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Review

Watershed Ecohydrological Processes in a Changing Environment: Opportunities and Challenges

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Abstract: Basin ecohydrological processes are essential for informing policymaking and social development in response to growing environmental problems. In this paper, we review watershed ecohydrology, focusing on the interaction between watershed ecological and hydrological processes. Climate change and human activities are the most important factors influencing water quantity and quality, and there is a need to integrate watershed socioeconomic activities into the paradigm of watershed ecohydrological process studies. Then, we propose a new framework for integrated watershed management. It includes (1) data collection: building an integrated observation network; (2) theoretical basis: attribution analysis; (3) integrated modeling: medium- and long-term prediction of ecohydrological processes by human–nature interactions; and (4) policy orientation. The paper was a potential solution to overcome challenges in the context of frequent climate extremes and rapid land-use change.

Keywords: ecohydrological processes; watershed management; climate change; human activity

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1. Introduction

Watersheds are the fundamental unit of Earth's terrestrial ecosystems and on a large-scale, watershed, agricultural, urban, forest, wetland, lake, and river ecosystems are important components of surface processes in the watershed [1]. Watersheds are complex systems with hierarchical structures and whole functions, and are composed of a water resource system, an ecosystem, and a socioeconomic system [2]. Thus, the watershed is the basic unit of hydrological response and the basic unit of hydrological and water resources research, making it the ideal basic spatial scale for the study of ecohydrological processes. In most situations, watersheds are typically characterized by complicated and prevalent human-natural interactions. Due to fierce water use competition between humans and ecology, the overexploitation of water resources has seriously deteriorated the watershed ecosystem. Many basins, such as theTarim River [3], the Yellow River [4], the Aral Sea basin [5], the Nile River [6], and the Mississippi River [7], and so on, have been confronted with the processes of severe ecological and environmental problems in the last few decades. Anthropogenic factors may directly lead to changes in ecosystem structure and thus have an impact on hydrological processes (including water quantity and quality) [8,9]. Meanwhile,, water pollution, water withdrawals, inter-basin transfers, and dams are also affecting the ecosystem [10].

Watersheds provide a range of ecosystem services (for example, water yield, climate regulation, soil conservation, primary productivity, and biodiversity) [1]. Unfortunately, climate change and human activity have seriously deteriorated the watershed ecosystem (such as water shortages, water quality worsening, biodiversity loss, and desertification) [11], and consequently have caused a set of environmental problems that threaten water security, food security, and ecological security [12]. Collectively, they have profound implications for the water and biogeochemical cycle, but these implications are not fully understood [10]. Considering that conventional approaches based on watershed management, conservation, or technological solutions to address environmental degradation have often failed or fallen short of their goals [13], it is especially important that ecohydrology has the potential to address these pressing environmental issues. As a result, ecohydrology processes are a major concern for the sustainability of water resources and ecosystems around the world. Ecohydrological studies typically focus on understanding the linkages, interactions, and feedbacks between hydrologic flows and ecosystem processes, as well as how these interconnections are manifested and exert distinct controls across multiple scales [14]. At the basin scale, ecohydrology processes are complex systems influenced by many interacting factors such as terrain, precipitation, humidity, air temperature, soil and vegetation type, land use, and land cover. Many researchers believe that climate change and land-cover change are usually the two most critical factors affecting watershed ecohydrological processes [15–18]. Some studies discovered that the effects of underlying surface conditions and climate variability on changes in terrestrial ecosystems in large-scale watersheds around the world are comparable [19,20]. Watershed ecohydrology processes are essential if we are better to understand how the changing environment impacts the complex watershed systems and support integrated river basin management. Additionally, the development of watershed ecohydrology processes agrees with the philosophy of the Global Water System Project (GWSP) [21], the Panta Rhei [22], and the Future Earth program launched by the International Science Association (ICSU) [23] and will contribute to solving the last category of the twenty-three unsolved problems recently identified by the hydrology community [24].

In addition to anthropogenic hydrologic alterations, future changes [25] in climate will likely further impact watershed ecohydrology processes. Water is an important factor in maintaining the balance of ecosystems. The spatial geographic locations of watersheds vary, and climatic elements (such as precipitation, evapotranspiration, and temperature) also change, directly affecting the water cycle and the distribution pattern of vegetation in the watershed [26]. On the one hand, climate change can directly affect the ecosystem's precipitation recharge [27] and temperature rise [28] to increase evapotranspiration, while changes in the watershed water cycle can affect the ecosystem's ecohydrological processes [29]. On the other hand, climate change brings floods [30] and droughts [31], and extreme hydrological events seriously interfere with the normal hydrological fluctuations and hydrological cycles of ecosystems, affecting ecosystem patterns and even degrading and disappearing functions [11]. The interaction between land-use change and climate variability and the directionality (increase or decrease) of both in water resources change; therefore, both have important synergistic or counteracting effects on water resources change in terms of quantity or quality, but, in any case, they pose important challenges for future watershed ecohydrology management.

Integrated water resources management (IWRM) theory considers that there is a correlation between water resources, water environment, water ecology, and water hazards in a basin [32] and that a series of problems arising in a basin under a changing environment is the result of coupled ecological and hydrological processes [33]. Understanding how these challenges and opportunities associated with watershed-based management affect the ecohydrological processes is crucial to producing actionable science and developing efficient and equitable watershed management programs [34]. Linking IWRM and ecohydrology for the sustenance of watersheds and environmentally friendly economic activities is vital for ensuring continued water flow and a steady supply of watershed services for societal needs, and the integrity of aquatic vegetation and animal species [35,36]. However, a comprehensive description and summary of how changing environments affect watershed ecohydrological systems and water resources management is lacking. Indeed, the combined role of drivers, i.e., climatic and non-climatic factors, in ecohydrological processes remains a major challenge for the field and, despite the range of scientific research projects proposed, the question remains as to how to face the challenge in the future. The challenges relate to three issues: (1) how to identify and quantify the specific contributions of natural and human drivers of ecohydrological dynamics; (2) how to assess and model the combined effects of global change interactions on ecohydrological processes in watersheds; (3) how human societies can respond to rapidly changing climate and land use.

With these requirements in mind, we cover four objectives in this paper, as illustrated in Figure 1. To address these aims, this paper is organized as follows: initially, how human activities and climate change affect ecohydrological processes are presented in Section 2; Ecohydrological models and integrated water resources management (IWRM) in a changing environment are part described in Section 3 and Section 4 respectively; while Section 5 provides a discussion of the opportunities and challenges facing ecohydrological processes in watersheds; and finally, in Section 6, we make some conclusions.

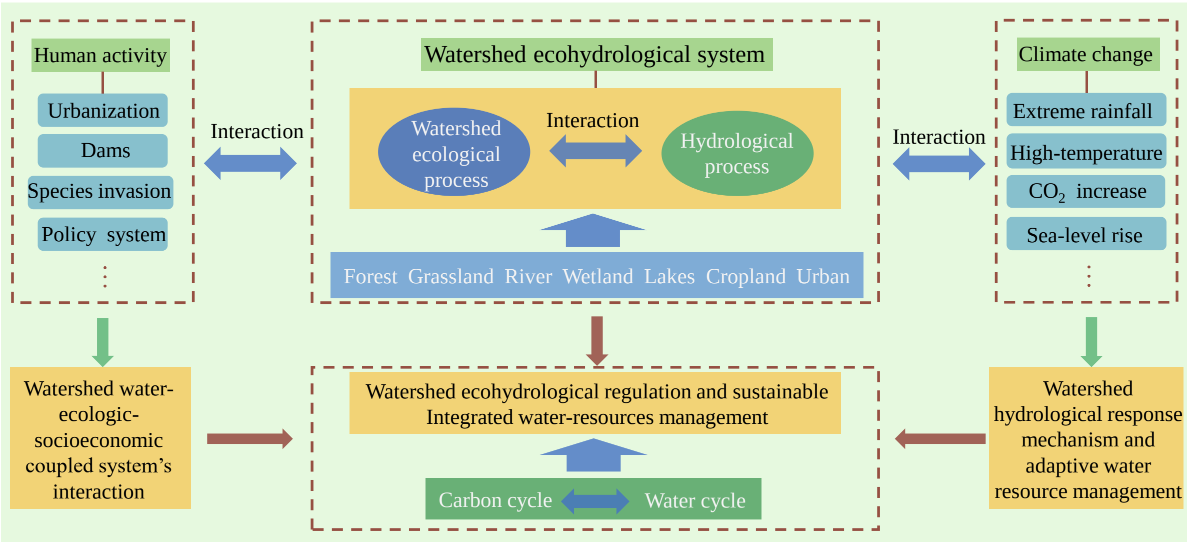

Figure 1. Key objectives ecohydrological processes in watersheds.

2. Ecohydrological Processes

In recent decades, researchers have gradually found that climate change and land-use change can alter the water balance [37], energy balance [38], and carbon budget [39] of watershed systems. Subsequently, they will have unpredictable effects on ecohydrological processes (Figure 2). Among these, ecological processes focus on the dynamic characteristics of plants, animals, and micro-organisms in a changing environment. Hydrological processes are concerned with the evolution of the hydrological cycle including precipitation, evaporation, infiltration, and runoff in a changing environment (Figure 2). Ecohydrology has evolved over the decades and research in each of the related fields has involved multiple scales (Figure 3). At the catchment scale, ecological process studies focus mainly on plant water use and coupled water–carbon modeling. Hydrological processes are mainly concerned with key processes of the water cycle, such as evaporation and runoff. Then, we will discuss ecological and hydrological processes under environmental change separately, which are important for watershed ecohydrological management.

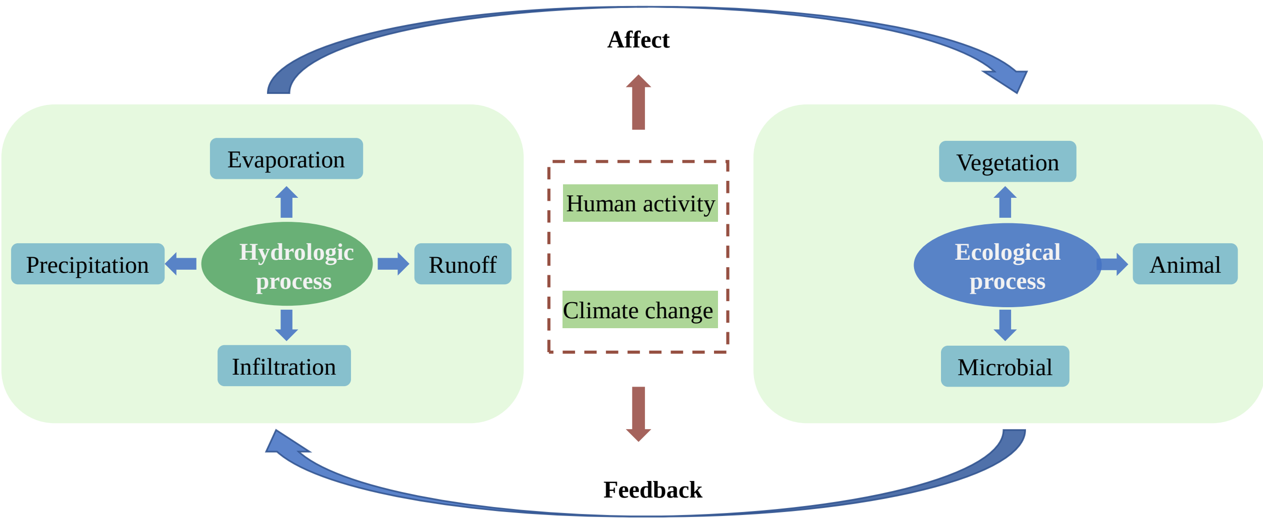

Figure 2. The interactions and feedback between hydrologic processes and ecosystem processes.

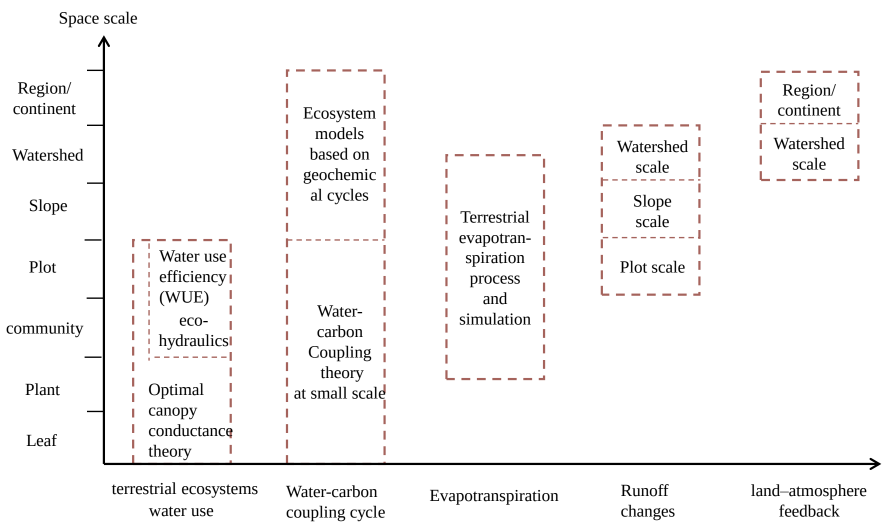

Figure 3. Research hotspots and spatial scales of ecohydrological processes. Adapted with permission from Ref. [40]. 2021, Genxu Wang.

2.1. Ecological Processes

Watershed ecosystems include terrestrial and aquatic ecosystems. Terrestrial ecosystems play a significant role in carbon sequestration, water purification, soil retention, sandstorm prevention, and water retention. Aquatic ecosystems make a positive contribution to water supply, pollutant dissipation, flood regulation, and drought resistance. At present, watershed ecological processes mainly focus on the dynamic evolution of vegetation structure, carbon cycle, and ecological restoration.

2.1.1. Ecosystem Structure and Function

The prompt environmental changes include rapid climate change without historic precedent, in addition to land use change, resulting in a widespread transformation and depletion of ecosystem structure and function [41]. Water quality, water quantity, and human activities are the dominant factors of vegetation community change in the watershed dominant factors. Ecological environments, especially the primary producers, are being affected by climate change factors, including changes in temperature, precipitation (including floods and droughts), and atmospheric carbon dioxide.

Sudden climate change can have a dramatic impact on water availability, plant productivity, and land–air interactions. At the beginning of this century alone, there was a 7% increase in global semiarid climate conditions. This is due to the arid conditions in the Western Hemisphere and wet climatic conditions in the Eastern Hemisphere switching to semiarid [42].

Ajaz Ahmed et al. [43] used geographically weighted regression (GWR) to model forest ecosystem processes at the watershed scale and to explain the influence of ecological drivers in the southeastern United States, which provided insights for identifying and better understanding the effects of climate factors. Medvigy et al. [44] found that ecosystem function is coupled with meteorological variability (e.g., precipitation and solar radiation), which leads to a reduction in carbon storage. Some studies have assessed the impacts of climate change on animals. For example, de Moraes et al. [45] projected species distribution models for the 16 endemic bird species considering the two future gas emission scenarios (optimistic and pessimistic), which showed that six of these birds species will have less than 10% or no future suitable habitat due to climate change in all emission scenarios at least by 2050. Extreme climates (e.g., droughts, floods) can be devastating to ecosystems, and although some reports indicate that brief droughts increase species richness [46], direct or indirect (pest [47], wildfire factors [48]) declines in terrestrial ecosystem biomass resulting from drought are substantial [49]. At the same time, the impact of human-induced land-use change on ecosystems has received widespread attention [50]. Wasser et al. [51] quantified land use effects on forested riparian buffer (FRB) vegetation structure using LiDAR data that found that about 50% of streams in the watershed had FRB corridors <= 30 m wide. A growing body of research is proving the idea that ecosystems adapt to a range of human activities such as agricultural activities, urbanization, deforestation [52], inter-basin water transfers [53], etc., through dramatic restructuring (e.g., changes in species structure, biological invasions, reduction in biodiversity, etc.). Similarly, for aquatic ecosystems, it is widely accepted that the influence of anthropogenic disturbance on most hydrobios was primarily negative. Species invasions may reduce biodiversity and the value of ecosystem services, and increase drought across the region, indirectly contributing to desertification. There are many causes of ecological invasions, from overproduction to wildfires to changes in rainfall patterns to CO_2 concentrations. Moreover, these causes are often interrelated and interact with each other [54]. In summary, there are some responses to climate change and human factors for ecosystem structure, such as changes in species composition and shifting geographic ranges and distributions, and it may be negatively affected in most areas. Changes in ecosystems directly or indirectly affect watershed ecohydrological processes, altering watershed water quantity and quality [55], and posing challenges to sustainable watershed management.

Due to the population explosion, there is a global need for ecosystems to provide more services; however, dramatic global change, including unprecedented climate change and human disturbance, has led to large-scale declines and shifts in ecosystem services (ESs) [56]. Runting et al. [57] indicated that the influence of climate factors on most patterns of ESs was primarily negative, with a ratio of 59%, but varied with service types, driving factors, and assessment methods. For example, Zhang et al. [58] analyzed the impact of climate change on Chinese forest ecosystem services using the value of ecosystem services approach and found that the area of Chinese forest is decreasing; however, the value of Chinese forest ecosystem services is increasing in the context of global warming. A recent study showed that most of the research on climate change impacts on ecosystem services is concentrated in developed countries (26% in the United States and 42% in Europe), but it is more important to follow up with developing countries, which are more sensitive to climate change. The same thing happened in developing countries, such as China, where the urbanized area and bare land area increased by 170% and 84%, respectively, between 1978 and 2008, resulting in a 24% reduction in local cultural services, due to dramatic social development and the absence of detailed ecosystem service assessments [59]. A growing number of studies have demonstrated that anthropogenic disturbance on ES changes towards the bad side. A range of climatic factors, such as temperature and precipitation, are likewise included in most studies of the effects of land-use change on ESs [18]. The same study pointed out that the interactions and feedbacks between drivers are usually not accurately described when considering the combined effects of meteorological changes and non-meteorological factors, which may lead to different results. This may be because many of the ecosystem services that people specifically need are mutually dependent [60].

In summary, the impact of global change on ESs needs to be quantified to obtain a more accurate assessment, which is significant for policy management. In the context of global warming and climate mitigation (e.g., China, the U.S., and Europe have successively proposed carbon neutrality targets), there is still a great deal of uncertainty about future climate and land-use changes. General circulation models (GCMs) based on different scenarios of shared socioeconomic pathways (SSPs) and representative concentration pathways (RCPs), provided by the Intergovernmental Panel on Climate Change for the fifth assessment process, can be used to quantitatively explore ES changes caused by the interaction of various driving forces (Figure 4). Previous land use projections have mostly been made at low spatial resolution and do not take into account global economic development and climate mitigation policies. To overcome these limitations, in this paper, a coupled SSPs and future land use simulation model (FLUS) is proposed to quantitatively simulate future land use/cover change (LUCC) under different scenarios. In addition, to improve the accuracy of basin-scale future climate simulations, in this framework we coupled the regional climate model RegCM4, which improves the resolution of general circulation models and improves climate factor errors (Figure 4).

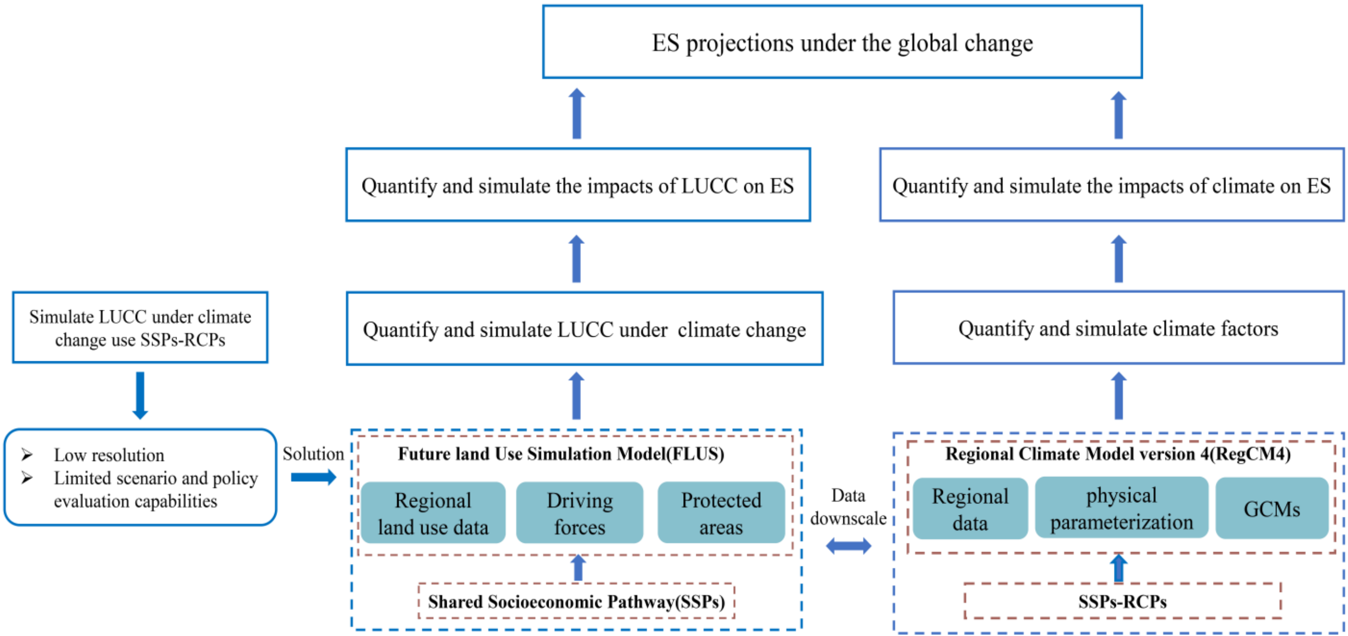

Figure 4. The challenges and solutions of quantitative assessment and simulation of effects of climate and land-use change on variations in ecosystem services.

Most studies have often led to uncertainties in assessments and simulations due to the difficulty in quantifying the impact of land use and climate change interactions on ESs. Studies on global climate change suggest how terrestrial and aquatic ecosystems will respond to the coupling of such dramatic changes in hydrological processes with land-use change, due to climate change that will lead to a general intensification of the Earth's hydrological cycle in the future, accompanied by a general increase in precipitation, evaporation, and extreme weather events, is a serious challenge for the study of ecohydrological processes in watersheds. Based on these results, this paper proposes a new research framework (Figure 3) that aims to provide a potential solution to key future research questions.

From the above, it can be seen that dramatically changing ecosystems contribute to changes in the water and carbon cycles, further altering watershed biogeochemical cycles [61,62], which affect all aspects of the watershed hydrological cycle, including surface runoff, groundwater recharge, evaporation, etc. Previous work provides the basis for subsequent research on the impacts of climate change and land use on ecosystems, including drivers, sensitivities, and research frameworks. Future research needs to further consider climate–land-use change interactions in a socioeconomic context and apply process-based models to quantitatively assess and predict the potential impacts of changing environments on future ecosystems.

2.1.2. Carbon Cycle

The carbon and water cycles of ecosystems interact and together form a biogeochemical cycle, specifically, which may provide a more resilient ecological structure [63]. From the perspective of a paleoecologist, human and climate change may cause changes in ecosystem properties, but because ecosystems are resilient and buffer such changes, in the end, ecosystem function does not change substantially. This seems to be a revelation about the dilemma facing human society today, where, on a scale of tens of thousands of years, mankind destroys only itself.

The role of the carbon cycle plays in the ecohydrological processes of watersheds was essential to protect ourselves. It is widely believed that excess ecosystem carbon storage contributes to higher gross primary production (GPP), which often leads to inadequate water supply in the basin. Different geographical locations and land management may have different impacts on carbon cycling in watersheds [64,65]. For example, Forzieri et al. [66] showed that, considering the continuous global warming and a possible intensification of natural disasters in coming years, carbon sequestration could be severely decreased in the near decades. On the contrary, climate change displayed a positive effect on carbon storage in the Alps, because growing temperatures facilitate forest expansion into higher altitudes. Forest ecosystems are the largest terrestrial carbon reservoir, accounting for 39% of global soil carbon stocks. The next closest ecosystem in terms of carbon storage is the peatland [67]. The draining of water from peatlands and their use for farming and forestry by humans has led to the degradation and damage of large amounts of peatland and the deposition of thousands of years of carbon, which could be released overnight. Sixteen per cent of global peatland loss comes from similar human activities. Rewetting has been proposed as a climate change mitigation strategy to reverse this trend. In the last decade, a growing number of studies comparing greenhouse gas emissions from rewetted and virgin peatlands have shown that reactivating the system can reduce greenhouse gas emissions, but these studies have generally been based on shorter time series, while studies on the carbon sink of reactivated drained peatlands are scarce, so the net effect of rewetted peatlands on global warming remains uncertain [68].

It is important to note that carbon cycling often has an impact on water quality as well. The release of nutrients from human activities increases carbon accumulation in lakes and rivers, leading to eutrophication [69]. In a warming climate, the increase in the concentration of carbon dioxide in the air also leads to changes in water pH, which, to some extent affects spawning favorable environmental conditions. In most case, water use efficiency closely is related to interactions between the carbon and water cycles at the watershed scales [70], which can be used to predict the impact of the carbon cycle on hydrological processes in a watershed.

In summary, much of the research has focused on quantifying the processes that couple ecosystem carbon stocks and the hydrological cycle. Water cycle processes directly drive biochemical processes, which in turn influence ecosystem community succession and productivity. At the same time, reactivation of drained peatlands has become a research hotspot in the field due to the increasing urgency to adapt to and mitigate the effects of climate change. The interactions between ecohydrological processes and biological systems, such as coupled carbon–water processes, should be further strengthened in the future to provide scientific guidance for the conservation and realization of sustainable ecosystem services.

2.1.3. Ecological Restoration

The practice of ecological restoration or eco-restoration is becoming increasingly important in the face of increasingly degraded ecosystems. Although there is much ambiguity about the drivers of ES change, appropriate policy and management can be effective in improving ESs. For example, Ouyang et al. evaluated the results of the first phase of ecological restoration in China and the study found that natural restoration had a positive effect on most ecosystem services, particularly carbon sequestration, soil, and water conservation. Mayrinck et al. [71] assessed the environmental benefits of afforestation in Canada and found that shelterbelts have significant potential to mitigate climate change.

Ecological restoration projects often place enormous pressure on regional water resources while improving ecosystems. China's ambitious Three Northern Protected Forests program is likely to consume large amounts of water in the future, placing enormous pressure on the demand for water from local people and ecosystems [72]. As a result, these protected forests are showing signs of degradation, especially in arid and semiarid areas [73]. The same confusion exists in the alpine zone, where reforestation policies and natural forest conservation programs have not increased the value of ecological services in northeastern China [74]. This all reflects ignorance of ecological water demand thresholds. Numerous global change articles show that the environment is likely to worsen in the future, and ecological restoration practices that do not take climate change into account may lead to worse ecosystems. The implementation of ecological restoration plans must consider the natural resources and human socioeconomic activities of the regional ecosystem at the watershed scale, which leads to difficulties in identifying and quantifying ecological water demand thresholds for watersheds.

2.2. Hydrological Processes

The recent global water crisis and intensifying climate change have raised widespread concerns about water scarcity and deteriorating water quality around the world. Ecohydrological processes are critical in providing effective information for policymakers and managers to address water resource challenges. Decades of research into the hydrological functioning of managed and unmanaged watersheds have provided a solid basis for understanding how watersheds respond to human disturbance and management activities. However, the empirical, theoretical understanding we currently observe may not be sufficient to address the problems we face today [75]. Global environmental change has affected the hydrological cycle in watersheds, heightening concerns about watershed water quantity and quality.

2.2.1. Watershed Water Cycle

A major factor threatening the hydrological cycle of the basin is the explosive growth of the population [76,77]. Population growth, socioeconomic development, and the deterioration of the water environment over the past decades have led to increasing global demand for freshwater resources, even in water-rich regions of the world [78]. By 2030, the world is expected to face a 40% global water shortage under a business-as-usual scenario [79]. In contrast to other water resource management, inter-basin water transfer projects are an important way to quickly alleviate regional water imbalances and functional water shortages. As a result, global water diversion projects have been increasing in recent years [80], particularly in China, including the famous South–North Water Transfer Project [81]. The diversions have, to some degree, increased the hydrological connectivity of the basin [82], improved water quality, and mitigated eutrophication in closed water bodies, but the introduction of water bodies with higher pollutant loads could lead to ecosystem degradation and functional shortages of water resources [83]. Accordingly, the operation of the transfer project may alter flows in the basin and further affect water quality [84].

The water cycle is affected by the physical environment of solar radiation and volcanic eruptions, as well as by fluctuations within the climate system, and there is ample experience from the paleoclimatic record of significant changes in the past [85]. As the climate warms, the general increase in atmospheric greenhouse gases drives dramatic climate feedbacks [86], exacerbating atmospheric moisture transport and associated extreme precipitation events, and increasing atmospheric absorbed energy and reflected radiation which regulate evaporation and precipitation on a global scale [87], leading to a global redistribution of water resources [88]. The interaction and feedback of regional climate change and basin hydrological cycle processes has become one of the most important issues in the study of hydrological processes. In general, weather patterns controlled by large-scale atmospheric circulation as well as small-scale physical events alter key water cycle characteristics, such as the frequency, intensity, and duration of rainfall, and change the number of water resources available [89]. On land globally, precipitation varies considerably from year to year and decade to decade, especially concerning to the El Niño–Southern Oscillation (ENSO), but precipitation on land is generally increasing [90]. As surface temperatures continue to rise, heavy precipitation is expected to become more intense in the world's major basins [91–97], and basin droughts are becoming increasingly severe at a constant annual precipitation level [98–102]; a recent article based on a PRISMA scoping review of drought impacts found that the lack of a standard drought index may be a major impediment to studying drought impacts [103].

Higher atmospheric temperatures increase the water-holding capacity of the atmosphere by about 7% per degree Celsius, causing a general global rise in evaporation; evaporation is regulated by energy fluxes over wet regions, but for drier regions evaporation is limited by surface water availability, which, in wetter watersheds, can result in higher potential evaporation [104,105], while in arid and semiarid regions means dryness and more intense and prolonged droughts [106]. Therefore, the water cycle responses during wet and dry periods are expected to be distinctly different on seasonal or sub-seasonal timescales. The reaction of plants to climate variability and rising atmospheric CO_2 levels also shapes the intensity of evaporation from watersheds. Depending on how they change, plants may expand [107] or improve [108] the effects of warming on surface drought, as well as decrease evaporation from the land surface and aggravate decreases in continental relative humidity and precipitation, at the same time restricting increases in runoff [109,110].

Climate change has been found to not only alter evapotranspiration and precipitation patterns, but also to have profound impacts on water quality issues in lake reservoirs. Extreme high temperatures due to climate change are characterized by multiple spatial and temporal scales and multifactorial changes in water bodies, which may be more conducive to causing eutrophication in water bodies [111]. The impact of changes in CO_2 concentrations in water bodies on ecohydrological processes under global change has also received much attention in recent years, as the pH of water bodies is determined by their CO_2 balance, and it has been shown that elevated atmospheric CO_2 concentrations directly or indirectly increase CO_2 concentrations in surface water bodies [112], producing large amounts of DIC and DOC [113]. The impact of extreme precipitation events on water quality is extremely important. Extreme rainfall events exacerbate the risk of non-point-source pollutant transport, increase pollutant loads to water bodies [95,114], are a major cause of water quality degradation, and pose a significant threat to human health [115] and biodiversity [116].

In the Anthropocene, human perturbations, indirectly through changes in atmospheric circulation caused by aerosols and greenhouse gas emissions, lead to a weaker hydrological cycle, which connects directly to the availability and quality of fresh water [117], and also naturally from disturbances to the land surface and the pumping of water from surface and ground systems for farming, commercial, and domestic uses [118,119]. Human activities directly modify land surface evaporation, with seasonal irrigation from agriculture increasing evaporation from the basin on the one hand [120], and land use changes, including deforestation [121,122], revegetation [123], and desertification, on the other hand, that may further modify evaporation from the basin by altering the surface energy balance and water balance, potentially affecting local climate. The influence of ecological structure on the hydrological cycle is huge and obvious [124]. Branch's study of the climate mitigation effects of large-scale plantations in desert areas found that the method could be used to modify regional climate and increase rainfall in arid regions, helping to alleviate the growing water shortage in arid regions [125]. However, afforestation programs that are not tailored to local conditions can also have negative effects [126]. China is recognized as a world leader in afforestation and has achieved considerable environmental success through large-scale afforestation [127], but due to inappropriate management upfront, additional tree cover adds additional evapotranspiration and expands local water use, and future climate change will further exacerbate local water conflicts [128].

Anthropogenic disturbances also directly influence precipitation patterns and runoff (including baseflow, flood flows, and dry flows), and water use to some degree offsets or governs regional climate change [129]. Large-scale deforestation may reduce rainfall, with numerous studies in the Amazon basin estimating smaller reductions in precipitation (about −2.3% to −1.3%) [130]. However, small-scale deforestation can actually increase local precipitation [131]. There is a long history of research into the effects of the evolution of ecosystems such as forests and grasslands on water quantity, with most studies showing that increased flows are often observed after deforestation [132,133] and that drought climates can be mitigated by forest management to increase surface flows and soil moisture during periods of extreme drought [8]. In contrast, afforestation may have a negative effect on runoff. Pei et al. [134] studied the hydrological impacts of large-scale afforestation activities in the mixed agro-pastoral zone of northern China. They found that afforestation caused a reduction in blue water and a gain in green water, and this study suggests that afforestation reduces annual runoff, which may have important implications for water management in the arid areas studied. Different plantations can also affect runoff, with Farley et al. [135] finding a 75% reduction in flow when eucalyptus was planted in grassland and a 40% reduction when pine was planted. The reasons affecting flow variability are complex, and current research has focused on the effect of vegetation characteristics on flow, with little attention paid to the spatial heterogeneity and temporal dynamics of the hydrological effects of non-preparation factors such as climate, topography, and soils [136]. Accurate assessment and prediction of vegetation type and spatial distribution in the regulation of peak and dry flood flows are very important for flood prevention and mitigation [137]. Different watershed conditions have led to different conclusions as to whether vegetation can increase dry weather flows and mitigate droughts as much as one would expect, and no uniform understanding has been reached [138,139]. This because the two effects of increased infiltration of forest to create baseflow and increased evaporation to reduce baseflow can cancel each other out, and the potential impact of forest management on groundwater infiltration recharge has been largely overlooked. As forests shrink and wetlands are destroyed, the basin's ability to produce high-quality water to be used, mitigate the effects of extreme precipitation events, and maintain a healthy basin ecosystem will also be undermined. Many factors influence flooding, and vegetation can only mitigate small to medium and local floods to a certain extent and cannot replace flood control projects [140]. The most immediate effects on the ecohydrological processes in the basin originate from the dams [141]. Large dams have transformed large rivers from flowing to static, resulting in variations in water levels and flows far beyond their natural magnitude due to massive evaporation of stored water or its diversion by humans for irrigation or water transfer [142]. On the one hand, dams undermine river connectivity and water stability by reducing seasonal flows, most notably by cutting peak flood flows and storage period flows [143]. For example, the construction of the Xiaolangdi dam mitigated 78% of the potential flooding in the Yellow River basin [144]. On the other hand, dams, by regulating seasonal flows, not only help to meet water demand, but also effectively mitigate river droughts [145].

In summary, it is clear that climate variability and anthropogenic disturbance are the main factors driving changes in the hydrological cycle and leading to spatial and temporal variability in water availability, and that identifying points of change in the natural water cycle is essential to distinguish between climate and human impacts on the hydrological cycle [146].

Currently, the methods used to study change points focus on experimental methods (e.g., time trend methods and paired basin comparison methods), basin models, conceptual methods (e.g., Budyko hypothesis and Tomer–Schilling framework), and analytical methods (e.g., climate elasticity methods and hydrological sensitivity analysis) [147], as shown in Table 1. While all of the above methods can analyze multiple causes of runoff changes in watersheds, the assessed impacts of climate change and human activities still differ significantly from the observed runoff changes, possibly due to conceptual oversimplification and the omission of some physical processes. Furthermore, while the direct impact of human activities, such as vegetation change and land use, on runoff is considered, the impact of indirect human modification of climate through greenhouse gas emissions is not analyzed [148].

Table 1. Attribution analysis and method on runoff changes.

	Method	Study Area	% Contribution of Climate Change to Change in Streamflow	% Contribution of Human Activities	Changes in Runoff from Base Period
Experimental methods	Time trend methods	Heihe River Basin, China [149]	8–76%	24–92%	Increase
	Paired basin comparison methods	Small catchments in Australia, New Zealand, and South Africa [150]	10–72%	28–90%	Decrease
Basin models	Australia Water Balance Model	Poyang Lake catchment [151]	26.8%	73.2%	Increase
	SWAT	Dongjiang River Basin, China [152]	58%	42%	Increase
Conceptual methods	Budyko hypothesis	Weihe River Basin in China [153]	34.7–65.3%	30.5–69.8%	Decrease
	Tomer–Schilling framework	Midwest watersheds, US [154]	-	Mainly because of human activity	Decrease
Analytical methods	Climate elasticity methods	Weihe River Basin in China [155]	22–29%	71–78%	Decrease
	Hydrological sensitivity analysis	Yihe River Basin in China [156]	−19%	119%	Increase

The adverse impact of such activities is not confined to the quantity and distribution of water, but also increasingly affects water quality. Watershed ecosystems such as forests, grasslands, and wetlands not only hold the soil in place and absorb and recycle chemicals needed for growth, but they also break down and recycle substances that are harmful to biological health. Changes in the area of forests and grasslands can alter the soil erosion process, and the change of vegetation to other land uses in the watershed has increased the sediment flux of rivers, to some extent [157]. The Yellow River in China, for example, has the highest sediment flux of any river in the world [158], probably due to deforestation and agricultural development on the Loess Plateau from 960to 1950 [159]. Today, due to the revegetation [160,161] and the construction of the dam [162,163], the sediment content of the Yellow River is being reduced significantly. In addition to changes in physical properties, such as sediment and temperature, mining, agricultural activities, and dam construction in the basin can bring new pollutants into the river. For example, the conversion of forest to agricultural land is associated with an increase in riverine nutrients, leading to large-scale eutrophication [164]. The use of chemical fertilizers and pesticides has led to the widespread distribution of pesticides [165] and heavy metals [166] in the world's major watersheds. More than 80% of the world's transboundary rivers, including many large rivers, are heavily impacted by excess nutrients and industrial effluent discharges [167].

Overall, the impact of climate variability and subsurface change on the water cycle in the basin has progressed considerably over the last 20 years, both in terms of water quantity and quality. The processes affecting the hydrological cycle are complex, with results obtained at different scales or even completely opposite, and there is still no unified understanding. As ecological conservation requirements increase, new challenges are posed to the development and application of the basin hydrological cycle, and simplified ecohydrological processes do not meet current needs.

2.2.2. Urbanization Effects on the Water Cycle

As urbanization accelerates, the interaction between cities and the natural environment increases, and cities become one of the most intense parts of the interaction between human activities and natural systems, making the water cycle in urban areas increasingly complex. Changing surface thermodynamic and aerodynamic proper ties from urbanization can affect precipitation by altering stability and turbulence and can be further perturbed by the effects of aerosol pollution on cloud microphysics, while enhanced urban heat island effects are also thought to produce complex mesoscale circulation patterns, leading to urban moisture island effects and urban dry island effects [168]. Urbanization also tends to reduce surface permeability, leading to an increase in surface runoff, due to impermeable cover reducing soil infiltration [169]. For example, urban warming is significantly greater in the Yangtze Delta than in rural areas, with urbanization leading to a 0.75 °C average daily temperature increase, and the distribution of net radiation between sensible and latent heat is a key factor in controlling urban warming effects. At the same time, urban sprawl reduces water vapor from evapotranspiration, exacerbating the dryness of urban cores [170]. A devastating heavy precipitation event in July 2021 in the city of Zhengzhou in Central China, with a maximum 24 h precipitation of 645.6 mm, resulted in 292 deaths and 47 missing persons [171]. However, the physical mechanisms responsible for these extreme events, including mesoscale atmospheric circulation and local-scale urban atmospheric interactions, remain uncertain and poorly understood.

The process of urban expansion has also brought about a deterioration of water quality, both in surface water bodies and groundwater, especially in developing countries. The emerging organic contaminants (EOCs) [172] (e.g., pesticides, pharmaceutical microdyes, estrogens, microplastics, etc.), heavy metals (e.g., Pb, AS, Hg, Cd, etc.), and inorganic salts (e.g., nitrates, fluoride, etc.) in various water bodies have created new challenges for water management and pose a great threat to ecology and human health. For example, the Ganges River, the largest river in India, which supports 36.1% of India's population, has been rapidly urbanizing for a long time, and untreated industrial and agricultural wastewater has brought serious pollution problems; even banned pesticides are often detected in the Ganges, and the ecotoxicological risk of such banned products is very high [173]. In addition to physical and chemical pollution, microplastic pollution in the Ganges River is also of concern. The amount of microplastics in the river is closely related to population density and urbanization, and it is estimated that 1–3 billion microplastics are discharged daily from the Ganges River into the Bay of Bengal [174].

Urban ecohydrological processes profoundly affect the urban water cycle, heat balance, and the transport and transformation of pollutants, and these effects interact with each other, which, together with the high degree of social and natural coupling, makes urban ecohydrological processes more complex in both time and space. Most of the current research on urban ecohydrology is qualitative, and with the enhanced availability of multisource data, there is a need for more detailed research on urban ecohydrological processes.

3. Ecohydrological Models

We need to predict how climate change and human activities will change ecohydrology. Ecologists and hydrologists develop predictive models to predict how environmental changes will affect the hydrological cycle and the future characteristics of ecosystems. Many models have been developed to understand the effects of environmental change [175], but biological responses and hydrological changes remain difficult to predict.

One reason is that most models predicting changes in ecohydrological processes ignore underlying mechanisms, such as changing environmental interactions, ecosystem succession, and human economic and social impacts, and instead simply extrapolate the relevance of current climate change and land-use change to ecohydrological processes [176]. These omissions are troubling because we know that these missing ecohydrological mechanisms play a key role in regulating ecohydrological processes under environmental change. As unprecedented environments become more common, the current correlation between ecohydrological processes and climate and land use becomes irrelevant. The non-smooth nature of hydroclimatic conditions and ecological relationships challenge existing ecohydrological modeling approaches, for example, individual hydrological extremes (e.g., sudden floods or prolonged droughts) may have immediate ecological consequences that are unpredictable under long-term averages of long-term utilization data. Populations may be vulnerable to local extinction as a result of individual events or a series of extreme events. Non-smoothness will not only lead to changes in the environment but also to increased variability, which will expose ecosystems to more frequent and intense extreme hydrological events, which can also have a strong impact on biodiversity [177]. Process-based simulation models are currently limited but are emerging so that ecohydrological systems can be effectively assessed [60].

In addition, the development of ecohydrological models for watersheds is essentially an interdisciplinary problem, requiring the use of ecohydrology, sociohydrology, and socioeconomics in the modeling process [178]. Most of the existing models belong to independent disciplines, such as hydrological, ecological, and economic models, which usually separate natural processes from human socioeconomic simulations and cannot achieve dynamic feedback between socioeconomic and ecohydrological processes, and there is an urgent need to establish bidirectional coupling of complex human–nature systems [179].

4. Integrated Watershed Management

Traditionally, watershed management has focused on protecting and maintaining water resources through good land management—through the efforts of governments or social groups, the effects of conscious human activities (such as deforestation, urbanization, farming, and recreation) that result in land cover change can be avoided [180]. Such watershed management is important for sustainable watershed development, but what often happens is that watershed managers are forced to react. In other words, it is usually because something has such an unexpected negative impact on the ecosystem that a response is made. This pattern of reactive management can be seen globally and will continue. Examples of such reactive management can be seen in South Africa 100 million annual projects to eliminate invasive species to conserve water, in the United States' massive expenditure of resources on preventing and fighting wildfires and restoring watersheds after fires, and in China's recent launch of ecological conservation and high-quality development of the Yellow River Basin, which is expected to cost billions of dollars.

Another change that has occurred in watershed management is the widespread recognition that large-scale management of the landscape to increase water production has been an unrealistic (and frankly, rarely successful) solution to the growing water scarcity problem. The global watershed now faces a range of intractable problems such as frequent heat waves, widespread extreme precipitation, environmental pollution, desertification, and species invasions that are increasingly beyond the reach of traditional means. Ecohydrology has emerged as an integrated approach to managing water resources and ecosystems in watersheds, using an understanding of the relationships between hydrology and biology at the watershed scale to achieve improved water quality, increased biodiversity, and sustainable development [181]. Understanding water–biota interactions based on a comprehensive understanding of basin-scale hydrological processes and quantification of the hydrological cycle leads to quantification of nutrient cycling and energy flows, and finally to the use of ecological engineering and policy management for dynamic management of water, ecological, and socioeconomic issues arising in the basin. Sustainable agriculture [182], riparian buffers [183], artificial wetlands [184], rainwater harvesting [185], sponge cities [186], and other ecohydrological approaches are increasingly being used in integrated watershed management.

At the same time, a new paradigm of water resources management, which combines the needs of human socioeconomic development with the functions of ecohydrological systems, sees stakeholder participation as playing a crucial role in sustainable watershed management [187], and raising public awareness of watershed ecomanagement requires extensive publicity and guidance. The new integrated watershed management requires the combined efforts of ecologists, hydrologists, sociologists, government staff, and the public to dynamically develop holistic plans for integrated watershed management that take into account the changing circumstances of human activities and climate change.

5. Future Research Needs

Based on the above analysis of ecohydrological processes, we summarize the challenges of managing watershed ecohydrological systems in the face of unprecedented human disturbance and persistent climate variability. These challenges focus on the difficulty of quantifying the impacts of natural and anthropogenic factors on ecohydrological processes, the lack of assessment and prediction of ecohydrological interactions in a changing environment, and the development of policies to manage watersheds. To address these issues, we suggest a new framework for integrated watershed management (Figure 5) as a potential solution to the challenges and an important future research direction.

The new framework to address the above challenges consists of four steps: data collection; theoretical research; integrated modeling; and policy orientation. Specifically, multiscale datasets are the basis for identifying the drivers of ecohydrological processes and translating them to scale. In the face of a rapidly changing environment, integrated modeling provides technical support for predicting future ecohydrological processes in the basin and provides policy guidance for the future dynamic management of the basin.

5.1. Long-Term Datasets at Multiple Scales

Multiscale datasets are the basis for addressing key questions about ecohydrological processes, from the plot to the basin scale, and at different timescales. The focus of ecohydrological element observations remains at the point or plot scale. Remote sensing tools are an effective way to achieve expansion from point to surface scales. Therefore, in the future, there is a need to focus on building integrated multiscale detection networks such as ground-based observatories, remote sensing, and drones. Many of the discoveries that have led to major theoretical advances in ecohydrology are based on relatively long-term datasets, including understanding complex ecohydrological processes in the Heihe River Basin, China [2], and the ecohydrological impacts of species invasions in the southeastern United States [188]. Long-term datasets help to understand the time lag of ecohydrological responses to environmental change. Several ecohydrological monitoring programs have been established globally, such as FluxNet, NEON, EUROFLUX, and the Heihe Watershed Allied Telemetry Experimental Research (HiWATER) [189], and others. However, the construction of integrated detection networks for typical watersheds in developing countries is still lacking, and this is an important area for future work.

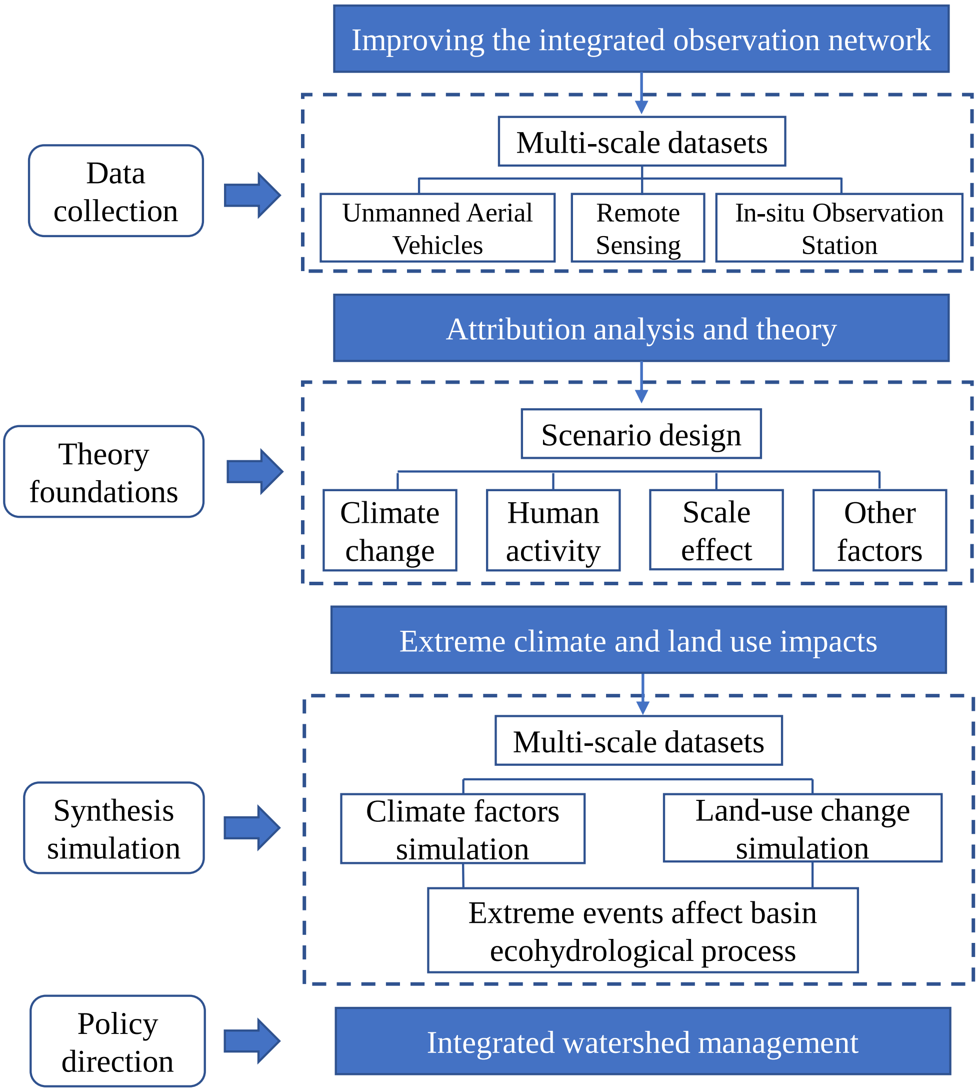

Figure 5. A framework for integrated watershed management in a dramatically changing environment.

In situ monitoring of natural systems at multiple scales, controlled experiments, and remote sensing provide rich datasets for understanding ecological processes, and developments in information technology and big data help to detect multiscale ecohydrological processes and strengthen the spatiotemporal links between socioeconomic and natural processes. However, the mismatch between natural and socioeconomic processes at different scales requires data assimilation to integrate data from different scales, disciplines, and sources. Developments in geospatial modeling, machine learning (ML), and deep learning (DL) make it possible to obtain useful information from a wide range of big data. Jin et al. [190] proposed a multisource data fusion method using the random forest algorithm to correct unreliable information and achieved an accuracy of 85.80% for land use data. However, as ML and DL models are difficult to interpret, they can easily be regarded as black-box models until the physical mechanisms involved are understood. Although several methods have been used to process the data, there are many sources of error in multisource data that may amplify the uncertainty in the output of the model, making the use of multisource data in ecohydrology still challenging.

5.2. Attribution Analysis and Scale Effect

Attribution analysis is necessary to better identify the factors influencing ecohydrological processes. The nonlinear relationships that lead to alternating thresholds and multiple states of ecohydrological processes are becoming clearer and clearer [191]. Such shifts can be gradual or suddenly triggered, especially when ecohydrological processes are affected by extreme events that produce unexpected conditions. In the context of watershed management, we need to quantify the impact of natural and human activities on ecohydrological processes and explore how they actually affect them. Examples include the analysis of alternating desertification and oasis attribution in arid systems, and the attribution of extreme events in urbanization processes. Ecohydrological processes are subject to both natural and human activities, exhibiting complex spatial and temporal heterogeneity and nonstationarity.

Ecohydrological processes are usually assessed at specific spatial and temporal scales, and results at different scales may be inconsistent or even lead to opposite conclusions. At the same time, the spatial heterogeneity of geographic patterns, climatic factors, and human activities leads to inconsistent influences at different scales. Fang et al. [192] studied the effects of rapid urbanization and climate change on ET in the Qinhuai River basin in China and found that the factors driving changes in ET varied with spatial scale. Shen et al. [193] suggested using units for specific planning/design/analysis purposes in the evaluation of ESs, but current research has focused on units with administrative boundaries (48.1%) rather than units with purposes (7.7%), which may not be sufficient to understand the multiscale evolutionary patterns of ESs. Scale effects make models of mechanisms often unreliable when extrapolated to new conditions, which requires the need to incorporate the scale effects of ecohydrological processes.

5.3. Understanding the Response of Watersheds to Climate Change and Land Use Change

The integration of climate and land-use change interactions is a key step in assessing and modeling the impacts of coupled climate and land use on watersheds. Scenario analysis can help people make decisions when they do not know what will happen in the future. It can also look at a wide range of possible extreme events that could happen in the future, which can be a good way to interact with coupled climate–land-use change. Phase 6 of the Coupled Model Intercomparison Project (CMIP6) can be an effective aid in coupling the effects of climate variability and land-use change when developing watershed management policies [194]. The shared socioeconomic pathways [195], i.e., SSP126, SSP245, SSP370, and SSP585, also provide information on population and economic development under different development patterns. Under diverse climate change scenarios, land-use change evolves in response to the adaptation of different development modes such as population policy and economic growth, to achieve the coupling of these two driving factors. For example, Wang et al. [196] proposed a framework that integrates the system dynamics model, PLUS model, and Integrated Valuation of Ecosystem Service and Tradeoffs (InVEST) model to dynamically simulate changes in LUCC and carbon storage at the city level based on SSP–RCP scenarios provided by the CMIP6. On the one hand, Allan et al. [197] used a participatory scenario development process that incorporated socioeconomic elements encompassing multiple scales and sectors, providing the necessary technical support and reference for future socioeconomic scenarios in the basin. On the other hand, Dong et al. [198] proposed a scenario-based land-use change framework that offers the possibility of modeling future land-use change in the basin. All of these projects provide a key basis for quantitatively assessing and predicting the impact of future environmental change on the ecohydrological processes in a watershed.

5.4. Integrated Watershed Management

Globally, integrated watershed-based water resources management is already widely practiced. Several disciplines, such as climatology, hydrology, ecology, sociology, and economics, work together to develop policies for watershed management, while stakeholder committees are established, both of which are being emphasized in almost all projects. The project "Integrated Study of Ecohydrological Processes in the Heihe River Basin", initiated by the National Science Foundation of China (NSFC) in 2007, is a good example of the implementation of integrated watershed management [199]. This stakeholder participatory and interactive planning approach will not only improve our understanding of the interactions between nature and society in the study basin but will also facilitate the interaction between science and management, integrating scientific research and social development into basin management. Through this interactive management process, water use and management scenarios will support water resource planning and decision-making. The performance of water resource carrying capacity or ecological thresholds in the basin will be calculated and compared through multiple sources of data collected, including remote sensing data and socioeconomic data, to evaluate the performance of water resource management plans across the basin. If the basin evaluation indicators before and after plan implementation show improvement and are consistent with safe water operating space, then the management plan will be able to meet the competing water demands of stakeholders across the basin and remain within the water security thresholds. Otherwise, the management plan will need to be revised to mitigate water resource issues. While significant progress has been made in every aspect of integrated watershed management over the past two decades, the collective decision-making process, including government decision-making authorities, scientists, and watershed stakeholders, has not yet been able to interact efficiently.

6. Conclusions

A good understanding of ecohydrological processes is essential for watershed ecosystems, human life, and economic growth. Increased demand for freshwater, unprecedented climate variability, and intense human activity will pose even greater challenges to the world's major watersheds [200]. Watershed ecohydrological processes will be at the forefront of watershed management science, providing decision-makers with the information necessary to ensure that watersheds are ecologically healthy. There is considerable evidence that many challenges to integrated watershed management remain, including the difficulty of identifying the effects of natural and anthropogenic drivers on watershed ecohydrological processes, scale effects in watershed ecohydrological processes, and how extreme climate events and rapid land-use change interact and alter watershed ecohydrological processes [201–203].

To adapt to these challenges and in the face of rapid environmental change, we propose a new framework for integrated watershed management. It includes (1) data collection: building an integrated observation network; (2) theoretical foundations: attribution analysis; (3) integrated modeling: medium- and long-term prediction of ecohydrological processes by human–nature interactions; and (4) policy orientation. This is a potential solution to overcome the challenges in the context of frequent climate extremes and rapid land-use change. Overall, this systematic review can provide important potential solutions for sustainable watershed management in a context of unprecedented environmental change.

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