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Characteristic and pattern of urban water cycle: theory

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ABSTRACT

Urban water cycle is one of the foremost contemporary research topics in hydrological research, and it forms the foundation of urban water resources management. This study serves to provide better analysis and understanding of the changes in urban water cycle such as number of factors, complexity of processes, magnitude of impact, etc. It serves to sum up the integration of nature and anthropogenic water cycle, in the form of a bi-modal urban water cycle model. The work focuses on the difference and compatibility of scales and methodology in urban hydrological processes, in order to highlight the gaps in urban water cycle research. This includes developing a unique model to simulate the characteristics and evolution of processes in urban areas, with the intention of supporting future urban water resources management.

Keywords: Water cycle; Urban; Hydrological model; Water resources

1. Introduction

City is the symbol of human civilization and the most active area of social economic activity. The accumulation of population in urban areas has significantly changed the local material and energy fluxes, accompanied by changes in underlying surface conditions, and changes in natural fluxes of water, sediment, chemicals, etc., as well as the continuous increase in waste heat emissions. These changes lead to significant changes in water cycle elements, such as infiltration, runoff generation, and confluence and their fluxes. The city presents a unique water cycle characteristic of water intake, water conveyance, water use, water drainage, wastewater treatment and recycling. The increasing intensity of urban water cycle has adverse effects on regional hydrological cycle and water use security, resulting in the deterioration of urban water resources and its water ecosystem and bringing about great challenges for providing safe water supplies for the urban population [1–3]. Based on such a complex background, effective management of urban water resources should be based on scientific understanding of the effects of human activities on urban hydrological cycles and the environment. Fully consider the whole social and economic system, and make effective mitigation measures for these impacts. Because there are great differences of the influence of urbanization in time and space, it is, therefore, necessary to quantify and assess these impacts in terms of local climate, urban development, engineering and environmental conditions, cultural activities and other socio-economic indicators. The analysis of urban water resources management should be based on the urban water cycle, and the analysis of urban water cycle will be helpful for the ex-post test of modern urban water resources management methods (including sustainable development, comprehensive management of urban water cycle, low impact development and eco-hydrological methods, etc.).

2. Theoretical connotation of urban water cycle

In nature, affected by solar radiation, potential energy and other energy, through evaporation, water vapor transport, precipitation, infiltration, runoff and other hydrological processes, the circulation, transformation and continuous migration of water in the three phases of gas, liquid and solid

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is the water cycle. In the urban area, the change of underlying surface and the construction of water supply and drainage infrastructure have changed the original "four-water" conversion path [4–7], conversion mode and conversion intensity of the area. Urban water flows not only in rivers, lakes and wetlands but also in urban water supply and drainage networks and canals according to people's use, processing needs. Water will no longer comply with the natural law of "water flows downwards", but can flow upwards through artificial power and flow to places where people need to use it. In the general pattern of the original natural water cycle, the lateral structure of the water cycle – the social water cycle is formed, which constructs a unique dualistic water cycle model of urban units [8–10].

The urban water cycle consists of two major sources of water: municipal water supplies and precipitation [11]. Municipal water sources usually need to be introduced from outside the city, and sometimes from other watersheds, and their water diversion will vary greatly due to local water demand and water resources management. Municipal water sources may not flow through all the pathways of the urban water cycle. After entering the urban areas, such water sources are distributed within the city, some of which will flow into the city's underground water, and the rest will be converted into municipal wastewater after the utilization of the urban population, and eventually return to surface water. Another important source of water, precipitation, usually goes through all the pathways of the water cycle. The precipitation occurs in various forms in the city area. Through the hydrological loss (including interception, filling, evaporation and emission), a part of precipitation infiltration down to ensure soil water and groundwater recharge, and the other part is transformed into surface runoff, which may also flow into the receiving water through natural or artificial ancillary works.

Urban water cycle is a dualistic nature–social water cycle process, which studies the natural hydrological processes such as precipitation, evaporation, infiltration, runoff generation and confluence, etc. in urban areas and the interaction, transformation and influence of water in water supply, water use, drainage, wastewater collection and management, and the effective utilization of receiving water bodies and other social processes. Compared with non-urban areas, due to the change of underlying surface, the construction of water supply and drainage network and the diversified use of water resources, the hydrological cycle in urban areas is more complicated. There are many external influences and interventions, and the urban hydrological cycle derived from it is also called urban water cycle.

3. Characteristics of urban water cycle

The city is the most concentrated and intensive area of human activity. The natural water cycle and the social water cycle in the urban areas depend on each other and influence each other in the natural and social activities of the city. The interface between the two is the urban water system, which is not only the carrier of social water cycle movement but also the tool and media for human interference with the natural water cycle [12]. Under the influence of urban water system, the urban area has become the region with the highest frequency of water exchange and the highest circulation intensity. Therefore, the urban water cycle has different regional characteristics, which are different from the natural water cycle, mainly in the following aspects.

3.1. Factors involved in the water cycle increase significantly

In order to meet the needs of urbanization development, the construction of urban water system is becoming more and more perfect. The natural water cycle and urban water system are constantly coupled with each other in time and space, which changes the transformation path of surface water and groundwater in natural conditions, and brings additional elements to the regional water cycle process [4,5,13]. The provision of urban water services and the construction of related infrastructures have changed the process and elements of urban water cycle transformation. In urban areas, the cycle elements of natural water cycle such as rainfall, infiltration, runoff and evaporation can no longer balance the water cycle in corresponding areas, and significantly increase the water intake, water use, water consumption, emissions, water diversion and other related factors.

3.2. Water cycle is more complicated

Urban construction has changed the underlying surface; urban water supply, drainage, sewage treatment systems have changed the natural path of runoff; the increase of urban water supply pressure, water demand for building water ecological city and the development of science and technology cause continuous increase in reclaimed water, rainwater utilization, regional transferred water and other aspects, which increases the complexity of water cycle in urban areas. The precipitation is controlled by water conservancy works such as sluices, dams and dikes. Water supply and drainage are transported by various impervious pipes, and the flow and pollutant purification are artificially intervened [14]. The original natural water cycle path of "rainfall-infiltration-slope runoff-runoff confluence-evaporation" is changed to an interactive dualistic water cycle path of "rainfall-infiltration-slope runoff-runoff confluence-evaporation" and "water intake (supply)-water use-water consumption-water drainage-sewage treatment-recycling". After raining, the precipitation on the urban permeable area is still recycled by natural path, while that on the impervious area enters the social water cycle path through the drainage network. In this path, surface water or ground water is manually extracted or treated directly through the water supply network for use by urban departments. The waste water produced is directly discharged or treated by sewage and discharged into the natural water body through the drainage pipe network part. The cycle is subjected to the interaction, transformation and influence of natural forces and artificial forces.

3.3. Strength of water cycle is higher

Urban areas are highly dynamic and complex entities. They need water, food, energy and raw materials to maintain the stability of the system. Water flow is the most basic and important logistics of various urban streams. City population, industrial production, commercial activities are concentrated. Production and life cannot be separated from water at any moment. With the convenience and high guarantee rate of urban water supply, the water intake, water supply and drainage process of the urban water system are always highly coupled and interlocked at all times. The frequency of water cycle is very strong. Urbanization has promoted the development and utilization of water resources with the basic characteristics of water consumption, and intensified the process of social water cycle. The increase of artificial water consumption leads to the decrease of actual runoff in the lower cross section, and even changes in the natural hydraulic connection between rivers and lakes. With the increase of water consumption in each sector of the city, the output of vertical evapotranspiration in the region increases overall [9,15,16]. Therefore, the process of urban water system has high strength in water cycle process.

3.4. Urban water system is more unified

The basic objective of urban water system is to ensure the benign cycle of water, and the water supply and drainage should be closely integrated to form a complete and coordinated system with the unity of water supply and drainage. In the water cycle of urban society, water supply and drainage are the two process of "borrowing water" and "returning water" from nature [17]. As far as quantity is concerned, the amount of "borrowed water" is greater than "returned water"; from the quality point of view, the quality of "borrowed water" is better than "returned water". In order to make the water cycle healthy and sustainable, on the one hand, we should save water, reduce water consumption and pollution; on the other hand, we should carry on the regeneration treatment to the water, so that the receiving water body can maintain the self purification ability. Otherwise, the urban drainage will pollute the water body, and will directly affect the water supply quality of the city and its related areas. Thus, the urban water system will be caught in a vicious circle directly from the source of the urban water system – the water intake link. In addition, urban drainage can be used for ecological, industrial, municipal, agricultural and even domestic water after treatment with different standards. From the point of view of resource property, the drainage and sewage treatment system can also be regarded as "water processing plant", which takes urban wastewater and produces urban recycled water with corresponding function. In developed cities, waterworks and sewage treatment plants have formed a system of interdependent and cooperative work in some areas. The relationship between water supply, water use, water consumption, drainage and reuse has become closer and unified in urban areas, and the pattern of mutual dependence and dependence has become more prominent. The urban water system forms a continuum which is closely linked with the urban sustainable water use as its core.

4. Urban water cycle model

In natural state, the four paths of precipitation, slope land, river channel and underground of natural water cycle are the typical collection structures of surface and line [10]. In urban areas, a water cycle extension path is built, which consists of water supply, water use, water drainage and water reuse. The laying of large scale supply and discharge pipelines is increasingly separated from the natural water cycle, which realizes providing water to a diversified user body, collecting, transporting and treating the waste water that has been removed and other basic functions so as to support economic development, protect human health and environmental safety. The water cycle has evolved into six paths: water intake, water supply, water (use) consumption, water drainage, wastewater treatment and reuse, accompanied by a built-in efficient water recycling of water drainage, sewage treatment, reclamation and reuse, drainage, which is a typical dissipative structure from point to line and plane. The four paths of the natural water cycle interact with the six paths of the social water cycle, forming a complex system structure of the dualistic nature–social water cycle, which is unique to the urban region.

The change of hydrological situation in urban areas has always been due to the construction of urban infrastructure. The infrastructure provides services such as water supply, drainage and sewage treatment for urban areas. But, in turn, it has an interactive effect on the hydrological cycle in urban areas, mainly reflected in separation mechanism and coupling mechanism of water system which form the urban dualistic water cycle model. The specific principles are: (1) Separation mechanism: urban social water cycle and urban natural main water cycle have their own systems, for example, the reconstruction of urban pipe network reduces the amount of underground water seepage, and the reuse and treatment of sewage and reuse of water reduces the discharge of sewage. The hardened ground of the urbanization separates the ground system from the soil and the underground system. The rain water pipe network for the city artificially changed the flow of urban rainwater and sewage. (2) Coupling mechanism: the relationship between the flux of social collateral water and the flux of main channel fluxes is complementary and dynamic. The increase of water consumption directly results in the decrease of actual runoff in the downstream section. When the external water diversion enters the urban area, the leakage loss of the water distribution network will partly enter the underground aquifer, and most of the water will become waste water when used in the city. The collected wastewater will be disposed of at the sewage treatment plant and then discharged into the receiving water. The hardened ground of urbanization leads to the increase of runoff, the decrease of groundwater recharge and the change of hydraulic link between rivers and lakes. The structure of the urban water cycle is shown in Fig. 1.

5. Difficult points of urban water cycle research

River basin water cycle has been studied for a long time. All kinds of methods and models have been mature, but the urban water cycle has its unique characteristics compared with the natural water cycle. When transplanting the model and method of natural water cycle to the urban area, it will encounter many difficulties. Generally speaking, these are mainly the following aspects.

5.1. Research scale

The research scope of mesoscale water cycle is 200–2,000 km^2, and the scope of small and medium scale

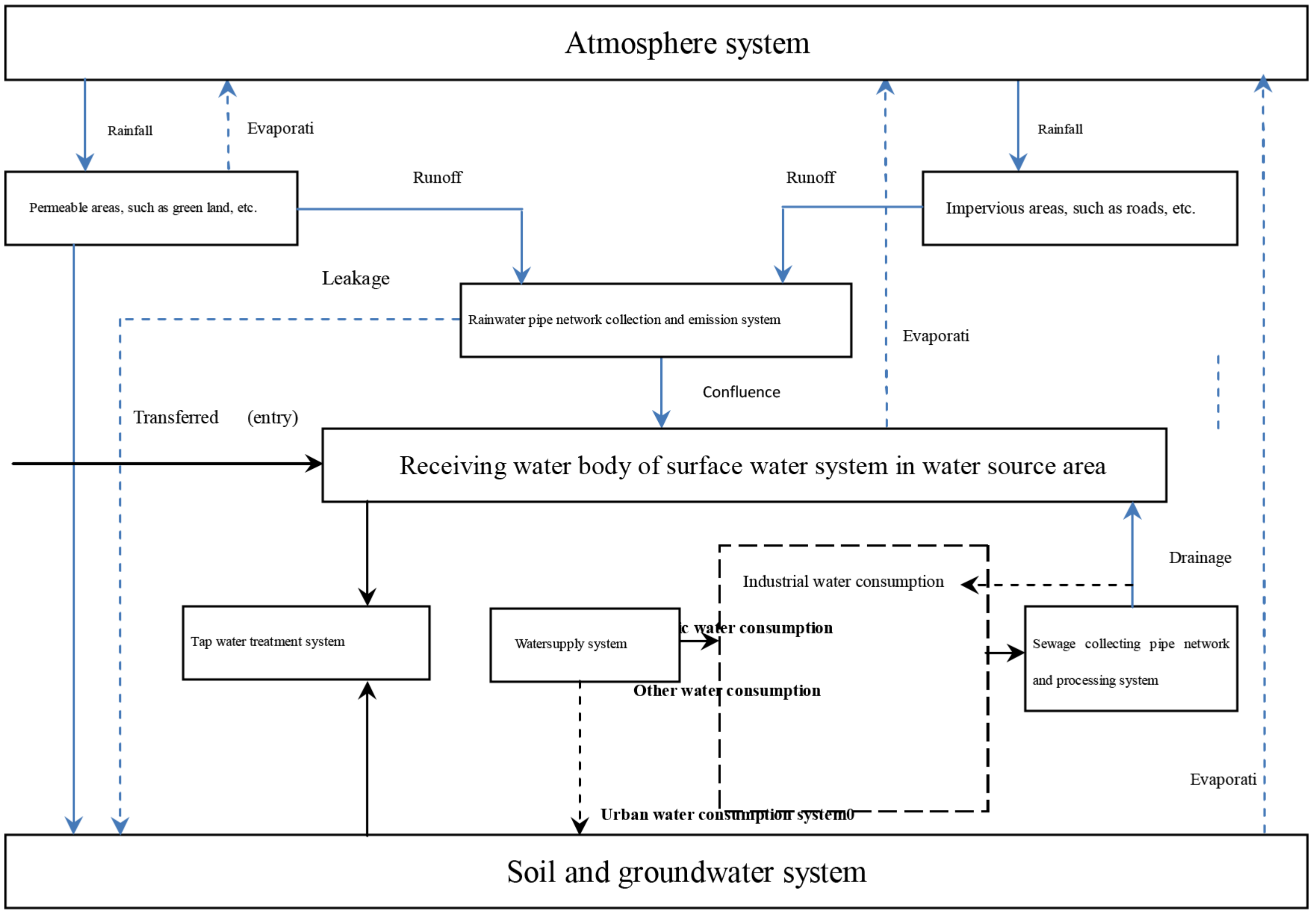

Fig. 1. Urban water cycle structure.

research is generally less than 200 km². The research scope of urban water cycle is determined in the urban area and surrounding area, and the scope is generally small and medium scale. The spatial scale of the research is reduced, which makes the accuracy of the required information data higher, such as the need for high-resolution urban remote sensing images, detailed network distribution and other information, so as to classify and recognize the underlying surface of the city, to judge the characteristics of the variation of the underlying surface height in the urban area, to analyze the hydrological processes of each patch, and to study the real situation of the hydrological cycle in the urban area.

5.2. Scale matching

The urban water cycle is not only a natural process of precipitation but also an artificial process of municipal water supply. It has two typical characteristics of "nature and society", and the two factors influence each other. There are many water cycle processes. There are differences in the temporal and spatial scales of the atmosphere and soil in the natural processes. Social process is accompanied by natural process, but has its unique characteristics. There is a significant scale matching and unification problem between the two [10].

From the time scale, the natural water cycle above the earth surface is closely related to the atmospheric process, and is usually represented by a shorter time scale, such as day, hour, minute and second; the change of soil and underground processes below ground surface is relatively slow, and is usually characterized by longer time scales, such as day, month and year. The time scale of water intake, water supply, water use and drainage in the social water cycle is similar to the surface process of the natural water cycle. But the reality is that the management departments calculate the water supply and demand data according to the management needs, which is not made in real time, on a long-time scale, such as year, month, etc.

From the spatial scale, the natural water cycle includes runoff generating units such as topography, slope surface and underlying surface, confluence units such as slope, channel, stream, tributary and main stream. The spatial scale span varies greatly as small as hydrological response units, as large as region, watershed. For the social water cycle, from the industrial, the water appliance at the end of living water users to the water supply and drainage system, and then to large-scale inter-basin water transfer project, the space scale span is also very large. But at the same time, according to the management needs, the statistics, analysis and reports of water supply and utilization are often macrodata of different regions and sectors, which is difficult to correspond to the administrative areas under the jurisdiction of the city. Therefore, multi-process, multi-scale spatio-temporal coupling method and water supply and drainage data distribution are the key technical difficulties in the study of dualistic water cycle.

5.3. Mechanism and calculation of urban water consumption

At present, the calculation of urban water consumption mostly adopts water quota, water consumption coefficient, remote sensing inversion, water balance and so on, combined with single experience or comprehensive estimation, it belongs to the black box model of urban water consumption calculation. How to scientifically recognize the water consumption mechanism of urban industry, life, ecology and other links and processes and establish a model of quantitative calculation of water consumption in urban units, which makes the urban water consumption calculation also have a physical mechanism, is another difficult point in the study of urban water cycle.

5.4. Methodology

According to the specific purpose of water cycle research, the commonly used research methods are prototype observation, physical model and mathematical model. For the research of urban water cycle, these three methods are usually required simultaneously. The prototype observation mainly complements and monitors the social water cycle process of water intake, water conveyance, water supply, water use and drainage. The current observation network is weak and needs to be improved, more attentions should be paid in the future research. The physical model focuses on the study on the precipitation infiltration and runoff generation in the complex underlying surface of the city [18,19]. Mathematical models are widely used in solving large scale water cycle problems in large watersheds. For urban communities, how to describe hydrological cycle, artificial water and drainage process in a more detailed way? It is still necessary to combine prototype observations with the information provided by the physical model in a mathematical model, and develop the tools of urban water cycle research, to provide a powerful support tool for the study of urban water cycle [20–25].

6. Conclusion

As a current research hotspot, urban water cycle needs to understand the natural process, social process and reciprocal feed mechanism of urban water cycle from the microlevel. A comprehensive analysis of the connotation, characteristics and models of urban water cycle will help to study the mechanism of urban water cycle and water ecological response in a more detailed way. At present, the study of urban water cycle has entered a new stage. The combination of geographic information system, remote sensing and other modern methods, model test, remote sensing, cross integration of hydrology, ecology, economics, social atmosphere and social water cycle, and in-depth understanding of the urban water cycle theory and recycling model, have a positive role in the development of urban water cycle simulation tools, and promoting fine management of urban water resources, providing theory support for the construction of water ecological civilization city, guaranteeing the safety of urban water supply, and improving the efficiency of water resources utilization and urban water ecological environment.

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