Overview of Water Balance in Urban Areas

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Keyword: urban water balance, hydrologic models, forcing data, active urban environment

Introduction

The water mass balance, as one of the most essential and basic rules in hydrology, has been widely used in water relevant researches, contributing to the studies of basin hydrology. Based on the water balance equation, lots of hydrologic models, like the HDSM model and the FLEXI model, are invented to explore the hydrological processes quantitively.

While there have been substantial studies concerning the water balance of natural catchments since the development of hydrology, the research of urban hydrology just started 60 years ago since the striking trend of urbanization. Some researchers compared the different hydrological performances of urban and rural areas (Grimmond and Oke, 1986); Some researchers explore the effects of urbanization on surface water, and groundwater quality. Some researchers study the human effects on short-term weather and long-term climate (Changnon, 1976);

This article reviews the development and the deficiency of urban water balance researches and aims to provide an overview of urban water balance.

Method

Recent water balance researches regarding urban areas are always based on data acquiring. Field measurement is one of the most widely used methods to collect accurate data. The types of data collected are decided by the specific research purpose, the scope of which are broad, covering nature, meteorology, urban construction and society aspects, such as precipitation intensity, air temperature, bright sunshine hours, relative humidity, wind speed, water quality, soil moisture, land use condition, population, etc.

The position and number of monitoring sites are determined by the position, boundary and spatial scale of the research area. The location of monitoring sites could be located both inside and outside of the research area. In the data-sparse areas, the information from nearby stations is also essential. Spatial interpolation is necessary to fill the gap in unknown areas (Yashvant Das, 2015). As for the time consideration, the observation period and time scale are determined by the research period and time scale.

Except for field measurement, massive satellite data and images are collected continuously and broadly by remote sensing in recent years, which makes the data-driven hydrological analysis possible. Spatially distributed precipitation and evaporation estimations can be derived from the real-time satellite information. Land use maps can be used to analyze urban and rural areas, and pervious and impervious areas with remote sensing-based tools.

Even some crucial hydrological parameters like the storage capacity in the root zone can be estimated with satellite data by linking this parameter with vegetation classes (Savenije and Hrachowitz, 2017). This data innovation directly promotes the development of water balance researches and becomes powerful support for hydrologic models.

In the water balance equation, all the hydrologic behaviors are divided into three main fluxes: precipitation (P), evaporation (E) and discharge (Q), in which the evaporation can be further divided into interception (I), transpiration (T) and conventional evaporation (E). Furthermore, the classification methods of discharge fluxes are more complex and diverse, based on the different definitions of water storage and local conditions. According to the classification method of Savenije(1997), the water storage can be divided into four types, surface reservoir storage (Ss), unsaturated reservoir storage (Su), groundwater storage (Sg), water bodies storage (Sw) and water consumption storage. All the water flow paths will cause the mass changes of these water storages, including the infiltration from surface water to unsaturated zone (F), the percolation/recharge from unsaturated zone to groundwater (R), the capillary rise from groundwater to unsaturated zone (C), the overland flow on the earth surface or from the earth surface to water bodies (Qs/Qsw), the subsurface flow in unsaturated zone or from unsaturated zone to water bodies (Qu/Quw), the seepage from groundwater to water bodies (Qgw) and artificial water intake from surface water, groundwater and water bodies (U) (Savenije, 1997).

In urban areas, depending on distinctive local conditions, the concrete discharge fluxes are various. For example, in the water balance research of Lelystad district, Ven der Van and Voortman divided local discharge processes into three parts: the water seepage that enters the research area (K), the discharge of stormwater sewerage out of research areas (Qr), and the subsurface drainage discharge (Qd) (2007).

Considering different research targets, space, and time intervals, the classification, and definition of both the water storage and flux can be different. In some situations, some small or slow sub-flows could be neglected for calculation convenience.

Discussion

Because of the relatively small urban space, the spatial scales of most urban water balance researches are limited. As for the time scale, most urban water balance researches focus on a relatively small time scale, such as seasonally, monthly, daily, and even hourly. One practical reason is that part of urban water fluxes performs sensitive to the natural condition. In other words, the temporal variation of some natural indexes (including precipitation, temperature, moisture, radiation, wind speed, and vegetation cover) is remarkable, which will lead to distinctive hydrological behaviors and belie the subtle changes of some urban artificial water fluxes. The other technological reason for these small time scales is that some small or slow sub-flows could be neglected compared with other significant fluxes like precipitation or evaporation, which benefits calculation convenience. Therefore, the time scale is a key issue in urban hydrology researches.

However, as mentioned before, an accurate urban water balance research is based on sufficient data supports. In some practical cases, many important sub-flows are overlooked due to the lack of detailed data. These over-simplified water processes will not only lead to a deceptive water balance condition but also bring misleading simulation results of peak or low flows, endangering the design of urban water measurements.

For these hydrologic models focusing on the rainfall-runoff relationship, the evaporation is undoubtedly the most important middle term. Grimmond and Oke (1986) discussed the effects of water storage and external water supply on evaporation with a simplified water balance model. They studied the relationship between water storage and evaporation capacity from the view of energy balance and argued that the temporal pattern of external water supply and evaporation appear to be strongly positive connected. Furthermore, they argued that irrigation is the main water source in their study suburban area.

STOWA (Droogers, 2009) compared two regular formulas of evaporation calculation: the Penman-Montheith and Makkink equations. This research stated that Penman-Montheith is more accurate in calculating the potential evaporation than Makkink. The error of potential evaporation calculated by an inaccurate formula will directly bring the errors of runoff or other parameters in the water balance equation.

Yashvant Das (2015) exploited the Budyko theory and studied the effect of the aridity index on the ratio of actual evaporation and precipitation. In this study, the potential evaporation was computed with both of Thornthwaite's and Penman's method to bring a certain extent of accuracy. Because of the sufficient rainfall during the Monsoon season and the small-time interval, the water availability, infiltration-excess runoff, crop water need are neglected. In this research, the small-scale spatial and temporal variation of water balance characteristics is analyzed.

With sufficient data supports, more complex water balance models could be built with more specified water fluxes. The research of two experimental basins (a residential area and a parking lot) in Lelystad depicted a relatively complete water balance picture (Van de Ven, Voortman 1985). This research discussed the distinctive characteristic of urban hydrology, especially the hydrologic connection of subsurface zone and groundwater: The upward seepage from deeper groundwater to the unsaturated zone is the main flux of water inflow in both two experimental basins, which does not exist in many other areas. Another interesting item of this water balance model is the import of drinking water and industrial water, which is not small and significantly influences the whole urban water regime (Ven, 2007).

On this basis, D.Kuijk (2014) further discussed the influence of climate change on the water balance condition in Lelystad. This simulation showed that, compared with a moderate climate change scenario, land-use changes by human interference, such as increasing the paved surface will cause larger and more direct changes in urban hydrology. In an extreme climate change scenario, increased precipitation and potential evaporation will lead to larger variations of actual evaporation and groundwater level in a year.

Redfern and Macdonald et al. (2016) explored the relationship between the infiltration process and urban impervious surfaces. They found that the common way of grouping all constructed surfaces including roads, roofs, and footpaths together as impervious surfaces is inaccurate and will bring a deceptive water balance result. Therefore, the linkage of urban surfaces and hydrologic behavior should be re-discussed. One interesting topic in this research is the activity of urban nature. For example, urban surfaces change over both long and short timescales, which are always neglected in the literature. For short timescale, the cracks and joints on the aged road surfaces offer preferential pathways for infiltration. For long timescale, the water holding capacity and infiltration potential of degraded green space and soils are degrading. This study argued that the urban environment is an active and complex system like the natural catchment, and therefore more active urban hydrologic models are necessary to deal with the complex urban environment.

Conclusion

The study of urban water balance is based on the study of hydrologic behaviors in natural catchments. The exploration of natural hydrology is relatively advanced, as specific hydrologic processes have been analyzed and particular water balance models can be exploited according to different geography, topography, and ecosystem conditions. However, most water balance researches regarding urban areas remain simplified. The models of urban water balance only remain simple structures and neglect the variable local condition, which may result in remarkable calculation errors and bring risk to urban design.

Except for the over-simplified problem of urban water balance models, the activity of the urban environment is also neglected. In fact, the urban features are changing, such as land use condition, soil type, urban ecosystem, urbanization degree, etc., which should become dynamic inputs in urban water models.

The development of urban water balance research needs temporal and spatial big data as supports. Newly arising data acquiring methods like remote sensing may play an important role in the development of urban water balance research and bring an active and adaptive urban water balance model in the future.

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