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Review of Social Water Cycle Research in a Changing Environment

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Abstract: The Social Water Cycle (SWC) is a macroscopic and open system in which water derives from, and eventually returns to, the natural water circulation system. The two flows are integrated via coupling patterns such as infiltration, etc. In recent years, SWC has been deeply affected by global climate change and the excessive expansion of human activities. Therefore, it is essential to upgrade the cycle.

This paper firstly presents the related knowledge hierarchy, the dualistic water cycle between nature and society, coupling patterns and driving mechanisms, evolving processes of water volume and quality, and SWC modeling. Based on these items, the relevant theoretical research is reviewed and a forecast made on the orientation of future studies.

The research is of great theoretical and practical significance in advancing towards a water-saving and anti-fouling society, practicing water demand management, and promoting the development of modern hydroscience, technical innovation systems and basin water resource management in China and similar developing countries.

Keywords: Social Water Cycle; Dualistic water cycle; Social Water Cycle modeling; Water cycle research review; Outlook

1. Introduction

For the past few decades, social water cycling processes and resources have been deeply affected by global climate change and the excessive expansion of human activities [1,2]. As a result, water problems and crises are occurring in many regions. This is mainly due to the driving force, cycle structures and cycle parameters having undergone a dualistic evolution effect, in which the Social Water Cycle (SWC) [69] exhibits both social features and natural features – resulting in the attenuation of water resources, water and environmental pollution, ecological degradation, etc. [3-5]. Meanwhile, human activities are increasingly influencing the water cycle. Greenhouse gases are changing the driving force of the water cycle, and transformation of the basin underlying the surface composition is changing the characteristic parameters of flow concentration. In other words, manual water taking-consuming-draining is transforming the structure of the water cycle. The basin water cycle system has evolved from a 'natural' mode to a 'natural-social' mode (dual mode), especially in populated areas [6]. Under the influence of excessive human activities, the decreasing flux of the natural water cycle, or hydrologic cycle as it is also known [70], and increasing flux of the SWC have affected the original ecological and environmental service functions of the basin water cycle system, and has consequently led to a series of problems concerning ecology, environment and resources.

The SWC is an open system. It takes water from nature and finally returns it to the natural cycle system via drainage and evaporation, coupling with the process of infiltration, etc. The whole cycle evolves with economic development [7]. Initially, the process was water taking-consuming-draining. Then in the middle stage, it became water taking-feed water treatment-consuming-sewage treatment-draining. Latterly it includes water taking, feed water treatment, water distribution, primary consumption, recycling, sewage treatment, reclamation and draining [8]. In this much more complicated system, there are several closed subsystems involved, such as the urban cycle, rural cycle, water cycle for corporations, etc. The SWC system is increasingly being divorced from the natural system. For instance, the amount of water returned into canals and fields is decreasing due to agricultural water-saving; the infiltrating amount is also diminishing because of pipe network transformation; and the total discharge is diminishing due to urban sewage reclamation and industrial water recycling.

Generally, in light of these issues, mainly involving increased social water consumption, there is a need to strike a balance between maintaining water supply volume and protecting the eco-environment [9]. With current technological supporting systems, theoretical and practical research based on the natural cycle system and targeted at water supply management needs to be optimized to promote a water conservancy policy [10]. In the case of the SWC, many domestic and overseas studies are concerned with the necessity and urgency of balancing these social and natural systems. However, because of the complexity of the systems, the studies are basically content with describing and popularizing the basic theories and concepts involved. Some focus only on a specific subsystem (mostly in urban cycles) or process (irrigation, water supply, drainage, etc.). They seldom explore the integration of water supply management and regulation into the SWC – an important issue to be resolved in order to meet the needs of self-disciplined management and anti-pollution development.

In addressing this, this paper firstly presents the related knowledge hierarchy, the dualistic water cycle mode (natural and social), coupling patterns and driving mechanism, evolving processes of water volume and quality, and SWC modeling. Based on these items, the relevant theoretical research is reviewed and a scientific forecast made on the likely orientation of future studies. The research is of great theoretical and practical significance in advancing towards a water-saving and anti-fouling society, practicing water demand management, and promoting the development of modern hydroscience, technical innovation systems and basin water resources management in China and similar developing countries.

2. Research status review

For a long time, the focus of SWC research has been mostly on understanding and utilizing the natural water cycle system. In the 1970s, however, the amount of natural water supply became inadequate, with negative eco-environment consequences, and alerting people to the need for better water cycle management. They began to describe, review, adjust and finally improve the specific subsystems and processes involved. By the mid of 1990s, the internal structures and basic processes were being studied from the perspective of the overall system, enabling some phased achievements to be made over the years [13,14].

2.1 The SWC concept

The SWC is a branch of water resources science although, in the past, it was always considered to be an aspect of the hydrology discipline. The concepts, related knowledge and research into water resources science were not established as an independent science system until the 1950s. Dating back to 1997, British scholar Stephen Merrett proposed the 'hydrosocial cycle' (SWC) based on the hydrological cycle [15], providing a quick overview of the structure of the SWC. With sponsorship from the World Bank, Global Water Partnership, World Water Council, etc., there appeared a variety of water flux prediction models such as PODIUM, IMPACT, POLESTAR, WEAP and WATERGAP. During this period of emergence as a distinct discipline, Masahiko, for example, considers the 'social-natural' dualistic water cycle to be a meso-scale cycling process; Taikan Oki et al. made a quantitative analysis on the impact of social water uses on global water cycling flux; and Falkenma studied the interaction between the social branch and natural cycle [16]. In Japan, researchers established a 'Joint Committee' to develop a sound water cycle system comprising macro-scale (ocean-land water exchange and circulation), meso-scale (regional coupled natural-human cycling) and micro-scale (internal cycling in families and commercial buildings).

Studies of the urban water cycle mainly concentrate upon optimizing water resource allocation, and the design and operation of sewage collection and treatment. Practically, the water cycle in modern cities encounters problems such as aging infrastructure, inadequate facilities, climate change, the sustainability of the whole system and water pollution. Previous water resources management in changing environments has gradually moved from establishing large water conservancy facilities and increasing water supplies, to limiting consumption. Mitchell et al. [16] put forward a new concept of water resources management that considers all processes (natural and manual, surface and underground); calculates consumption-human uses and ecological water uses from different perspectives (environmentally, socially, culturally, economically, etc.); considers all related parties; and aims at sustainable development and striking a short-term, mid-term and long-term balance between the environment, society and economy. The main differences between previous and modern urban water systems are summarized in Table 1-1.

Table 1-1 Previous and Modern Water Systems Compared

Previous urban water system	Modern urban water system
The human waste should be disposed of.	The human waste can be recycled and reused for crops.
Rainwater should be drained to deserted areas.	Rainwater can be collected and returned to rivers and canals or used for irrigation.
Water from all sources should be treated according to drinking water standards only to meet the demands.	The supply amount, water quality, reliability, etc. should be taken into consideration comprehensively to meet the needs of water users.

Water is for single use.	Water can be recycled.
'Gray Infrastructure' made by concrete, metal and plastics, etc.	'Green Infrastructure' including gray infrastructure and soil and plants.
Large and centralized water systems and treatment plants.	Small and distributed water systems and treatment plants.
Uses same planning and same technology.	Uses diverse planning and technology with new management strategies.
Manage water supply, sewage recycling and sewage treatment with according to previous experience.	Systematically and synthetically manage water supply, sewage and rainwater recycling by use of technologies.
Cooperation = interpersonal relationship building. Working with others when necessary.	Cooperation= participation. Win-win cooperation to solve problems effectively.

In Urban Water Engineering and Management, Mateus et al. [17] explore hydrologic processes, related facilities, planning and management by using case studies of water resources management, emergency management and the impact of climate change on urban areas, finding climate variation to be the main influential factor in the 21st century water cycle. In 2011, *American Next Space* also made a comparison of current and future water resources management in urban areas as summarized in Table 1-2.

Table 1-2 Current and Future Urban Water Resources Management

Items	**Current**	**Future**
Scope	Clean water supply for public use, drainage and flood regulation	Larger scope in the long run, including river health, transportation, entertainment facilities, micro climates, energy sources, grain yields, etc.
Management Strategy	Separate and optimize the processes of the water cycle.	Adaptable, integrated, sustainable management for the whole cycle in uncertain environments. Improve living conditions. The uncertainties include the climate and water service needs.
Expert Database	Experts from a specific field of economic technology.	Experts from multi-fields such as sociology, technology, economy, planning, ecology, etc.
Services	Centralized and linear services, mainly based on economic technology.	Flexible services via methods of technology, sociology, economy, ecology, etc.
Involved Parties	Government	Governments, businessmen and the public
Risk	Controlled by the government.	Shared by private and public facilities.
Cooperation	Have little interaction with city planning.	Co-planning with water supply systems, transportation systems, sanity systems, employment and public services.

Considering the integrity of the urban water cycle in Hong Kong, Leung creatively proposes a management system which involves seawater, fresh water and recycled water, to improve the efficiency of the water cycle and reclamation, and lower the consumption of freshwater by 52%. At this time, Li Kuibai [l8] also points out that the urban SWC is a 'supplying-consuming-draining' process while, in 2002, Wang Hao et al. [19] develop the 'manual branch cycle' concept, which means human activities change the cycle path and performance of the natural water cycle, with the water cycle process evolving in a pattern of 'taking-delivering-consuming-draining-return' that decreases the amount of surface and underground runoff. Similarly, Jia Shaofeng et al. [20] also point to the SWC having an influence on the social economic system and human activities on water resources, and Chen Qingqiu et al. [23, 25] develop a conceptual model of the SWC in which the social economic system is the main influential controller for the interaction of the social and natural water cycles, with the SWC being the basic structure for water resources management and a sustainable cycling environment.

By the time of the current decade, Zhang Jie [26] has defined the SWC as a manual cycle formed when people use underground and surface water, raising a healthy-cycling concept including moderate water-taking, water-saving, advanced wastewater treatment and water recycling. Other studies focusing on the SWC mainly originate from this decade [27-29]. The majority are concentrated on water cycle systems and their internal structures in rural and especially urban areas, with findings in integral studies of the social cycle system being mainly from this decade [30,31].

2.2 Research progress into water volume and quality in social circulation

Natural climate cycles and events, such as in long term desertification in Africa; medium term *El Niño* effects in the Pacific and beyond; annual monsoons that affect India and as far as away is Cambodia, Vietnam and southern China; seasonal variations in temperate climates; and even immediate events such as sudden flash, outburst or break floods occur daily throughout the world, affecting both the quantity and quality of water in these regions. The contribution of human activity today is largely decreasing the volume of water available. This is mainly due to increased water utilization [35] and consumption due to population increase [37], increased per capita demand for water and increased production in the agricultural [37,38], construction [38] and other goods and services industries; decreased efficiency of water utilization [35]; the increase in developing and utilizing water resources [37]; and changes in the utilization of land. Water conservation responses can also have a detrimental effect on water supply [38], with Zhang Jinqi's [36] study of a water storage project in a mountain area finding that the expanded surface area of water increases evaporation and decreases the amount of runoffs; and water diversion and groundwater recovery and exploitation [33] increasing the flux of the hydrologic cycle and water consumption. Similarly, social drainage affects both the quantity and quality of water [35,38], particularly where recycled sewage is involved, which has been found significantly increase the amount of drainage pollutants [34,35]. Human induced climate change is also now being held responsible for the water reducing effects of diminishing green agricultural areas [33] and changes in the condition of land cover.

The effects of this combination of natural and human activities has led to a decrease in the total amount of water resources in Beijing, for example [33]. There has also been a general decrease in the Heihe River, where the amount of water flowing downstream area has similarly decreased, with continually decreasing groundwater levels having led to a worsening ecological environment in the Ejin Banner area, where a great quantity of *populus euphratica* forest has withered and the problem of deterioration of grasslands and sand storms further exacerbated. For areas where the amount of rainfall is large (generally more than 800), human activities have little influence on confluence and runoffs. However, for areas where the annual precipitation is small and the economy is well developed, the hydrologic regime has changed totally [37]. A further issue is the cost of treating polluted drainage and discharge into watercourses as a result of sewage recycling [34].

Many remedies have been proposed and implemented for the decreasing quantity of quality of water supply, including developing a strategy for sustainable development [37]; the use of appropriate penalty-subsidy incentive mechanisms [34]; protecting water resources [Qian Chunjian]; and improving the ecological environment in downstream river areas by recycling rainfall, which helps to control rainfall pollution and decrease peak discharge [40]. Vörösmarty et al. [42], for example, illustrate the environmental benefit of wastewater recycling by a simple water-balance relationship as seen in Figures 1-1 and 1-2. Nearly 50% of water is used in agricultural irrigation and 25% of water is consumed in cities and by industry. Figure 1-1 shows the water balance when water is disposed once it is used, while Figure 1-2 shows the balance by recycling. Around 20% of agricultural and urban water will be saved by using effective water-saving measures. By recycling and reusing waste water, nearly 90% of water can be used to supplement agricultural and domestic water, while water in regeneration recycling can reduce the amount of water that is taken from rivers and reducing the amount of pollutants discharged to improve downstream water quality. Likewise, biological treatment is available for water pollution although, as King et al. [41] discovered, as the amount of pollution increases, traditional Class II biological treatment becomes inadequate (especially when the removal rate of TN and TP is only 35% to 75% lower than the removal rate on COD, BOD and SS, which is 80%-95%) when the need for advanced wastewater treatment becomes critical. For this, they propose a strategy of: saving water; perfecting water cycling system plans; determining the amount and type of water recycling plants by considering all factors (economy, geography, technology, reclaimed water and scale effect); determining scientific technological process; obligating the space for stage development and reclaimed water pipelines; and reusing reclaimed water and wastewater in accordance with the requirements for different water quality. For all these approaches, it is necessary to provide some means of evaluation such as in terms of environmental-economical net benefit, for example, for sewage reuse in the whole hydrologic cycle system [34], or the influence of human activities on the hydrologic cyclic by using exponential moving averages [37].

However, there is little systematic research into *collateral circulation*. Natural and human activities are vital influential factors affecting collateral circulation and the main loop, with nature and the characteristics of the underlying surface being the leading determinants. Changing the utilization of land and the conditions of land cover by the conservation of water and soil on a large scale can improve the condition of the underlying surface. Establishing the relative strength and absolute strengthen indicators of collateral water circulation and the main loop, has enabled studies to be made of the influence of human activities in areas such as the Yellow River and its associated streams. In doing this, based on the dualistic water cycle approach, Walsh et al. [39] propose four unified evaluation methods: evaluations that unify supply, usage, consumption and drainage; evaluations that unify the water-usage process and the rainfall cycling process; unified evaluations of surface water and ground water; and unified evaluation of water usage, water efficiency and water benefits. Qian Chunjian, on the other hand, based on the concept of social water cycling, suggests a model of social water cycling and the whole presentation combined with three ways of developing and utilizing water resources in Suzhou city in Jiangsu province.

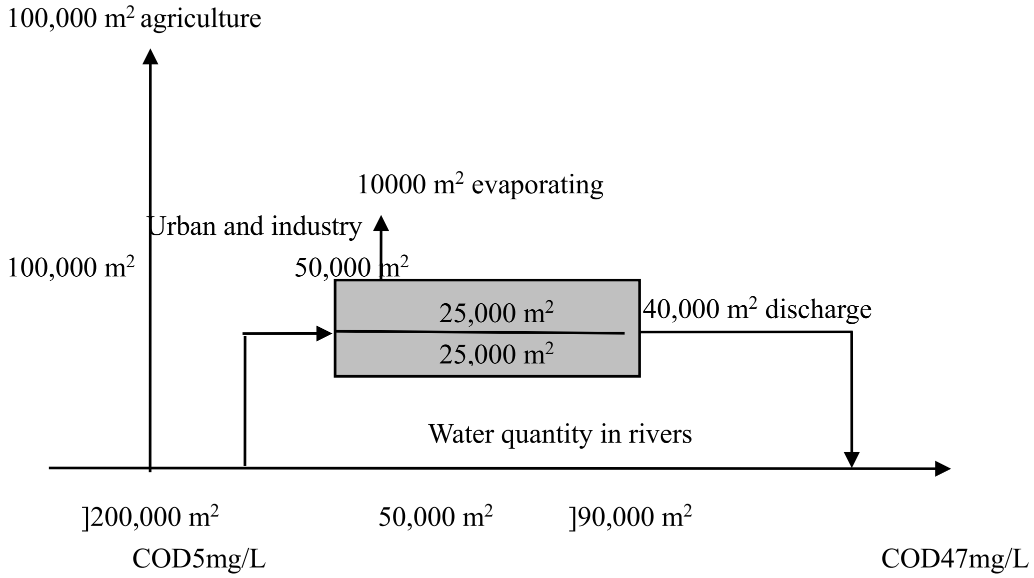

Figure 1-1 Disposable water-supply balance mode (150,000 m^2 water consumption needs 150,000 m^2 of fresh water and its net consumption is 110,000 m^2) (Vörösmarty et al. [42])

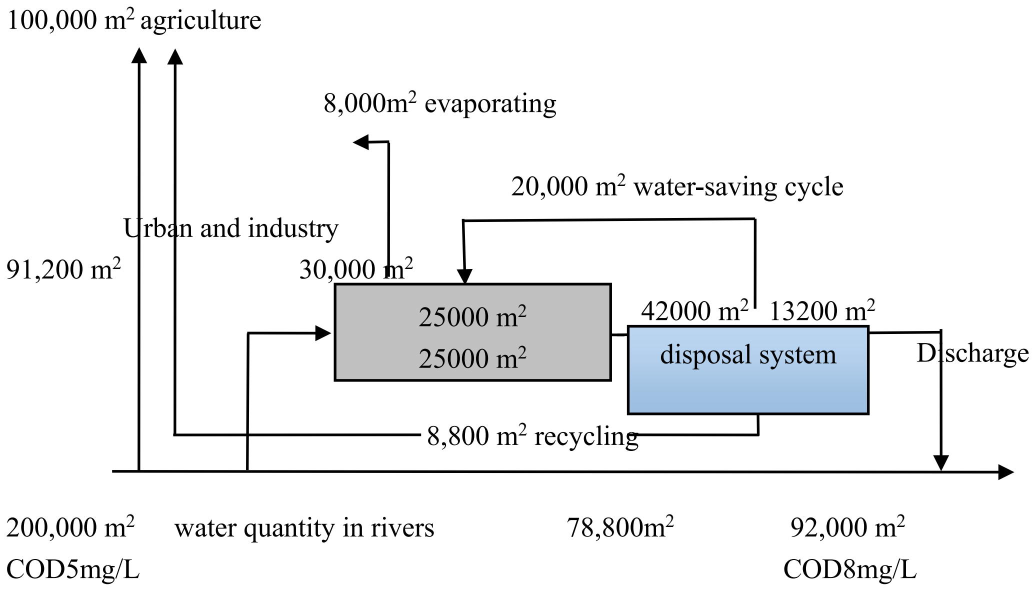

Figure 1-2 Balance model of recycled-and-saved water (a 150,000 m^2 water consumption needs 91,200 m^2 of fresh water and reduces nearly 88,000 m^2 of fresh water in rivers) (Vörösmarty et al. [42])

2.3 Development of the natural-human dualistic water cycle coupling and balance-constraint mechanisms

There has been much interest in the combined effects of natural and human induced effects over the years. Wang Gangsheng et al. [49], for example, use a Distributed Time Variant Gain monthly water-balance model to recognize climatic variations and human activities by means of quantitative analysis involving setting up background parameter sets of human activity-surface runoff coefficients, surface runoff indicators, a underground runoff irrigation coefficient, evaporation and diffusion parameters and the initial values of land humidity. Similarly, He Guoqing et al. [50] study the changeable characteristics of rainfall, runoff, relationship of rainfall-runoffs and evaporation of the main rivers in the Guangdong province to establish the rainfall-runoff relationship before human activities, to comprehensively analyze the rules and degree of human activity affecting the water cycle. Likewise, Liu Jiahong [52] provides a detailed analysis of the water cycle process in the seas and oceans, illustrating in detail the research basis, definition, key factors and progress of advancement as well as the changing regulations in the dualistic water cycle factors in the Haihe River basin. Liu Changming [46] has also studied the influence of human activities and climate variation on the Yellow River basin's changing environment by experiments and models of the water cycle.

In the process of studying these mutual effects of the natural water cycle and the SWC, the relative influence of climatic variation and human activities has also been much debated and analyzed, with Yao Zhijun et al. [44] applying an accumulative filter and Kendall rank correlation method to the qualitative and quantitative analysis of interannual and annual distribution rates, to show that the runoff of the Chaobai River is decreasing and that human activities are the major cause. Similarly, Wang Qingping et al [48], while arguing that precipitation change is the main reason for interannual undulatory change of water resources in the lower reaches of the Luanhe River basin, claim that it is human activities that have led to a notable decline in the quantity of water resources in the basin, including the indirect effects of utilizing water and land resources for agricultural irrigation as well as the direct effects of constant water transfer to outside basins. Hamed [47], taking the upstream of the Tanghe River as an example, has also studied the influence of climatic variation and human activities on the quantity of runoffs in the upstream of Baiyangdian where, in order to maintain its ecological function, it is necessary to maintain a certain minimum instream flow and carry out dispatch and monitoring of ecological water in the wet land. Based on hydro-meteorological data from 1960 to 2008 within the river basin and use of the elastic climate coefficient and hydrologic simulation method, the results indicate an obvious decreasing trend of annual runoff at a rate of 1.7 mm/a; with 38%-40% being attributed to climate change and 60%-62% to human activity.

In the process, research into natural water cycling and the SWC over last decade has gradually moved from fragmentary and scattered studies to become more concentrated and systematic, as well as from simple to complex and from partial to comprehensive. On the one hand, the natural water cycle is closely related to the SWC and they can mutually interact with each other organically at any place and time. On the other hand, one of the key advanced research areas of SWC today is how to extend traditional water balance theory, and the factors involved, so as to realize the transition from different dimensions and enrich dualistic water cycle theory and modes in the water cycle system of modern society. According to Liu Changming [46], for example, it is necessary to develop a dualistic water-resource evolutionary model and water-resource evaluation method. In this way, by considering the renewable quantity involved, the population and economic bearing capacity can be assessed, which will provide evidence for recovering and creating a sustainable and manageable water-supply system in the river basin. In 2004, Wang Hao et al. [51] put forward the basic structure and models of the dualistic water cycle of the projects of national "ninth-five-year", "tenth-five-year" technical plan and 973 plan project, continuing to study the systematic water cycle model that is coupled by the distributive water cycle model and concentrated water resources distribution modes. Jia Yangwen et al. [53], under the premise of illustrating dualistic water cycle theory, also propose a dualistic water cycle that is made up of a distributive basin water cycle model, rational allocation model of water resources and decision-analysis model of multi-objectives, verified in the area of the Haihe River, for use as a scenic analysis instrument in planning and managing its basin water resources.

On the one hand, therefore, human activities and manpower change the natural characteristics of the water cycle, expanding its time and cost attributes while, on the other, based on its primitive natural properties, water is a vital factor of production in the social and economic system and supports the development of society and the economy. As the basic factor in the natural water cycle, the ecological use of water necessarily places constraints on the development of economic society. The utilization of water must therefore maintain a rational balance of the water cycle system of the river basin in the development of economic society and in nature, ecology and the environment. In terms of Li Wensheng et al.'s [45] so-called "perfect water cycle" – what is needed is a situation in which, under the present status of owned water resource conditions and development, a river basin somehow continues its normal industrial activities and *while not allowing the SWC to damage the natural water cycle*.

2.4 Advances in SWC simulation techniques

(1) Modules of the natural water cycle process

Jeppesen et al [54] simulate the urban water cycle process of the Copenhagen Region (976 km^2) from 1850 to 2003 using a root system model, network generative model and improved Modflow-2000 model for root-zone water balance, water supply, waste water, storm runoff, groundwater runoff, surface runoff and the interactions between the various subsystems involved. With a long series of data concerning water levels, flows and inflows into the drainage system, they use a run-down method to calibrate the hydro-geologic parameter, storm runoff parameter and other parameters controlling the interaction between groundwater and piping systems at every step, to show that, due to the large exploitation of groundwater, its amount of seepage into rivers, lakes and wetlands was only 60 percent of that before urbanization. The recharge capacity of groundwater also decreased in the urbanization process because the impervious area increased while the drip irrigation pipe systems contributed little. This is very different from current reports that groundwater recharge will be increased through urbanization as the groundwater recharge rate of the Copenhagen Region is 20% higher than before because of increased rainfall in this phase.

Chèvre et al (2011) [55] have developed a new type of urban flood model that reflects the interactions between systems and hydrological processes and simultaneously reveals the significance of considering the complete water cycle in analyzing the role hydrological processes play in urban floods. This involved coupling a distributed hydrological model based on the physical mechanism and a drainage pipe network model, and used one-dimensional and two-dimensional traditional models to verify its applicability in areas with a high coverage of pipelines but is not accurate where there is a large proportion of land hydrological processes. Mackay [56] also studied the interactions between pavement surface runoff, flooded rivers and drainage pipes in urban areas in 2009, finding an original one-dimensional contact to exist.

(2) Simulating water-balance by integrating the urban water supply, storm water and drainage systems

In 2011, the Aquacycle model was established by Mitchell et al. [57]. This model helps in considering urban water supply, storm water and drainage systems by simulating their water flow and interactions and is used to evaluate different water-use strategies. As a city water-balance model, the time scale of Aquacycle is one day and its space scale is divided into units of minimum water supply area (such as a family, factory, agency or commercial building), clusters (consisting of groups of unified block units) and catchments (group of clusters). The hydrological processes simulated by the model include the urban irrigation of impervious land, household water demand, rainwater recycling and volume, and sewage systems. The Aquacycle model has been in the Athens region by Lekkas [58] to simulate rainfall route networks and water supply and drainage networks - two subsystems of the urban water cycle - and their interactions. The model can be used to simulate water consumption, the amount of waste water and displacement. In the application, the area was divided into different scales by the model (units, clusters, catchments) according to its structural characteristics, and different measured data used for calibration and to simulate physical features of areas. The model was used to examine three scenarios of local rainwater utilization, local waste water utilization and underground water irrigation for comparison with the basic scenario of current water conditions.

Galloway et al. [59] comprehensively consider city water balance, which provides a framework to evaluate water supply demands, recycling rainwater and sewage, and the interactions between water supply, sewage and rainwater. With an increasing mismatch between city water supply and demand and the city water system being more significant in social development, it was necessary to consider the sustainable development of the urban water system from multiple perspectives, such as water source, transportation, water usage, treatment and discharge. In the urban environment, water-balance provides good conditions for the design and operation of water management. Firstly, urban water system models were established at different levels and an Integrated Urban Water System Model was formed by overlapping indoor, outdoor and network subsystems. Secondly, environmental, economical and social service urban water performance indicators were developed. Then finally, hierarchical water analysis programs were also developed and water issues preliminarily analyzed with raw data from the city water system.

Hary et al. [60] developed an Urban Cycle model by comprehensively considering water usage, rainfall and sewage problems - using a hierarchical network model structure to provide continuous day-by-day simulation. The model couples the interactions of scales ranging from units to areas and uses cases to demonstrate the time-space effects of seasonal runoff to rivers under urbanization, and evaluate various relief measures within a framework of integrated water resources management.

(3) Effects of environmental water and ecological environment pollutants on the urban water cycle

By using the water equilibrium model Aquacycle, Mitchell and Diaper [61] identified the route to the sustainable development of the urban ecological environment, researched flow in urban areas and the aggregate balance of pollutants, developed their Urban Volume and Quantity (UVQ) model, which matches the pollutants with the flow processes of urban rainfall-runoff and the water supply-drainage system. Water transportation and the processing units in these two systems is determined by the transport and spatial distribution of pollutants in the urban environment. The model can also simulate the production, accumulation and transportation process of pollutants.

In the EU SWITCH project, city water-balancing tools were used to read and assess urban water resources management strategies [62]. Data relating to water storage capacity, water quality, energy consumption and simplified life-cycle costs can be input by the model under the lowest spatial and temporal resolution. The data used by CBW make it possible to quickly build a model from the existing space map. Verified for feasibility and effectiveness by UK's Birmingham City as an example, CBW provides an improvement on the Aquacycle model by adding a more detailed description of the urban water cycle, energy consumption and life cycle cost to the natural water cycle.

(4) Influence of socio-economic factors on the water cycle and water environment

A novel coupled System Dynamics and Water Environmental Model (SyDWEM) [63] comprehensively considers social economy, urban water affairs and environmental waters, and analyzes economic and population growth, water resources and environmental changes under rapid urbanization. With modules of social economy, water supply, water usage, pollutant generation, sewage treatment and environmental waters, it uses a socio-economy module to drive the model and uses the system dynamics approach to couples various modules together. In the case of the Shenzhen River, for example, the study predicts the watershed scale socio-economic policy needed and the influence of water planning on the social economy and environment.

(5) The energy coupling process in simulating the water cycle

Jia [64] simulates the catchment hydrological and energy processes in the WE-L model. On the basis of shortwave radiation, it derives sunshine hours, calculates long-wave radiation, and latent and sensible heat flux computational fluid dynamics (CFD) according to temperature and solves the problem of surface temperature. Artificial measures such as water supply, groundwater gradient, sewage discharge and energy consumption are also taken into consideration. The model has been applied to Japan's Ebi river valley (27 km²), with a grid size of 50 m × 50 m and at the time interval of 1 hour. After comparison, the river level and groundwater and surface temperature observations simulated by the model and water balance in 1993 were verified before reaching the conclusion that the future water cycle could be improved by adopting seepage trench measures.

The Single-source Urban Evapotranspiration-interception Scheme (SUES) model [65] expresses interception, evaporation and the dissemination process of rainfall in the form of biophysics based on the energy-balance equation. Associated with the Aquacycle model, SUES simulate amounts of evaporation and dissemination of vegetation under coverage (Leaf Area Index) changes in different seasons. SUES has been used to assess the effects of different city design strategies on the water cycle, and analyzed the influence of these strategies on atmospheric temperature from the perspective of capacity-balance. It also provides support in the quantification of water, in terms of the urban micro-climate environment, energy consumption and CO_2 emissions, and the improved capacity of the city climate model to simulate the exchange of water, heat and CO_2 in the land-atmosphere.

3. Review of the SWC

(1) Studies of the SWC are currently in their initial stages and have not yet acquired a unified, scientific and standardized concept. Considering the SWC simply as the movement of water in the socio-economic system does not fully reflect the importance of water to human economy and the complexity of its movement, and fails to adequately show the subjective initiatives in the SWC and negative effects of the virtuous cycle of human beings. The effects of interference and changes of human activities on the natural water cycle are ignored to an extent when the SWC is viewed as the collateral circulation of the natural water cycle [66]. Human activities of high intensity have had a great impact and the SWC has become juxtaposed with the natural water cycle. Thus, “water collection–water use-water consumption-drainage” in the traditional sense is just the external form or accompanying process of the SWC. Its content is not yet fully understood and further studies of the basic connotation, structural frames and cyclical process of the SWC are needed.

(2) In research into water quantity and quality evolution of the water cycle system, the socio-economic system is generally considered as a wholistic "black box" or "gray box", lacking any fundamental understanding of the underlying causal mechanisms involved. Future work needs to focus on thoroughly analyzing these "black box" or "gray box" processes, clarifying their evolution and identifying the development and the associated evolution mechanisms.

(3) Throughout the development of studies on the evolution coupling and balanced mechanisms of the dual water cycle, population growth and the permanent desire and action of human beings to improve consumption levels (quality of life) constantly promote the scale of economic (or wealth) expansion. This has led to the world’s vast and unpredictable economic growth to date and increasingly prominent water problems in the form of serious shortages and worsening water environment [67]. Thus, the effect of climate change and human activities on the SWC will be key junction points of studies on the coupling and balanced coordination mechanisms of the natural water cycle and the SWC. At the moment, knowledge of the evolution coupling and balancing mechanisms of the dualistic water cycle is relatively scanty and in urgent need of strengthening in future.

(4) With the development of economic society and updating of modern techniques, the more models of the basic process of the SWC are needed to simulate the SWC process in as much

detail as possible. In terms of model simulation, all studies agree that the water cycle model is an important tool for understanding the basic processes involved by simulating and analyzing rainfall, evaporation, infiltration, runoff and their processes and predict the future of the water cycle. In doing this, scale conversion (into macroscopic, mesoscopic and microscopic) presents a particular problem in modeling the SWC and one in need of further development too.

4. Research prospects for SWC theory

With the rapid development of economic society, the flux of the SWC constantly increases to being even more than that of the natural water cycle. The SWC has therefore become an indispensable component of study on the evolvement of the water cycle system, and the means by which the evolution mechanism and regulation of basin water cycle systems under human activity can be quantitatively evaluated is a key problem. It is also necessary to further strengthen the foundation and regulation of the SWC by improving knowledge concerning the connotation, operation mechanism, process regulation of the SWC and the coupling mechanism between the SWC and the natural water cycle. This suggests the need to examine basic theory by research into:

(1) the coupling mechanism between the natural and SWC systems for a jointly formed water cycle system. With the development of human society and economy and frequent human activity, the proportion of the SWC of the whole water cycle has gradually increased. Given the concept of a function mechanism between the social and natural water cycle, what is now needed is to develop this into a coupling mechanism and to see what kind of interaction mechanism is generated. A key scientific problem is also to extend the traditional water balance principle and accommodate the transformation of different scales in order to deepen and enrich dualistic water cycle theory and cyclical patterns.

(2) social economic developing law and the virtual water flowing mechanism. The SWC is operated and evaluated in the social economic system process, but its driving force is mainly derived from the development and evaluation of economic society. Therefore, it is essential to strengthen the undertstanding of the developing law of economic society and its intrinsic mechanism by analyzing water by water, especially the virtual water that flows with the development of the social economy. This is a simulation of the quantified measured water resources in the social economy and widely exists in crops, livestock products, industry, etc. Therefore, the transformation relationship of water resources in the social economy system needs to be explained when studying the mechanism between the social economy system and virtual water.

(3) the evaluation of water quantity and the SWC quality. Generally, the traditional study of this is based on the intensive analysis the economic society system as a “black box” or “gray box” in attempting to reveal the development and evaluation mechanism involved. This is urgently needed to be resolved in order to set targets and thresholds for the control of water quality to balance water quantity and quality of ecological, environmental and other natural service functions with the social economy and social service functions.

(4) modeling techniques and ways of describing the SWC system. Simulation models provide one of the most important tools for hydrological science, but are also one of the most difficult to build. Simulating the SWC, for example, is an effective way of analyzing the SWC system but involves virtual social simulation consisting of spatialization and social economic statistics. Other applications include the simulation of the typical urban and rural SWC and the unit water cycle system structure, process and evaluation at the micro, meso and macroscopic scales. Simulation is also an important tool in realizing the "seamless" coupling, strengthened mathematical model descriptions and the introduction and development of modern information technology on the basis of studies of different types of mechanism of the SWC units [68].

(5) evaluation system and regulatory mechanism of the SWC system. SWC evaluation mainly includes health and efficiency assessments. A health indicator system of the SWC needs to be built, the aims and direction of water cycle control defined, the target system studied, and assessment method techniques developed for greater efficiency. For SWC control, a synthesis of former research results is needed and comprehensive appraisals carried out to provide a suitable reference frame. At present, assessments of the SWC and studies of control are based mainly on the dualism water cycle resources and their development, water resources management, water use processes and the utilization of unconventional water resources.

(6) the impact of global climate change and human activities on the SWC. Changes in greenhouse gas levels have resulted in a change in the river basin water cycle. This is especially the case with the development of economic society, which has had an increasing impact on the internal water cycle, greatly changing the SWC. The mismatch between the ecological system and water resources utilization has become increasingly apparent, as well as the impact of human activities and climate change on the natural ecology and water cycle systems. What is needed is the ecological environment protection of rivers and the basin water cycle, and exploratory and case studies of solutions that can serve to support the exploitation of their water resources.

5. Conclusion

Based on the systematic elaboration of general SWC theory, this paper reviewed the concept and connotation of SWC research, the evolution of water quantity and quality in the SWC system, the dualistic water cycle system coupling and balance-restraint mechanisms, as well as the simulation technology involved. It expounded the major progress made and features of SWC research, commented on the associated important scientific problems and finally presented and analyzed its leading edge issues. This prompts four major conclusions, in that

(1) at present, SWC research is in its initial stages – having not yet developed a united and scientific conceptual norm or connotation, and maintaining the traditional model of “taking water-using water-consuming water-draining water”, which is only the external form of the SWC. The construction frame and circulation process are in need of completion and enrichment.

(2) research on the evaluation of water quantity and quality in the SWC generally regards the economic society system as a “black box” or “gray box” and lacks a fundamental

understanding of its causal mechanisms. Future research needs to focus on discovering its evolutionary process and reveal the mechanism of its development and evolution.

(3) the SWC is a result of the social economic system, the major driving force of which is from the evolving social development. A better understanding of the social economic development process and its impelling cause is needed in order to reach the inner mechanism of the SWC itself.

(4) the study of the effect of both climate change and human activity on the SWC is a key joint issue for research into the needed natural water cycle and the SWC coupling mechanism and balancing restraint coordination. Population growth and increased human consumption levels lead to the greater use of water, and social economic development needs to strictly control the use of water resources to prevent further deterioration of the water environment.

6. Conflict of Interests

The authors have no conflict of interests related to this work.

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