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Response of hydrological system to urbanization: a case study in Tianjin City, China

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ABSTRACT

Urbanization, which essentially creates more impervious surfaces, is an inevitable part of modern societal development throughout the world. Hence, it is important to understand the impact of urbanization on the water cycle as it helps people understand how urbanization will severely disturb the environment and assist policy makers in balancing development and environment sustainability. The objective of this study is to understand and quantify the sensitivity of the hydrological system to urbanization. A coupled rural-urban hydrological model, MODCYCLE, was set up to simulate the effect of changes in land use on daily streamflow and groundwater and applied to the Tianjin watershed in China. The model uses digital elevation maps, land use, soil, meteorological, and climatic data to represent important parameters in the catchment. The fraction of impervious surface was used as a surrogate to quantify the degree of land-use change. The results show that the expansion of urban areas had a great influence on generation of flow processes and on evapo-transpiration. The surface runoff was more sensitive to urbanization. Based on the results from this model, people can make more informed decisions regarding the extension of urbanization and attempting to balance sustainability and development.

Keywords: Urbanization; MODCYCLE; Land use; Hydrology

1. Introduction

Urbanization is an inevitable process in human society development throughout the world. In fast developing countries such as China and India, where urbanization has transformed large areas of land occupied by large population, the urbanization process will affect the water cycle process locally with regional and worldwide consequences. It is therefore important to know how urbanization will affect the water cycle process: (1) it will provide better understanding on how urbanization affects the environment and (2) it will allow us to better quantify the impact of different extent of urbanization on water cycle process. This would help policy makers find a balance between development and environment sustainability. It also helps underdeveloped countries decide on their developing process and pathways.

There is a lot of research on how urbanization changes the water cycle process, mostly based on comparing land-use changes from the past to current developments [1–3]. Shuster presented a review of the impact of impervious surfaces on watershed hydrology, and they drew distinctions on different impact as a result of different types of impermeable surfaces. However, the review neither did focus on the regional impact

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of a combination of impermeable surfaces nor did it looked into the impact each of the hydrological processes closely. In a recent review by Jacobson (2011), the focus was on better understanding of the urbanized areas to better quantify the impact of urbanization. It was found that there is still a lack of methods to quantify the impact of urbanization in developing countries owing to a lack of accurate land-use information, and as a result, the uncertainties in such studies are high [4–6].

Globally, the expansion of urban areas has resulted in marked alterations to natural processes, environmental quality, and natural resource consumption [7,8]. The impact of urban areas on the water cycle has received increasing attention in recent years. A significant number of urban water researches focussed on water security, water services provision, and treatment [9]. However, there is a real need to understand the relationship between urbanization impact and the science of hydrology [10]. This is mainly due to the unavailability of good quality long-term data as well as the nonlinear complex process involved. Hamel conducted a review on the impact of urbanization on baseflow and the mitigation measures available [11]. They stressed the effect of connected impervious areas and the distribution of imperviousness when one considers baseflow (or low flow) impact; this point was again emphasized [12].

Expansion of urban space results in an increasing impervious landscape and expansion of artificial drainage networks that dramatically change the magnitude, pathways, and timing of runoff [13,14]. Changes to the urban landscape also affect hydrological response at contrasting scales. Traditional research has focussed on the catchment scale response to changes in land-use coverage via a lumped approach, aiming to determine the role of increasing impervious surfaces on rainfall runoff and water quality dynamics [8,15,16]. There is a lack of research on how different extents of urbanization will affect environment sustainability. The impact of the urban environment at the more localized scale, where features such as buildings (including their density and composition), paved areas, and synthetic infrastructure emerge, remains poorly understood [17]. Braud et al. (2013) investigated the issue of urban infrastructures, such as sewer overflow devices, and drainage and sewer networks and the impact of such structures on different flow components and flow regimes over a longer period of months and years. They found it useful to be able to conduct long-term monitoring of sub-catchments (and network infrastructures) which provided valuable information on the impact of urbanization on the monitored catchment.

The presence of significant areas of impervious surfaces alters the dynamics of infiltration and results in contrasting impact on baseflow behavior [18]. For example, although some catchment areas demonstrate a reduction in infiltration and recharge as a result of the widespread impervious surface, some pervious areas of urban catchments facilitate transfer of water from the surface to subsurface areas, though the efficiency of such areas remains an active research area owing to the complex structure of the urban subsurface [10]. The assumption that impervious surfaces result in zero infiltration was demonstrated to be incorrect, as highlighted that nearly 10% of annual rainfall infiltrates into the road surface network for an experimental site in the south of UK [19]. Removal of vegetation reduces evapotranspiration rates and may result in a temporary increase in infiltration rates, as interception losses reduce, though certain soils (e.g., Andisols) have demonstrated a reduction in infiltration when naturally occurring vegetation is removed. Further research is required to fully advance our understanding of urban infiltration dynamics, particularly in pervious zones where infiltration rates are often incorrectly assumed to be representative of undisturbed, natural areas.

The objectives of this research are twofold: (1) to quantify and understand the relationship between urban development and the main water balance components and (2) to explore the possible water resource impact of urbanization in the Beijing-Tianjin-Hebei (BTH) cooperation development strategy using Tianjin city as an example. Tianjin city is currently experiencing a lot of pressure for urbanization as well as ecological protection, and the study could potentially provide some insights into the balance between these two objectives. The ultimate aim would be to utilize our understanding to find solutions that would balance the economics of development and environment sustainability and help policy makers make more rational and informed decisions.

Tianjin city is undergoing rapid urbanization, and this can be noted in the actual changes to land use over the past 10 y. If the latest municipal development plans goes ahead, then the city will experience even more drastic changes [20]. The current urbanization rate stands at roughly 28%, planned to increase to 35% and 50% in the years 2030 and 2040, respectively. At the same time, the city plans to reduce the agricultural land use from 37% to 25% over the long term while only slightly reducing the ecological and undesignated space from 31% to 25%. It is on this basis that this paper investigates the sensitivity of urbanization in the Tianjin catchment.

In this paper, we will be analyzing the water cycle process under current urbanization situation in Tianjin municipality, a rapidly urbanizing mega-city on the east coast in China. The MODCYCLE model will be used to examine the impact of urbanization on hydrological system. A number of different future development scenarios based on increasing urbanization intensity are explored in the paper. The results of these scenario-based study about future urbanization on hydrological system will help planners and managers in taking proper decisions regarding sustainable development.

2. Study area and model

2.1. Study area

Tianjin municipality is located in the lower HaiHe Basin drainage area, northeast of China, and faces BoHai Sea on the east (Fig. 1). Its geographical coordinates are from 38°33′57″ to 40°14′57″N and from 116°42′05″ to 118°03′31″E. The population is around 15.17 million (based on 2014 census). The total area is 12,000 km^2, where the mountainous area is 727 km^2, accounting for 5.8%, and the rest of the land area consists of plains. The current agricultural and urban land use are approximately 59% and 28%, respectively. Tianjin city is an important part of China's new development strategy for the BTH region. The BTH region's

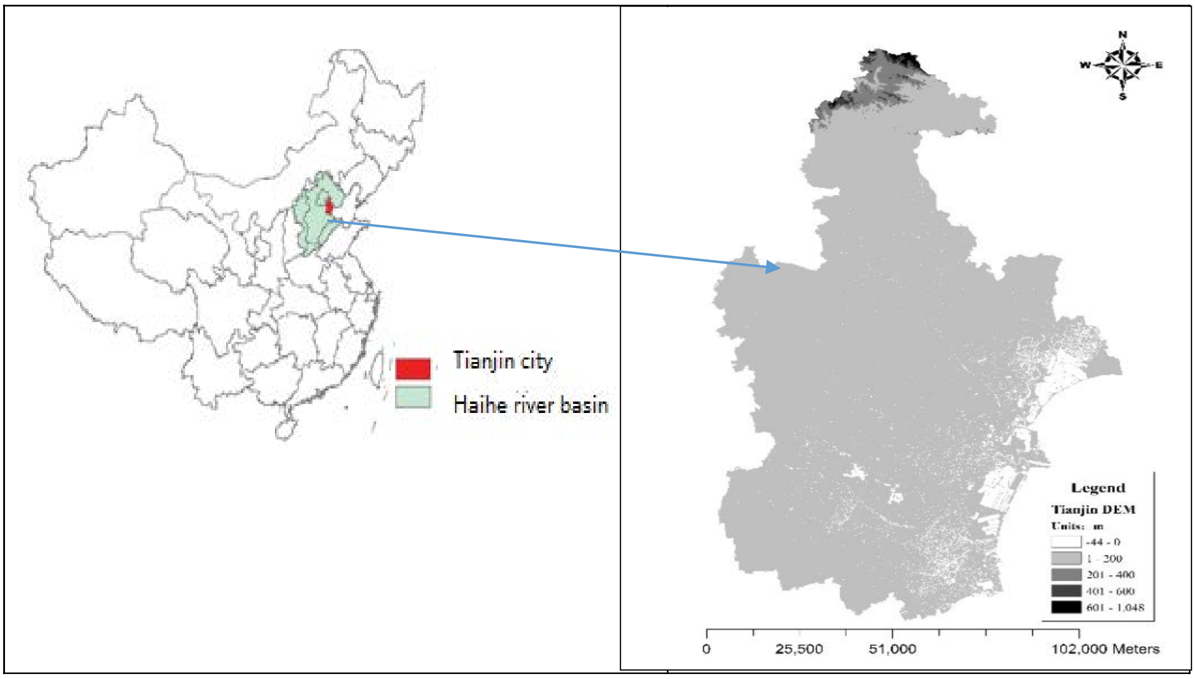

Fig. 1. Location map of Tianjin city located in Haihe river basin in China and DEM of Tianjin city.

coordinate development strategy aims at the relocation of all nonessential functions from Beijing to neighboring locations while at the same time it creates an opportunity to enhance three focused sectors: environmental protection, integrated transportation services, and industrial upgrading and relocation. Thus, the sustainability of urbanized solutions is very much intertwined with the impact on water resources, ecology, and air pollution. A detailed description of the study area can be found ref. [21].

The climate of Tianjin belongs to the warm temperate semi-humid continental monsoon, and average annual temperature is about 12°C. The average annual precipitation ranges from 560 mm in the North to 720 mm in the South. The annual potential evaporation ranges from 900 mm in the North to 1,200 mm in the South.

2.2. The MODCYCLE model

Modelling of the impact of urbanization can be conducted using a number of popular numerical software packages such as TOPMODEL, SWAT, MUSIC, MIKE-URBAN, or PUMMA [22–26]. In this study, the MODCYCLE model is selected owing to a configuration which is adapted specifically for the China rapid urban development scenario.

The MODCYCLE model (an object-oriented modularized model for basin scale water cycle simulation) is a distributed hydrological model similar to the SWAT model, as both uses the concept of hydrologic response unit (HRU) as basic function unit for computing water balance. The MODCYCLE model had been developed at the China Institute of Water Resources and Hydropower Research in 2013 and undergone various modifications over the years. Fig. 2 represents the schematic representation of MODCYCLE. The MODCYCLE simulation and computation of time step are highly flexible with fundamental unit of per day; hence, it is suitable for regional or catchment scale simulation as such the case in this study. The basic input data requirement are geographical delineation, such as digital elevation maps (DEM), land-use spatial and temporal distribution, and meteorological data such as precipitation, temperature, pressure, etc.

Similar to the SWAT model, a coupled Mannings' equation and the Green-Ampt equation is used to compute infiltration rate, surface runoff, and peak flows within each HRU. The MODCYCLE model emphasizes the anthropogenic impact and provides particular attention on water abstraction, usage, and disposal back to the natural system. The model can be used to simulate anthropogenic components such as abstraction for irrigation, dams, groundwater abstraction, and recharge and also on integrating these components with the natural water cycle. There are currently 8 different modules which consider anthropogenic impact and they are crop water irrigation water cycle, plant growth water demand and water cycle, interaction between municipal and industrial water usage, water storage control and operating patterns, recycling of water in traditional point source such as commercial complex, water transfer between rivers and storages, water recharge to support wetlands and lakes, temporary high water demand areas such as urban construction sites.

The MODCYCLE model includes additional components for anthropogenic water demand and disposal, water redistribution, reuse, and ultimately recharge to the natural water cycle. This modification is also done within each HRU and redistributed using water balance of the whole catchment. The modification is especially suitable for catchments which are subjected to extensive disturbances due to human activities and therefore a suitable modelling choice for this Northeast China catchment with an urbanization rate of more than 60%. The theoretical assumptions and detailed features of MODCYCLE are taken from ref. [27].

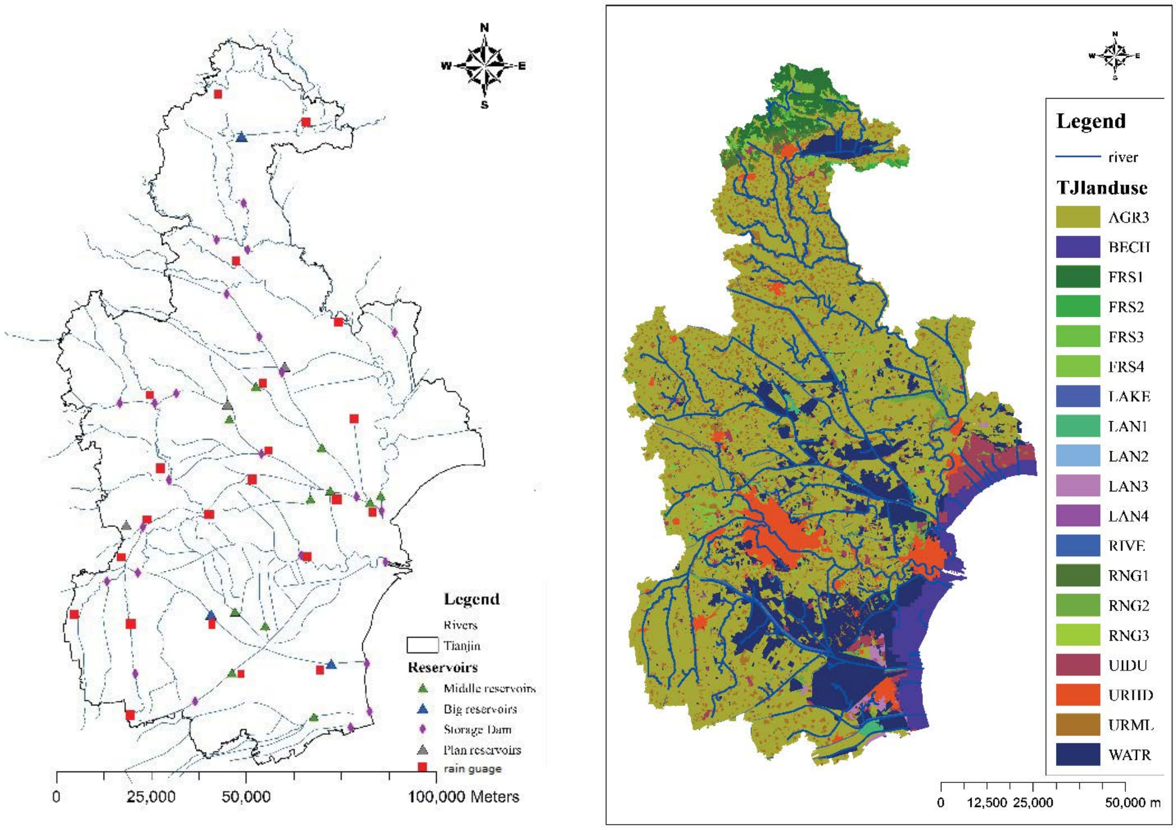

Fig. 2. The river system for the study area (left) and the land use (right).

2.2.1. Input data and construction of model

The simulating period is from 2007 to 2014, and input data include several parts as follows: (1) spatial-related data such as administrative map, remote sensing map from year 2005, DEM, river network, land-use map from year 2005, soil map, etc.; (2) local atmospheric and hydrology data; and (3) local water supply and usage data from 2007 to 2014. Fig. 2 shows the river system, reservoirs, and land use for the study area, and Table 1 provides detailed description of different land use in the area.

The actual river network of Tianjin is highly complicated and interconnected, and hence, there is a necessity to simplify the network and extract the main channels for simulation. The simplified network consists of 356 sub-basins and river systems. A total of 40 reservoirs, including 3 large and 12 middle reservoirs, and 25 small reservoirs are simulated. The catchment is delineated into 6,386 HRUs according to land-use types, soil types, and crop management.

2.2.2. Model calibration

As MODCYCLE is a distributed hydrological model, and it is necessary to calibrate the model based on the following aspects: (1) water balance; (2) the simulated basin outflow should be calibrated against the observed flow to determine the reliability of the model in surface water processes; (3) the simulated groundwater level of a region or a basin should be calibrated against the observed data to indicate the reliability of the model in groundwater processes; (4) the simulated soil water content of a region or a basin should be calibrated with respect to the reliability of the model in soil water processes; (5) the simulated evapo-transpiration (ET) of a region or a basin should be calibrated against the measured data to indicate the reliability of the model in the ET processes; (6) the simulated crop yield of a region or a basin should be calibrated with the actual production statistics to indicate the reliability of the model in the crop growth processes.

In this study, the model was calibrated using flow from two locations and groundwater level. The MODCYCLE model has been calibrated using runoff data from January 2007 until December 2011, and validation uses data from January 2002 until December 2014 as shown in Figs. 3 and 4. The Nash Sutcliffe coefficient for calibration is between 0.71 and 0.73, and the values for validation are 0.68 and 0.69, indicating relatively good results and that this model is suitable for subsequent urbanization study.

3. Formation of impervious surface fraction

The general approach in studying the impact of land-use change on hydrological system is to construct a number of scenarios based on historical data (either measured or remote sensing data) and to compare the results of the model simulation with reconstruction. In this study, the authors have chosen a conceptual approach by combining different scenarios based on the percentage of urbanization. The conceptual approach assumes gradual urbanization planning

Table 1
Land-use symbol and its description

Abbreviation of land-use type	Description	Area (km^2)	Area (%)
AGR3	Agricultural land	7,094	58.7
BECH	Beach	45	0.4
FRS1	Dense forest	223	1.8
FRS2	Shrub	31	0.3
FRS3	Coarse forest	190	1.6
FRS4	Other forest	21	0.2
LAKE	Lake	33	0.3
LAN1	Sea shore	461	3.8
LAN2	Sandy land	1	0.01
LAN3	Saline land	52	0.4
LAN4	Bare land	1	0.01
RIVE	River	270	2.2
RNG1	High-density grass land	133	1.1
RNG2	Mid-density grass land	171	1.4
RNG3	Low-density grass land	3	0.03
UIDU	Industrial land	372	3.1
URLD	Low-density residential land	889	7.3
URML	Mid-density residential land	546	4.5
WATR	Large water bodies/lakes	1,560	12.9

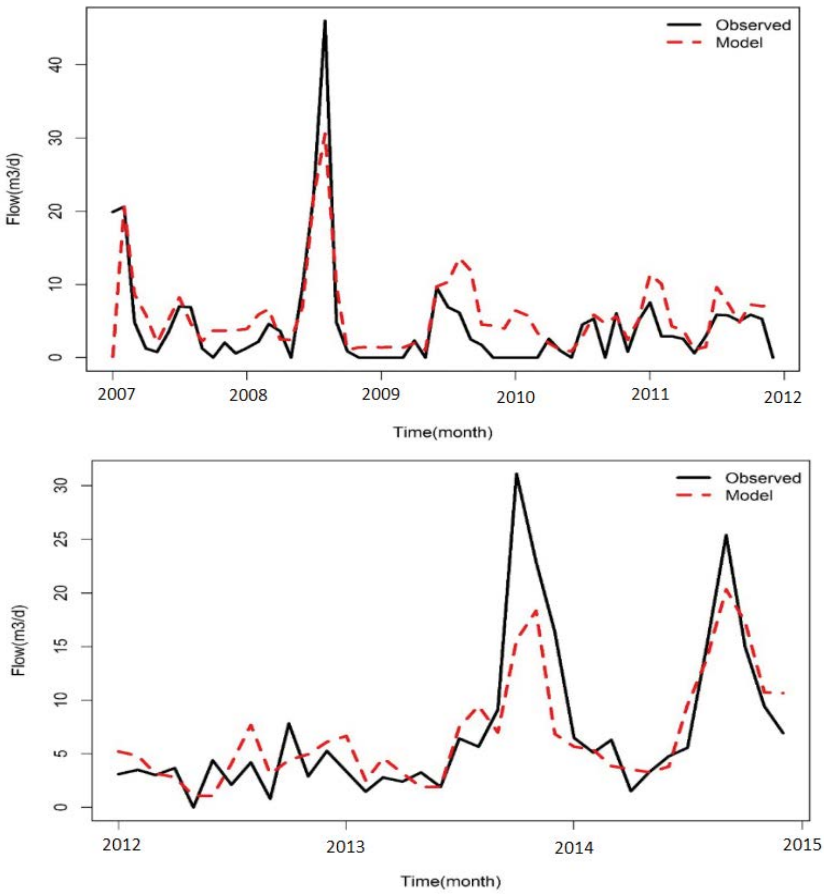

Fig. 3. Observed and simulated hydrographs for location of Jiyunhe for calibration (top) and validation (bottom).

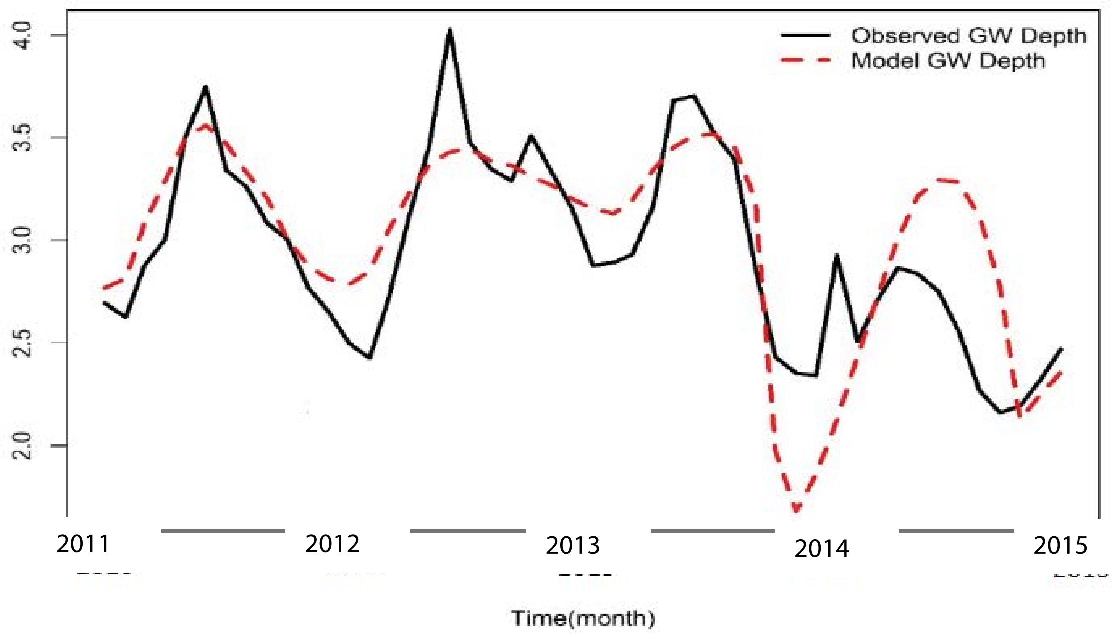

Fig. 4. Observed and simulated groundwater (GW) levels for location of Wuqing District for validation period.

for expansion, where the urban area expands slowly and a fraction of the municipality becomes city or town and the process repeats itself. A total of seven scenarios were derived in this study. In practical, urbanization process is not a linear process. But for any future planning, it is necessary to know the effect of urbanization on hydrological system. So, in this study, urbanization process is considered as linear growth of baseline. Therefore, the impervious land type was changed by 10% increments up to 60% in order to investigate how urban development will affect the hydrology cycle in this area. The urbanization process was assumed to proceed from downstream to upstream areas, as this follows the movement of human inhabitant according to the history of society development. Since, all watershed are generally affected by anthropogenic activity, the current level of urbanization was used as a baseline to compare the effect of increase in urbanization.

4. Results and discussion

Fig. 5 shows the urbanization processes for areas along the river considered in this study (for a better visualization, only current, 20%, 40%, and 60% are shown). The practical assumption was that most urbanization occurs near the river

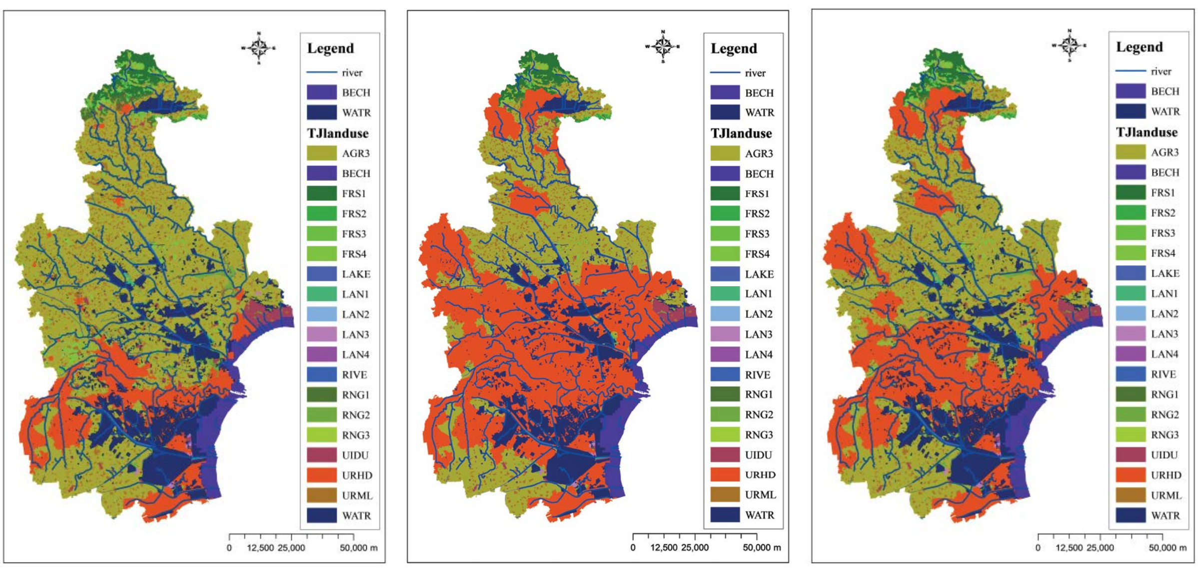

Fig. 5. Map for defining different levels of urbanization areas along the river network (left to right 20%, 40%, and 60%).

and in the floodplains since the ease of water transportation is essential for any urbanization activity.

Fig. 6 shows the average monthly precipitation in the watershed with most of the rainfall in summer (June-August). The ET for certain period (Dec-Feb) is higher than the amount of precipitation. The natural water cycle will compensate itself during this period resulting in a loss of moisture from the surface making it very dry.

The model was run for all the scenarios described in Section 3. Fig. 8 illustrates how the shape of the hydrograph changes in the watershed with an increasing amount of impervious cover. The impervious cover increases the volume of water and the rate of discharge. This often results in more flooding and habitat damage. Further detailed analysis of the results shows there was significant increase in total discharge from urbanization area where the runoff coefficients rose from 0.1 to 0.26 when the urbanization was increased from the current state by 60% as impervious layers, thereby resulting in a 160% increase of rainfall runoff ratio. The presence of urban landscapes significantly affects the surface runoff dynamics and runoff generating process. Results from this study show that the expansion of urban areas had a great influence on generation of flow process and on ET. The surface runoff was more sensitive to urbanization.

With regard to the change in hydrological fluxes with respect to current percentage of urbanization, a more detailed analysis of the catchment water balance for different scenarios revealed that the main component affecting a change in water balance component was the surface flow. A 60% increase in impervious surface in catchment caused an increase of 200% in surface flow but only increase the total flow by 120%. This is because of a decrease in lateral and base flow. This decrease is about 5% when a 60% increase is applied to the impervious surface correspondingly and the ground water recharge decreased by about 40%.

Fig. 7 illustrates the flow duration curve of total flow at different levels of impervious cover. From the flow duration curve, most of the differences are at high flows and top end of the medium flows. This suggests that most of the influence can be seen at higher flood which makes more difficult for urban planner as large higher flood will be higher in volume as well as rate of discharge will increase leading to less time for evaluation in case of flood.

The other major component of the water cycle is ET. The removal of vegetation, existence of an urban microclimate, heat island, increase of impervious surfaces, and conversely installation of green and wetland areas all affect the magnitude and distribution of urban evapotranspiration. It can also be noted that there is a 22% decrease in total ET when impervious surface was increased to 60%. Noticeably, vegetation ET has the largest reduction of 50% as compared with other component of the ET due to fact that urbanization leads to removal of vegetation and hence a corresponding reduction in evapotranspiration rates. At the same time, there is increase in ET due to snow, i.e. a 5% increase when the impervious surface has increased to 60% and is probably due to the fact that the snow on impervious surface has less chance to infiltrate when they melt and hence there is more time to evaporate and hence can evaporate at the rate of potential ET [28–30].

Fig. 8 shows the effect of impervious layer at monthly scale, and it is clear that the effect of impervious cover is more significant in summer (June-August) due to maximum precipitation. It is interesting to see that impervious cover does not have much impact on ET, total flow, or groundwater recharge at medium to low precipitation.

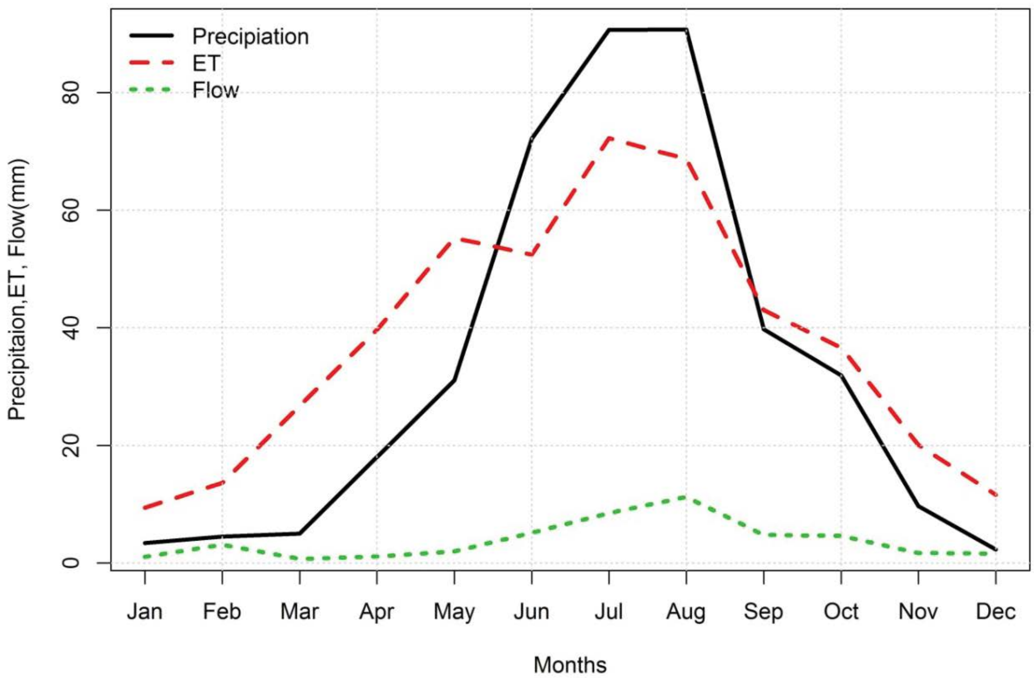

Fig. 6. Rainfall versus runoff of the Tianjin catchment.

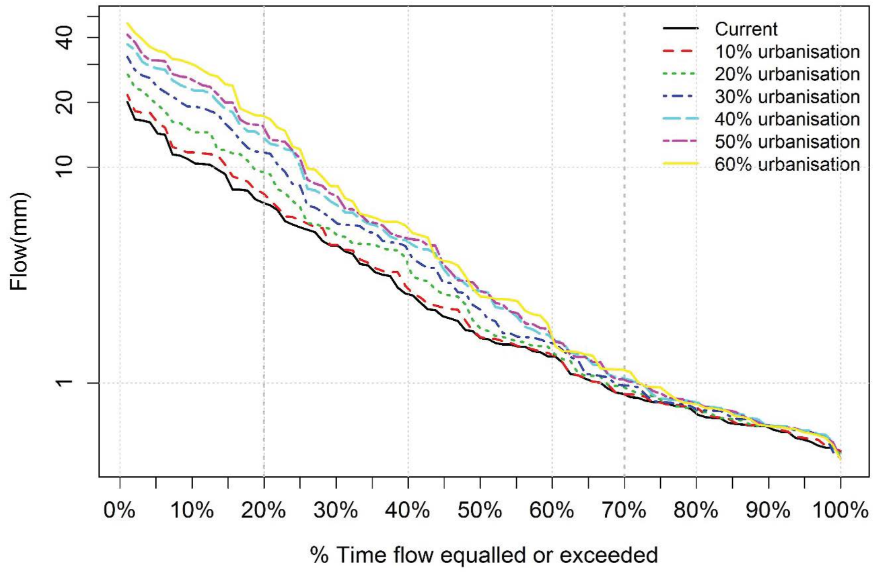

Fig. 7. Flow duration curve at different levels of impervious cover.

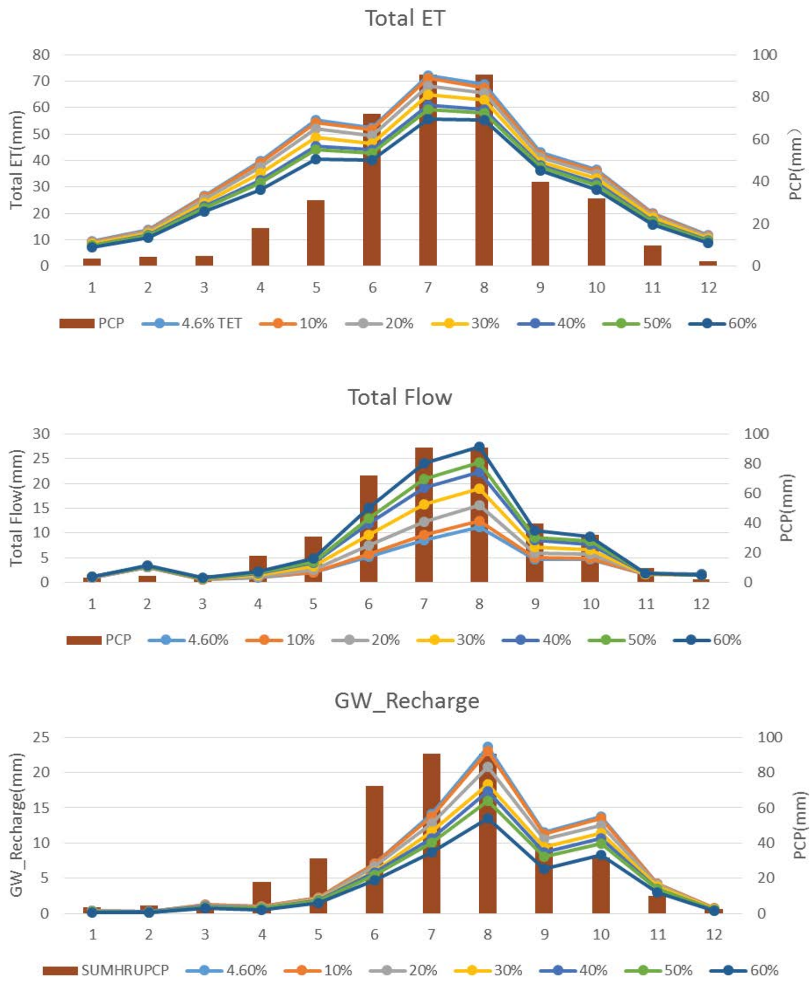

Fig. 8. Effect of impervious cover on total ET, total flow, and groundwater levels at average monthly scale.

The above results can be put into perspective of the planned Tianjin city future development. Although the mid-term goal of development is to increase the urbanization rate by 10%, this increase mainly comes from the utilization of unused (undesignated) land space, and thus, the increase in water demand is basically from the industrial and urban land use, without reducing agricultural water demand [31]. However, the situation for the year 2030 is very different; the increase in urbanization mainly comes from the reduction of agricultural land (from 58% to 25%), producing a dramatic reduction in agricultural water demand.

The above analysis demonstrates that distributed hydrological models such as MODCYCLE can be very useful tools to evaluate urbanization policy quantitatively. Due to the flexibility of such tools, several land-use scenarios can be quickly evaluated, assessed, and compared. Even though this study only considered simple land-use change scenarios such as percentage increase in urban area, the effect of such land-use change is quickly apparent [32,33]. Moreover, more detailed examination of the impact and effects on each hydrological component can be performed. Evidently, the land-use change scenarios can be extended to include changes to green space, rural to urban transformation, or restructuring of urban land use from industrial to high-rise residential buildings. Other types of analysis such as construction of sponge city or green corridors can also be incorporated in the future. Such analysis will help strengthen the policy of creating green space in urban areas and thus promote sustainable planning.

It is inevitable that the future plans of the BTH cooperation development strategy may increase the degree of imperviousness of this region due to urbanization. However, there is a lot of room for mitigation of impact on water resources when different scenarios of urbanization can be modeled and examined in detail prior to implementation. The results from MODCYCLE simulation indicate that spatial redistribution of development and the role of vegetation play a crucial role in deriving successful mitigation strategies.

Increasingly, urban hydrologists and engineers are assessing the local responses of urban areas to precipitation and the fate of rainfall once it interacts with both individual and small groups of buildings alike. It is therefore one of our aims to consider rainfall interaction with increasingly impervious surface in artifact of urbanization.

5. Conclusion

The main objective of this study was to understand and quantify the sensitivity of hydrological system to different levels of urbanization in a watershed. The MODCYCLE model was set up to predict the effect of change in land use on daily streamflow. The model uses land use, land cover soil type, meteorological, and climatic factors such as precipitation, temperature, sunshine hours, etc. to represent the hydrological process of the catchment and applied it to the Tianjin watershed in China.

Results show that the expansion of urban areas had a great influence on the generation of flow processes and in ET. The analysis of watershed water balance before and after land-use change revealed that main water balance component changed was the surface flow. The results should be examined together with the proposed Tianjin City Strategy development plan for the years 2015–2030 and demonstrated that there is a possibility of achieving sustainable growth and ecological water balance if the sensitivity of urbanization for the Tianjin catchment is properly understood.

Urban planners and policy makers can benefit most from the current study, as the current methodology allows them to create a scenario and analyze the effects of the planned urbanization levels on water resources. Further studies will be needed to generalize the methodology presented in this study and to consider rainfall interaction with urban structure. There is also a need to find balance between development and environment sustainability in different areas or cities to give a reference for those cities under similar conditions.

It is often known intuitively that the appropriateness of scale of urban development must consider both environmental impact as well as comfortability of the habitat such as green coverage, water availability, and local climatic conditions. The application of this methodology has demonstrated that MODCYCLE may be useful in determining the appropriate level of urbanization considering the relationship of water availability and paved surface.

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