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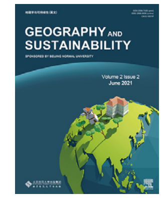

Hydrological cycle and water resources in a changing world: A review

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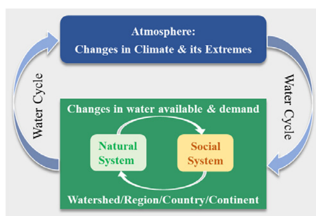
HIGHLIGHTS

- This water cycle study focuses on the impacts of climate change and human activities.
- River basin management requires an integrated model of hydro-bio-geochemistry.
- Co-evolution of the human–water systems should be the focus of future study.

GRAPHICAL ABSTRACT



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ABSTRACT

Water is the fundamental natural resource that supports life, ecosystems and human society. Thus studying the water cycle is important for sustainable development. In the context of global climate change, a better understanding of the water cycle is needed. This study summarises current research and highlights future directions of water science from four perspectives: (i) the water cycle; (ii) hydrologic processes; (iii) coupled natural-social water systems; and (iv) integrated watershed management. Emphasis should be placed on understanding the joint impacts of climate change and human activities on hydrological processes and water resources across temporal and spatial scales. Understanding the interactions between land and atmosphere are keys to addressing this issue. Furthermore systematic approaches should be developed for large basin studies. Areas for focused research include: variations of cryosphere hydrological processes in upper alpine zones; and human activities on the water cycle and relevant biogeochemical processes in middle-lower reaches. Because the water cycle is naturally coupled with social characteristics across multiple scales, multi-process and multi-scale models are needed. Hydrological studies should use this new paradigm as part of water-food-energy frontier research. This will help to promote interdisciplinary study across natural and social sciences in accordance with the United Nation's sustainable development goals.

1. Introduction

The earth's hydrological cycle links interactions between the atmosphere, lithosphere, biosphere and anthroposphere, and it is also profoundly affected by human activities and socio-economic development. With recent rapid changes in climate and land use, the global water cycle is experiencing high levels of spatial and temporal variability, which has resulted in numerous water-related issues that pose challenges to human water security. Therefore, obtaining a better understanding of the hydrological cycle and water resources has become a key concern for environmental and natural resources research (Braga et al., 2014; Xia et al., 2017; Wang et al., 2010a).

Water is the most fundamental natural resource. This strategic resource is a key environmental controlling factor and plays a non-substitutable role in maintaining and promoting sustainable socio-economic development. Water resources are renewable due to its cyclical nature. However, variability in climate and land surfaces means that the hydrological cycle and water resources are highly heterogeneous in both space and time. Presently, more than four billion people are affected by water shortages (Mekonnen and Hoekstra, 2016). The development and use of water resources have already surpassed the alarm level in many parts of the world, including China, thereby resulting in environmental issues including: rivers with little or no flow (Liang et al., 2010); ecosystem degradation (Palmer and Ruhi, 2019); water table decline (Bierkens and Wada, 2019); and lake/wetland shrinking (Zhou et al., 2019). These problems demonstrate that unsustainable water use has become a problem that hinders the sustainable

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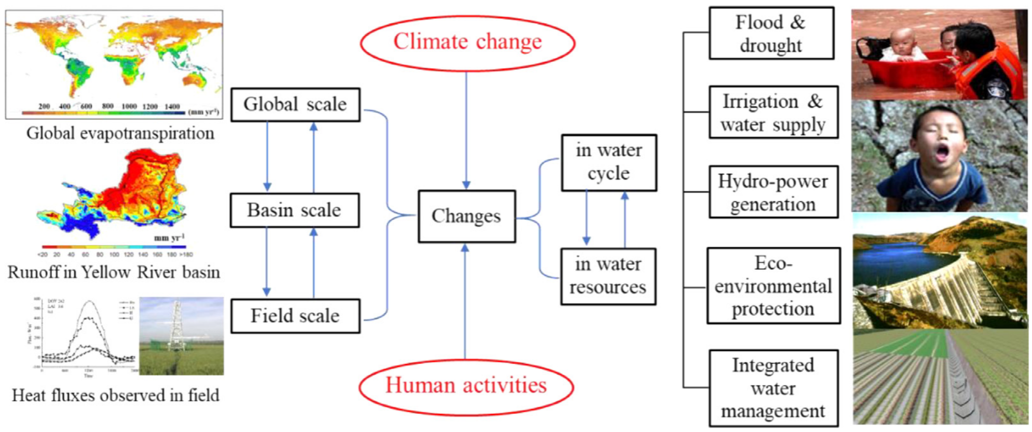

Fig. 1. Water cycle and water resources in a changing environment have cross-scale characteristics.

development of many economies globally including the: Yellow River basin in China (Chen et al., 2020); Murray-Darling Basin in Australia (Connell and Grafton, 2011); and Mekong River Basin in Southeast Asia (Ziv et al., 2012).

In this paper, we review the current status and existing issues of hydrological cycle and water resource research in the context of global climate change. We discuss the major challenges, key scientific issues and potential future research directions that need to be addressed in the future.

2. Current research status

The hydrological cycle includes hydrological processes at all scales within the hydrosphere, and is driven by solar radiation and gravity. The hydrological cycle is manifested in ocean-atmosphere-land interactions and the exchange of water and energy (Kleidon and Renner, 2013). Research into the global water cycle mainly focus on: macroscopic characteristics of the water balance, energy balance and hydrothermal coupling balance at varying temporal and spatial scales; and the fluxes in the hydrological cycle occurring at the land-air interface (Brutsaert, 2005). As shown in Fig. 1, water resource management involves studying the laws of formation, distribution, movement and evolution of water resources, and the application of these laws to meet human water needs and to manage environmental problems associated with these processes (Dingman, 2015). The main objectives of water cycle and water resources researches include: determining the temporal and spatial distributions of water resources; understanding the development and utilization of water resources during human development; and ecosystem conservation to ensure the sustainable use of water resources (Priscoli, 2000).

Traditional hydrological research is focused on: precipitation-runoff, evaporation, surface water–groundwater interactions; and water supply and demand in basins (Bierkens, 2015; Montanari et al., 2015). Many studies have treated the water cycle as an integrated system (Vogel et al., 2015). The water system has evolved from changes occuring in the terrestrial environment which ultimately influence the formation, deployment and utilization of regional water resources (Dingman, 2015). Some comprehensive studies of water systems have promoted the development of hydrology and other multi- and cross-disciplinary fields including: ecological hydrology; meteorological hydrology; cryosphere hydrology; urban hydrology; social hydrology; and global change hydrology. Together this has helped to expand the depth and breadth of water cycle and water resource research (see Fig. 2).

There is a growing need to develop and integrate methods and data sets to better address the complexity of the water cycle and water resource management. One way of doing this is through remote sensing which can provide large scale water cycle and water resources data over long periods for water cycle and water resources research. These data help to enhance our understanding of water cycle processes and mechanisms (Chawla et al., 2020). Advances in computer technology have increased the capacity for development of hydrological models ranging from simple conceptual models (such as the TANK model) to complex distributed and integrated water cycle process models (e.g., CLM). Data assimilation techniques that combine observations and numerical simulations are important for improving the accuracy of the water cycle and water resources simulations. The application of techniques such as big data analysis, artificial intelligence and machine learning to water cycle and water resources analysis is growing and will play increasingly important roles in facilitating in-depth research into water resources in the future (Chen and Wang, 2018).

2.1. Water cycle under global change

In the context of global warming, changes in the atmospheric system have accelerated temporal and spatial changes in the water cycle (Milly et al., 2005; Taylor et al., 2013), as well as exacerbating global and regional water shortages (Schewe et al., 2014). Climate change characterized by rising temperatures and more frequent extreme events such as heatwaves, heavy rains, floods, sudden droughts and persistent droughts have become critical concerns for the scientific community, governments, and the public (IPCC, 2014; Hao et al., 2018). Under climate warming, the global terrestrial cryosphere has undergone changes involving glacier retreat, snow reduction and permafrost degradation, all of which affects the water cycle (Ding et al., 2020). These impacts are in addition to those created by human activities (Vörösmarty et al., 2000; Wang et al., 2010b). Humans affect the water cycle through greenhouse gase emissions (Gordon et al., 2005; Piao et al., 2007; IPCC, 2014), as well as through water conservation projects and water consumption activities (Haddeland et al., 2014; Tang et al., 2015; Wada et al., 2017). Rapid population growth and increased consumption levels have put unprecedented pressure on the world's water resources (Dosdogru et al., 2020). Numerous studies are now focusing on the impacts of these global change on water resources (Tang, 2020).

The use of long-term historical data to analyze changes in the frequency, duration and intensity of hydrometeorological extreme events is the basis for understanding the impacts of climate change on hydrology. Sufficient evidence exists to indicate that climate change has already led to significant changes in the water cycle (Gudmundsson et al., 2021). In recent decades, attribution analysis of extreme events has developed rapidly, where long-term observations and model simulations, such as the CMIP climate model (Yang et al., 2020), have been used to compare the probability of extreme events in the presence or absence of climate change. Naveau et al. (2020) have developed methods for fractional attribution risk framework and optimal fingerprinting. How-

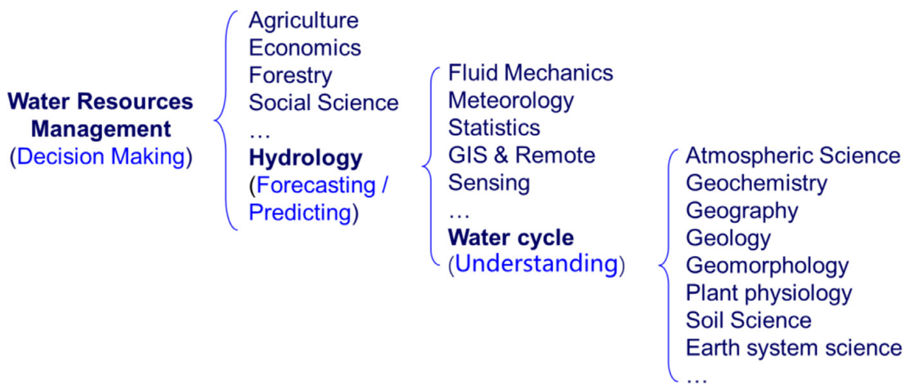

Fig. 2. Interdisciplinary approaches for understanding and managing water resources.

ever, Lott and Stott (2016) and Paciorek et al. (2018) have argued that there are uncertainties in the attribution of extreme events. The most reliable attributions are for extreme temperature-related events, followed by drought and extreme rainfall. However it is difficult to determine the impact of human factors on convective storms and extratropical cyclones. The effects of climate change, high-intensity human activities, changes in the underlying surfaces of basins, and non-stationary characteristics of hydrometeorological sequences lead to doubts about the traditional analysis methods for water resources based on the stationarity assumption (Lu et al., 2017). For example, the nonstationarity of runoff time series data has been studied by using the time varying moments model and the parameters of runoff probability distributions were linked to climatic or human activities indices (López and Francés, 2013; Du et al., 2015; Jiang et al., 2017). Non-stationary time series statistical models can reflect the changes in trends and covariates of the hydrometeorological extremes. However, the time-varying parameters used in non-stationary models estimated from the historical observations are not necessarily effective at predicting future trends (Milly et al., 2008). Thus, it is necessary to combine physical causes and to assess the impact of judgements about external environmental change.

By changing land-use humans affect the surface energy balance and the water cycle; intensities of extreme hydrometeorological events can be enhanced or weakened by land-atmosphere interactions (Diro et al., 2014). Given the heterogeneity of land surface processes and the susceptibility of feedback between land and the atmosphere to large-scale circulation anomalies, conclusions are lacking regarding the indirect impacts of underlying surface changes on extreme hydrological events and large uncertainties exist at the regional scale. The earth system approach based on the tightly coupled ocean-land-atmosphere processes is the main method used to: understand how the water cycle might vary under global change; and for developing appropriate prediction and estimation models. In recent decades, the maturing seasonal ensemble prediction technique based on the air-sea coupled climate model and land surface hydrological model has been applied to the prediction of extreme hydrometeorological events, such as persistent droughts and floods (Yuan et al., 2015). Regional climate or land surface/hydrological models fed with future climate scenarios are being used to simulate the frequencies, durations and intensities of future extreme meteorological and hydrological events. Combining future population and economic data to calculate indicators such as exposure or vulnerability to potential disasters could facilitate predictions of extreme event risk (Sutton, 2019). There are uncertainties in estimating extreme hydrological events and their risks due to large differences in outputs produced by different models (Yang et al., 2020; Ukkola et al., 2020). Thus, reducing the uncertainty of water cycle predictions and improving the ability to predict extreme hydrological events and their risks are major topics in water cycle research (Milly and Dunne, 2017).

As a consequence of global warming, rapid changes in the global cryosphere, such as ice, snow and permafrost have intensified the water cycle – thus there is an urgent need to increase research into these issues (Yao, 2019). The continuous change and expected future change in the number and size of glaciers, as well as the impact of changes in ice and snow on river runoff and water resources, are important research areas (Beamer et al.,2017). Research on permafrost mainly focuses on the current scale and speed of permafrost change (Wang et al., 2019; Zheng et al., 2020), as well as possible impacts on the water cycle and water resources (Wang et al., 2018). The development of global-scale glacier models has progressed recently, but physics-based glacier dynamics and frontal ablation processes are still lacking (Farinotti et al., 2020). Thus the glacier mass balance model needs to be linked with the hydrological model (Radic and Hock, 2014).

Because snow cover changes affect land surface heat transfer and runoff there is a need to increase remote sensing observations of snow cover and to use inversion technology to obtain more realistic data for use in hydrological models. In addition, research should be strengthened into snowmelt flood disasters. In terms of numerical simulations and predictions of cryospheric water cycle changes, multi-scale and multi-process coupled cryospheric hydrological models are urgently needed (Yang et al., 2015).

A major focus of hydrologic cycle and water resources research is on quantitatively describing the impact of human water use on the water cycle and evaluating the responses of land surface hydrological processes in light of climate change (Bierkens, 2015; Wada et al., 2017). In recent years, the parameterization scheme of human water use has been developed in land surface models (Pokhrel et al., 2016; Coerver et al., 2018; D'Odorico et al., 2018; Dosdogru et al., 2020). However more detailed land surface hydrological simulations and land-atmosphere coupling simulations are required to understand the interactions between human water use and the global hydrology-climate system.

2.2. Key processes and coupling in watershed hydrology

In recent decades, hydrological research has focused on the responses and mechanisms associated with alterations to the hydrological cycle in a changing environment. In particular, climate change has significantly modified the hydrological cycle, with an increase in extreme hydrologic events. Moreover, rapid social and economic development have affected human activities, and the demand for water in many parts of the world is increasing substantially leading to severe water shortages. To facilitate the sustainable development of human society it is necessary to expand the breadth and depth of the hydrological research, and strengthen understanding of the key processes using integrated research of the water cycle.

As shown in Fig. 3, atmospheric-hydrological coupled research can produce quantitative descriptions of the complete hydrothermal cycle process between the land and atmosphere, which is an important part of multi-process interactions in the water cycle in river basins. There is a need to elucidate the influences and feedback mechanisms for each link of the water cycle between the land and the atmosphere, and to improve the precision of hydrometeorological forecasts in river basins. Tra-

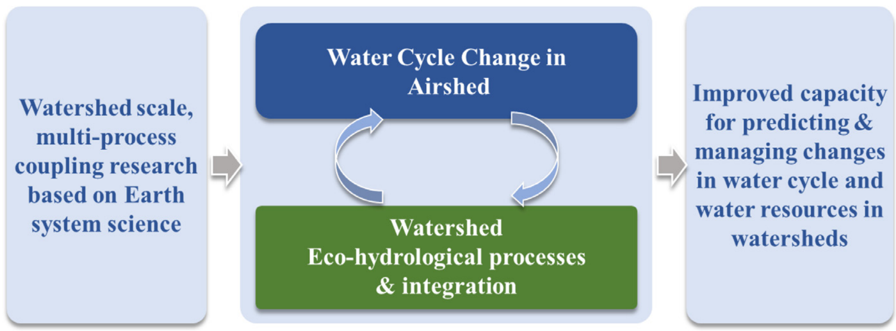

Fig. 3. Multi-process coupling and integration in watershed hydrology.

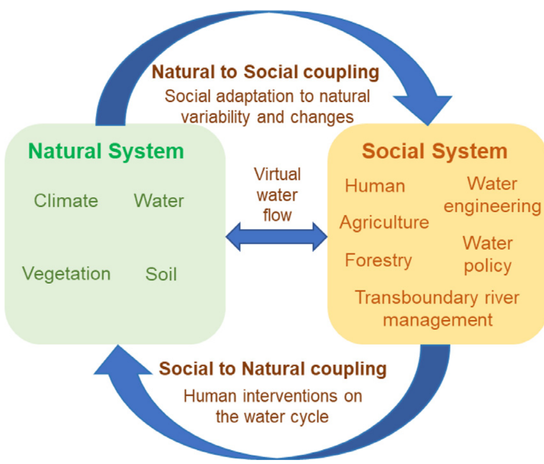

Fig. 4. Coupled natural-social water system.

ditional atmospheric-hydrological coupling studies have focused on the impacts of climate change on the hydrological processes (Donnelly et al., 2017; Hagemann et al., 2013). These studies have used one-way coupling methods, which are not suitable for a systematic understanding of the mechanisms associated with the hydrothermal cycle. However, further development of hydrological models and accumulation of observational data suggests that it is now possible to couple water use parameterization schemes (such as reservoirs and irrigation) into hydrological models so that the impacts of human activities on hydrological processes can be quantitatively evaluated.

Recently, hydrological studies have made remarkable progresses in multi-scale hydrological observations (e.g., Li et al., 2017), land surface-hydrology-society coupling simulations (e.g., Viola et al., 2021) and multi-source observation-model assimilation techniques (e.g., Liu and Gupta, 2007). This has significantly increased the breadth and depth of hydrologic research. Future hydrologic research should focus on: the changing laws and effects of the terrestrial hydrological cycle; the characteristics and mechanisms associated with changes in the hydrological cycle; predicting trends in the hydrological cycle; and the natural and social impacts of changes in the hydrological cycle. Water-based research should incorporate multi-scale and multi-process processes with the water cycle. The mutual coupling of multi-action processes has become a hotspot for cooperation across the physical, ecological, and biogeochemical processes in the coupled atmosphere–land–hydrological system.

2.3. Coupled natural-social water system

Qualitative and quantitative social hydrology research considers various social factors, such as the economy, environment, system, policy and consciousness and couples these social factors in the human–water system to serve as the internal social driving force (Fig. 4). Case studies of river basins are effective and greatly enrich exploration of the human-water coupled system. Depending on the amount of data available, various studies have analyzed the characteristics and laws of the co-evolving human-water coupled system according to the local conditions. In terms of the research scope, social hydrology has gradually expanded from considering irrigation and flood control issues to urban water use, water environment and cross-border water management problems (Sivapalan and Blöschl, 2015). The key areas for social hydrology research include: constitutive relations in social hydrology; comparative social hydrology; interdisciplinary research; and data collection (Sivapalan and Blöschl, 2015). Important factors for the further development of human–water coupled system models include: determining the constitutive relationships among social factors; selecting parameters; conducting sensitivity analyses; and enhancing the physical properties of the parameters.

Studies into the mechanisms associated with the coupled evolution of the human-water system based on hydrological sciences and interdisciplinary studies will become a hotspot for social hydrological research. Mining data and information from different sources can facilitate social hydrology case studies. Such case studies allow comparisons of watersheds under different natural and social conditions over various time scales and spatial scales, thereby helping to facilitate the coordinated evolution of the human–water system. Research methods and theories from various disciplines can be applied to quantitatively characterize social factors, improve the social equations and physical properties of the parameters resulting in better model simulations and predictions. Developing a robust model that yields better predictions will help to increase our theoretical understanding of the co-evolution of the human–water system. This will result in better water resource management as well as social and economic planning related to water resources – all of further our understanding of social hydrology.

Water, food and energy security are core elements of the United Nations 2030 Agenda for Sustainable Development (Obersteiner et al., 2016; Gao and Bryan, 2017; Bleischwitz et al., 2018). Coupled water–food–energy studies focus on natural resources and their interactions and feedback relationships from the perspective of systematic systems. This approach can overcome the traditional research paradigm based on single sector resources and it has rapidly become dominant in the international resources and environment field. In recent years, ecological environmental impacts caused by trade in products have attracted much attention, e.g., the flow of water among Chinese provinces and their cascading influences within and outside regions (Feng et al., 2014), and the trade between Chinese provinces and East Asian countries and their effects on land resources, water resources and energy. Most existing coupled water-energy-grain analyses were qualitative and lacked a deep understanding of the dynamic water–food–energy coupled system(Liu et al., 2018). There are a few models of the water–food–energy coupled system – the APSIM (Holzworth et al., 2018), the CoupModel and some other tools developed for the decision support (He et al., 2021). Coupled quantitative simulation models and decision support tools still need improvement. Investigating interactions between water, food and energy systems requires new methods and research. These

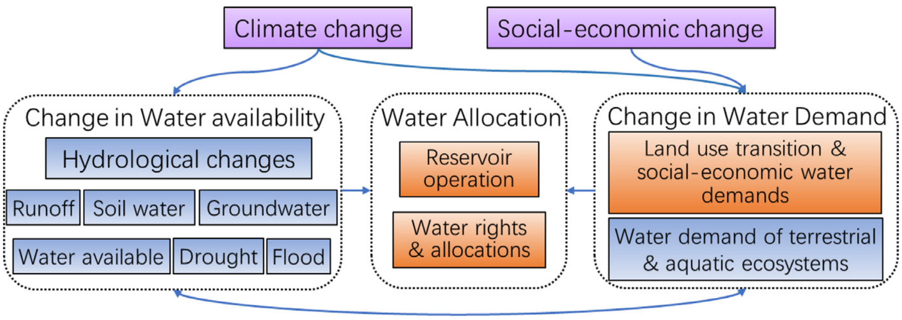

Fig. 5. Integrated management of watershed science.

methods must be able to resolve the interdependences between the systems in resource coupling relationships, as well as considering the complexity and multi-scale nature of systems of systems and their interacting mechanisms. These problems are difficult, but need to be addressed to facilitate policy-making and decision making.

2.4. Integrated river basin management

Due to the continuous development of the economy and society, the scarcity of global water resources has increased, and the competition and conflicts among users, departments and regions have grown(UNESCO and UN-Water, 2020). In addition, changes in the characteristics of water resources caused by climate change will continue to increase the uncertainty of future water resources and their associated risks (Milly et al., 2008). These new challenges affect the sustainable use of water resources, thereby demanding integrated river basin management as shown in Fig. 5. Due to the complexity of basin systems, effective information transmission is essential among the different modules of water resource management models, such as hydrology, ecological environment, economy, society, engineering and institution modules. The development of a comprehensive river basin model will allow the operation of hydrological systems, such as reservoir systems, groundwater systems and river basin systems to be driven by management goals, including socio-economic and ecological environment goals, while also considering constraints on water quantity and quality (Cai et al., 2002).

Future ecological watershed management research should focus on the integrity of the ecosystem, the mechanisms included in the model and the practical applicability to ecological regulation. It is necessary to consider the role of aquatic ecology in ecosystem integrity and to establish more scientific ecological assessment methods and models at the ecological mechanism level. Combining water ecological adjustments, such as human water demand and water conservancy project scheduling, can allow the formulation of goals for water ecological protection and the management of thresholds to help achieve the dynamic and harmonious coexistence of humans and nature (Ding et al., 2014). This is an important direction for future water system research. In the future, an ideal water resources management system should consider the uncertainties of the hydrologic and economic systems, as well as the adaptation mechanisms and behavioral characteristics of water users under changing environment and policy changes. This approach can guide the individual behavior of each water user to improve the efficiency and operability of water resources management systems.

3. Future development directions

3.1. Key processes and coupled integration of the water cycle

3.1.1. Eco-hydrological processes

Future studies of eco-hydrological processes need to address: the interactions of eco-hydrological processes and their feedback into the atmospheric system (e.g., Lian et al., 2020); the adaptation mechanisms of ecosystems to climate change and extreme hydrometeorological events (e.g., Vignola et al., 2009); the hydrological effects caused by changes in land use and cover (e.g., Luo et al., 2020); and ecosystem responses (Sannigrahi et al., 2018). The main focus of future research should focus on: (1) the co-evolution mechanism associated with the ecological–hydrological–geomorphological process in a changing environment and its response to extreme climate events and human activities; (2) coupling the complex mechanisms associated with underground ecological processes and water and soil processes; (3) coupling the mechanisms and models of the atmosphere–hydrology–vegetation in different climatic regions; (4) hydrological control mechanisms, ecological thresholds and stability in the ecosystem degradation and restoration process; (5) multi-scale ecological and hydrological observations and simulation methods; (6) eco-hydrological pattern, ecosystem carrying capacity and regulation; and (7) comprehensive integrated forecasting and management of the ecology–hydrology–social economy.

3.1.2. Hydrological processes in mountains

Mountains are sensitive to climate change (Belmont Forum, 2016), where the hydrological responses are closely associated with cryospheric processes in the alpine mountains (e.g., Wang et al., 2018). However understanding of alpine mountain hydrological change is limilted. Areas of future research on alpine mountain hydrology should include: (1) multi-source observation data fusion methods for snowfall and snow cover in high-altitude mountains; (2) observation technology needs to be developed to improve the automation and accuracy of observation; (3) methods for frozen soil monitoring combined with models and remote sensing to analyze changes in frozen soil at the basin scale; (4) developing distributed hydrological models based on physical mechanisms, including the glacier–snow–frozen soil cryosphere processes; and (5) simulation-based assessments of the impacts of changes in the cryosphere (glaciers, snow and permafrost) on hydrological processes in basins to quantitatively analyze the runoff effects of climate–cryosphere–vegetation changes.

3.1.3. Urban hydrological processes

In the past, urban hydrology focused on interactions between hydrology effects and urbanization (e.g., Zang et al., 2019). Coordinated development of the urban water system with the economy is key to city sustainability (Hoekstra et al., 2018). The key scientific areas that need to be answered in future studies include: (1) urban hydrologic monitoring and information acquisition technology; (2) hydrologic, ecological and environmental mechanisms in urbanized watersheds; (3) co-evolution of the urban water system and socioeconomic system; and (4) sustainable water use in urban agglomerations based on the water cycle.

3.1.4. Hydro–biogeochemical processes

Future research into hydro–biogeochemical processes needs to improve understanding of the coupled biogeochemical and water cycles and to fully consider the heterogeneity of landscape scales (e.g., Aufdenkampe et al., 2011). It is also necessary to understand how biogenic substances such as carbon, nitrogen, phosphorus and sulfur exchange with water and energy in the terrestrial–aquatic ecosystem, which is driven by hydrological processes from the molecular level to the ecosystem level (Vonk et al., 2019). A greater emphasis should be placed on the interdisciplinary integration of air, space and earth studies by focusing on the impacts of the interactions among environmental factors on ecosystem processes and functions (Lehtoranta et al., 2014). Areas for future research should include: (1) coupled interactions associated with the hydro–biogeochemical system cycle at the vertical-horizontal interfaces in watersheds; (2) coupling of biological, physical, and chemical processes in the watershed/regional biogeochemical cycle and the hydrological processes; (3) ecological processes and mechanisms associated with hydrology–biogeochemistry coupling; (4) impacts of global changes on hydro–biogeochemical processes; and (5) quantitative assessments of the impacts of changes in hydro–biogeochemical processes on environmental factors of the ecosystem, vegetation structure, biodiversity, water and soil.

3.1.5. Multi-process interactions and coupling integration in watersheds

A watershed is a complex system composed of water, soil, atmosphere, ecosystem and humans (Vogel et al., 2015). Under the multi-scale and multi-process interactions linked by the water cycle, water resources, water disasters, water environment and ecological problems in the basin are interrelated and affected (Vogel et al., 2015). Previous research has focused on changes and prediction of water resources, floods and droughts and why there is a poor understanding of integrated water problems (Blöschl et al., 2019). Thus key directions for future examination are: (1) interactions of multiple processes in different river basins; (2) modelling integrated watersheds with multi-processes coupling; (3) simulating and forecasting distributed hydrologic systems using big data and artificial intelligence in large river basins.

3.2. Natural–social water system and sustainable use of water resources

3.2.1. Social water cycle

The interactions between economic and social development and water systems are key issues for social hydrology research (Sivapalan and Blöschl, 2015). It is necessary to analyze: the interactions between the water system and society; clarify the impacts of the regional water cycle status on economic and social development; assess the impacts of the economic and social status on water system management control capabilities and water demand; the co-evolution of the human–water system; the scales of economic and social development; and the evolutionary trends in the water demand (Sivapalan and Blöschl, 2015). Future research into the social water cycle should focus on: (1) social hydrology data collection; (2) characteristics and mechanisms associated with the evolution of the human–water system; (3) analysis of human-water coupled system models; and (4) co-evolution theories of the coupled human–water system.

3.2.2. Water–food–energy system

Water, food and energy comprise a mutually coupled system, and understanding their relationships may be effective for solving water, food and energy security issues (Liu et al., 2018). Research into this system is also important for resource and environmental management and sustainable development (Liu et al., 2018). Future research areas include: (1) water–food–energy coupling mechanisms and mutual feedback mechanisms; (2) coupled water–food–energy models and decision support tools; (3) response of the coupled water–grain–energy system to external forcings; (4) mutual feedback among climate change, global trade and the coupled water–food–energy system; and (5) regional and global water-food-energy coupling and the cascading effects.

3.2.3. Water security and integrated river basin management for sustainable use of water resources

In a changing environment caused by both climate change and human activities, the water cycle and water resources have undergone profound changes (Milly et al., 2005), which have impacted human water use patterns (Raju and Kumar, 2018). The water resources system should be studied as a human–natural coupled system (Mao et al., 2017). One of the core issues is risk control to ensure the matching of human needs with the hydrologic system under unstable conditions (Milly et al., 2008). The scientific issues that must be addressed by integrated watershed management include: the evolution of the human–water relationship in a changing environment; coordination and dynamic adaptation of watershed systems; and intelligent decision-making (Mao et al., 2017). The key research areas include: (1) mutual feedback between water, food, energy and the ecological environment; (2) multi-stakeholder coordination and adaptation mechanisms; (3) evaluation, planning and management theories and methods to ensure water security and the sustainable water use; (4) hydrologic forecasting and combined use of theoretical methods; (5) dynamic forecasting and implementation of theoretical methods; (6) big data processing and water system knowledge discovery; and (7) water networking and smart water conservancy.

4. Conclusions

Research into the water cycle and water resources has enhanced social and economic development, and technological progress has further promoted research into the water cycle and water resources. The demand for social and economic development is the driving force that has promoted research into the water cycle and water resources which has been supported by technological progress. As the earth evolves into the human-dominated Anthropocene, the water cycle system is undergoing rapid changes in the context of global climate change with increasingly frequent extreme events disasters, cryosphere shrinkage, falling groundwater levels, water environment degradation and water shortages. Water is at the core of these problems. While these problems are related to natural factors such as extreme weather, human factors play a critical role. Some water problems occur at the local or regional scale, but their driving factors, impacts and feedback effects are often global. Thus research must be conducted based on the theory of earth system science. "Prosperity and detriment" is the eternal theme of the water cycle and water resources research, and it is important to improve predictions of changes in watershed/regional water resources and enhance the ability to prevent and reduce disasters in a changing environment. Water resources management must meet the needs of life, production and ecology in terms of the water quantity and quality, as well as having the ability to adapt to climate change by developing policies to mitigate water-related disasters.

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