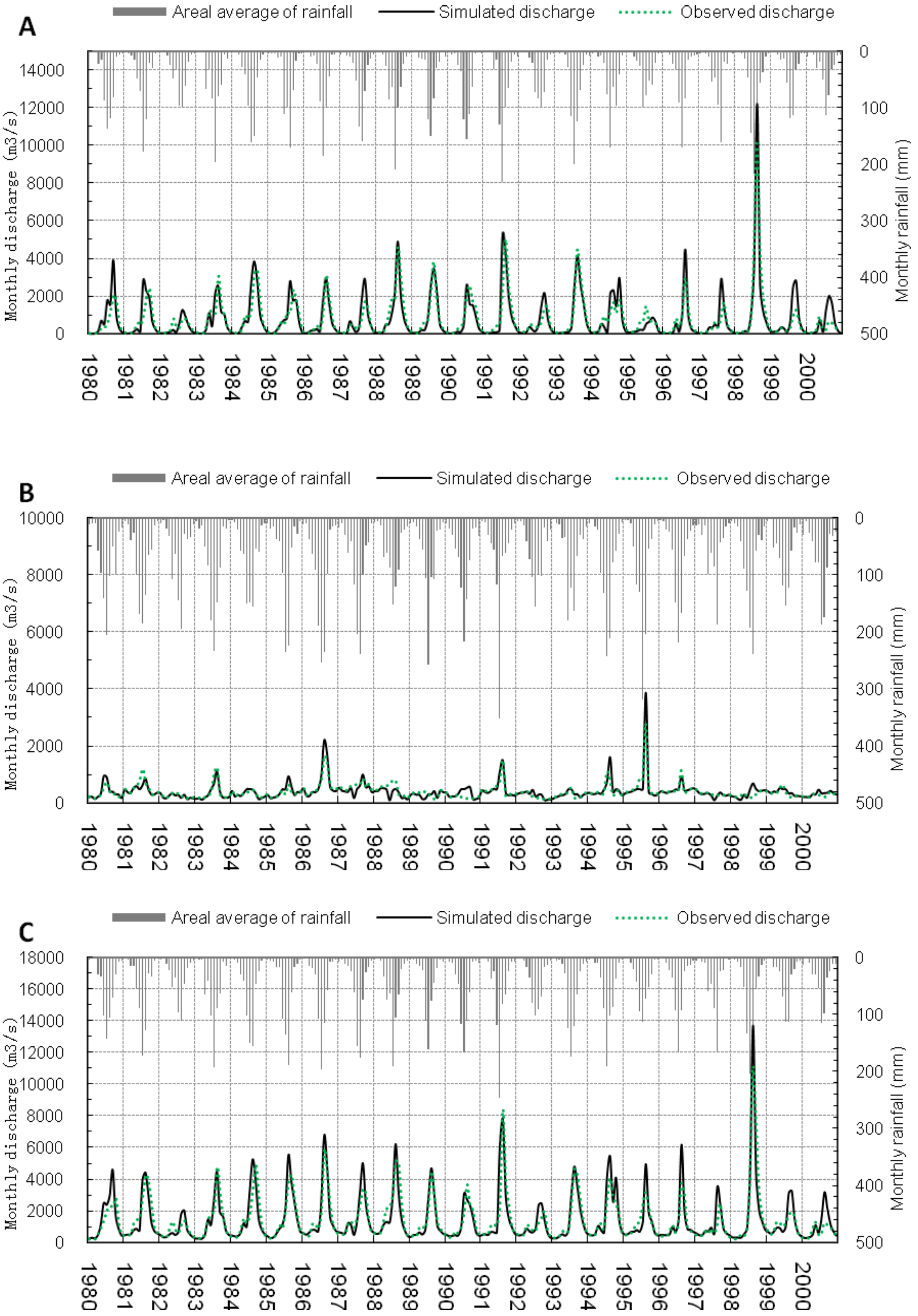

Fig 2 Verification of simulated monthly discharges at: (A) Danan station (Nen River), (B) Fengman Reservoir station (Ersong River), and (C) Haerbin station (main river).

Analysis of Response of water resources to different climate change scenes

Based on the verified distributed hydrological model of the basin Songhua River (WEP-L), keep parameters and input the eight climate change scenes to simulate the response of water resources to different climate change scenes. The eight climate change scenes and runoff variation is showed in Tab.6. Scene 1 and scene 2 are set to simulate that the temperature and precipitation both move up. The scene 1 is set to simulate the normal variation situation and the scene 2 is set to simulate the extreme situation of arising. Scene 3 and scene 4 simulate the situation that temperature and precipitation both decrease, and the scene 3 normally simulate the change, and the scene 4 extremely simulate the change. Scene 5, 6, 7 and 8 are set to simulate the situations that temperature has a reversed variety trend to that of precipitation. Scene 5 and scene 7 are normal scenes, in comparison, the scene 6 and 8 are extreme ones.

Tab 6 Response of water resources to climate change.

	Temperature	Precipitation		Runoff		evaporation		Infiltration	
	(℃)	(%)	(mm)	(mm)	(%)	(mm)	(%)	(mm)	(%)
History	0	0	536.9	99.9	0	449.5	0	226.8	0
Scene 1	1	5	563.7	103.8	3.9	465.5	3.6	234.4	3.4
Scene 2	2	10	590.6	112.6	12.7	482.8	7.4	244.1	7.6
Scene 3	-1	-5	510	87	-12.9	430	-4.3	214.4	-5.5
Scene 4	-2	-10	483.2	78.9	-21.0	411.8	-8.4	204.1	-10.0
Scene 5	1	-5	510	82.7	-17.2	440.5	-2.0	214.9	-5.2
Scene 6	2	-10	483.2	71.4	-28.5	431.3	-4.0	204.3	-9.9
Scene 7	-1	5	563.7	109.1	9.2	453.3	0.8	233	2.7
Scene 8	-2	10	590.6	124.1	24.2	456.7	1.6	240.5	6.0

According to the results, the runoff is very sensitive to the precipitation. Except the scene 1, all the scenes show that the percentages of the variation of runoff are greater than those of variation of precipitation. The scene 6 shows that the runoff will decrease almost 30%, when the temperature arise 2 ℃ and precipitation decrease 10% and the meteorological condition has appeared in 1978. Additionally, the evaporation and infiltration also have a positive relation to the precipitation, but not as sensitive as the runoff to the precipitation. When concerned the temperature at the same precipitation condition, the runoff doesn't have a different variation because of the opposite temperature, for example, at the condition of precipitation increasing 5% the percentage of the variation of runoff is 3.9 when temperature increased 1 ℃, whereas, is 9.2 when decreased 1℃. That's to say, as concerned the runoff, the precipitation increasing 5% is superior to the temperature increasing 1℃. Thus, the most definitively factor of water resources of this basin might be the precipitation rather than the temperature. But considering that spacial and temporal distribution of precipitation are not even and that the uncertainty of precipitation is very large, when temperature increase at the future, some places or some time might be very arid and some place other would be very waterlogged, which involve severe agricultural disaster.

CONCLUSION

Based on the basic information of Songhua River Basin, a distributed hydrological model which coupled with water use process is developed to simulate the hydrological circulation and its response to climate change. Verification results are comparatively encouraging, and the simulated discharge hydrographs comparatively match the observed ones. Thus, the simulation is able to apply to the study.

According to the simulation and scene, the runoff is more sensitive to the precipitation than the temperature. In addition, the evaporation and Infiltration have an evident positive relation to the precipitation. Considering spacial and temporal distribution of precipitation and the uncertainty of precipitation, the Songhua Basin is abjective to have extreme events such as drought and flood, which results the jeopardized the foodstuff security of China.

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