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Progress in watershed geography in the Yangtze River Basin and the affiliated ecological security perspective in the past 20 years, China

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Abstract: Bibliometrics was used to statistically analyze key zones within the Yangtze River Basin (YRB) funded by the National Natural Science Foundation of China (NSFC) and national ministries over the past 20 years. This study determined that funds that derived from national ministries have mainly focused on issues related to environmental pollution, ecological security, technological water regulations, and river basin ecosystems, which offer a better understanding of the national requirements and the scientific knowledge of the YRB in combination with data from the NSFC. Under a background of bolstering the construction of green ecological corridors in the economic belt of the YRB, this study proposes future conceptual watershed research initiatives in this region as a study objective by reinforcing the implementation of the Chinese Ecosystem Research Network (CERN) and by emphasizing the use of new technologies, new methods, and new concepts for the prospective design of frontier research under the perspective of geoscience and earth system science. This study promotes large-scale scientific field and research objectives based on big science and big data.

Keywords: watershed physiography; ecological security; earth system science; critical zone; C-N-H_2O coupling; Yangtze River Basin

1 Introduction

In geographical research, which accounts for either part or the entire earth surface as a basic unit (Hou, 1994), many studies focus on specific land or water surface systems (Davis *et al*., 2003; Di Virgilio *et al*., 2018; Fu *et al*., 2019); however, few studies have focused on surface systems where land–water interactions take place (Fu *et al*., 2015). Watershed physiography

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regards a basin as its elementary unit, applying qualitative metasynthesis respective of rules associated with material, energy, and information flow among subsystems that include human activities, geographical environments, and water bodies in an interactive land–water interface (Grizzetti *et al*., 2003; Wei and Sun, 2009; Xie *et al*., 2010). Based on functional morphological research of watersheds within composite regional systems and including human activities in watersheds on both large and mesoscales, the coordinated development of the upper, middle, and lower reaches of river systems and the ecological compensations can be investigated (Kates, 2011; Fu, 2014; Hao *et al*., 2017). This can provide a theoretical basis for the rational development and the utilization of policy-making decisions wherein the "water body" is the core of a watershed, as well as contribute to socioeconomic development, environmental governance, and an improvement in the welfare of locals on a regional and a basin scale (Gao and Bryan, 2017; Fu, 2018).

The Yangtze River is the longest river in China and the third longest river in the world with a total length greater than 6300 km which includes 180×10^4 km^2 of watershed area that occupies approximately one-fifth of the total area of China. Furthermore, the population of the region accounts for about one third of the country, and the cultivated land area accounts for one quarter of the country. However, the total agricultural output value accounts for 40% of the country (Lu, 2018). Moreover, the mean annual amount of water that the Yangtze River discharges into the sea is 9600×10^8 m^3, accounting for 39% of all surface water resources in China (Zhou *et al*., 2008; Zheng *et al*., 2015). The middle and lower reaches of the Yangtze River, whose watershed ecosystems are diverse, ecologically fragile, and suffer from complex ecological problems, exhibit obvious regional characteristics, playing a key connective role between the east and the west of China, namely, the Yangtze River Economic Zone and the Green Ecological Corridor (Zheng *et al*., 2014). Under continued and progressively worsening human impacts in the Yangtze River Basin (YRB), the status of the ecological environment is increasingly becoming more severe, while the trend in ecosystem degradation has not been fundamentally reversed (Lu, 2018; Chu *et al*., 2019). In recent years, under conditions of climate change, the Three Gorges Reservoir impoundment operation (Zhou *et al*., 2016), the excessive construction of reservoirs in the upper, middle, and lower reaches of the river as well as an increased intensity in wetland development, the YRB has been facing increasing water and soil loss, floods caused by barriers between water systems, lake eutrophication, severe salinization (Xia *et al*., 2012; Struck, 2014), and degradation in biodiversity (Kong *et al*., 2019), leading to the rapid deterioration of ecological functions in the YRB. This has led to the urgent need for its protection and restoration.

However, there is a lack of a unified understanding on the current status of resources in the YRB as well as river–lake water system connectivity and an assessment of its environmental effects. Moreover, this lack of knowledge also includes spatial and temporal differentiation rules associated with water and material cycling in the YRB and associative driving mechanisms, critical zone watershed processes, and the evolutionary mechanisms of service functions, especially in forecasting future developmental trends in the YRB under a background of global climate change. Accordingly, this study comprehensively analyzes research hotspots and key funding fields associated with geographical resources and ecological environments within the YRB in recent decades, while proposing future geographic research objectives and the strategic design of scientific research in the YRB to ensure continued ecological security of the important, sustainable socioeconomic development role it plays in China.

2 Progress of research on the YRB in the New Era

2.1 Research hotspots in the YRB supported by the NSFC over the past 20 years

From March to April 2019, we collected 856 fund projects on the official website of the National Natural Science Foundation of China (NSFC) (http://www.nsfc.gov.cn/). The collection conditions were as follows: (1) these projects were concluded from 1988 to 2017; (2) application codes included: C03 (Ecology), D01 (Geography), D03 (geochemistry) and E09 (water science and Marine Engineering); (3) funding category included all fund types; (4) the research scope was the YRB. Over the past 20 years, high-frequency keywords associated with YRB studies have been the "Three Gorges Reservoir", "Taihu Lake", "water bloom", "eutrophication", "Three Gorges Reservoir area", "Poyang Lake", "model simulation", "geographic information system", "spatial analysis", "urbanization", "land use", "Yangtze River Delta", "land-use change", "climate change" and "human activities" (Figure 1). The "Three Gorges Reservoir" (with a burst strength of 5.38) is a "bursting" keyword, while "Taihu Lake", "model simulation", "urbanization", and "Yangtze River Delta" reside within the midsection of the keyword relationship network.

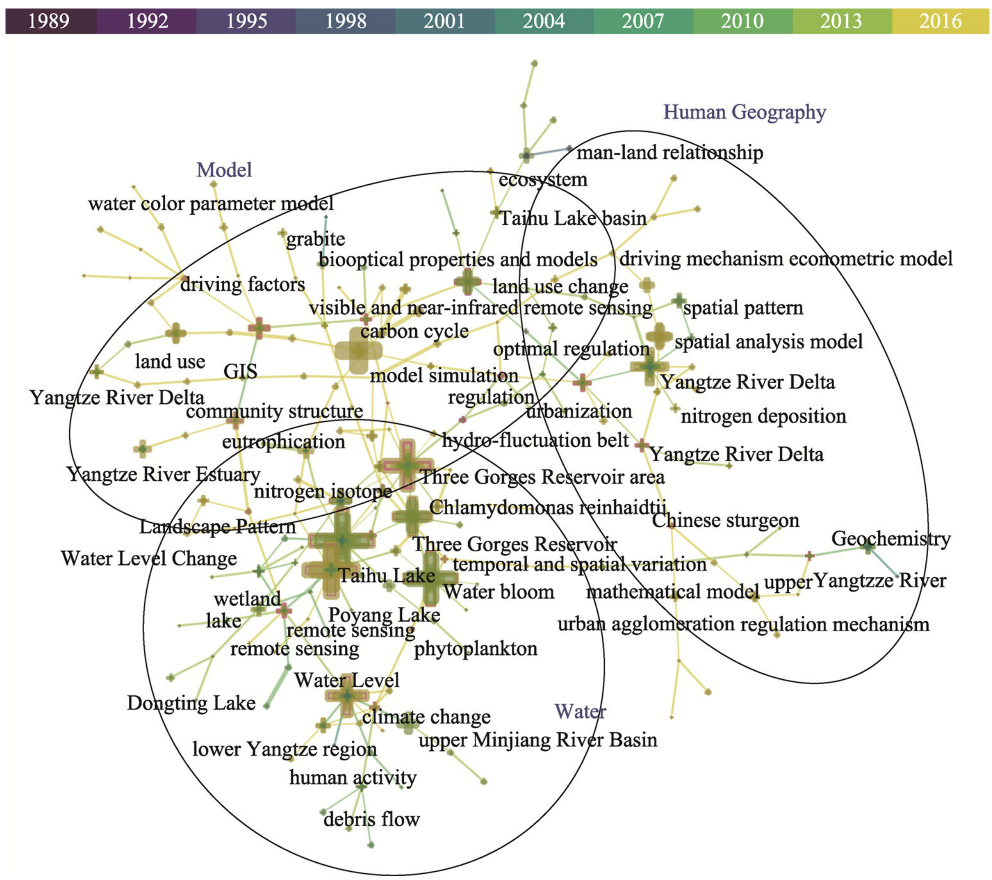

Figure 1 Main keyword co-occurrence relationship network in geoscience fields in the YRB supported by the NSFC

Research on geoscientific hotspots in the YRB can be divided into three categories according to co-occurrence relationships: 1) Hotspots related to water bodies that primarily include the “Three Gorges Reservoir”, “Taihu Lake”, “water bloom”, “eutrophication”, and “Poyang Lake”; 2) hotspots associated with human geography containing the words “spatial pattern”, “driving mechanism”, “optimal regulation”, and “land-use change”; 3) model-based hotspots containing the words “model simulation”, “bio-optical properties and models”, “water color parameter model”, “spatial analysis model”, and “econometric model”. The Three Gorges Reservoir, Taihu Lake, Poyang Lake, Yangtze River Delta, Yangtze River Estuary, and Minjiang River have been the main areas of focus in the YRB. Moreover, lakes, wetlands, phytoplankton, algae, water quality, land use, human activities, and moss have been the key study objects in the YRB, while remote sensing, corresponding latitude, geographic information system, model, and measurement have been the main research methods used in the YRB.

The YRB played an important role in Geosciences, especially in the research of community structure and eutrophication. In the past 20 years, the number of NSFC funded geoscience research projects increased steadily. Among them, the proportion of projects in the YRB supported by NSFC increased in a fluctuating trend (1% to 6%), and the growth rate had accelerated since 2005, reaching a peak in 2014. The YRB had become a hot area in the field of Geosciences. Among the projects concluded in 2017, the number of projects supported by the NSFC for the YRB is 125, accounting for 6.4% of the total number of projects in the field of Geosciences. Over the past 20 years, with 2005 being the key demarcation point, the NSFC has increased its subsidies to the YRB (Figure 2). Projects it has funded associated with keywords such as “Yangtze River Delta”, “land use”, “Taihu Lake”, “water bloom”, “ecosystem”, “Three Gorges Reservoir”, “Poyang Lake” and “model” constitute greater than 5 million yuan per year. Moreover, 2015 and 2016 saw a significant growth in funding in the YRB. The amount of project funding based on keywords such as “water bloom” and “eutrophication” increased dramatically in 2015, while a dramatic growth was also seen in 2016 for keywords such as “Yangtze River Delta”, “Poyang Lake”, and “model”.

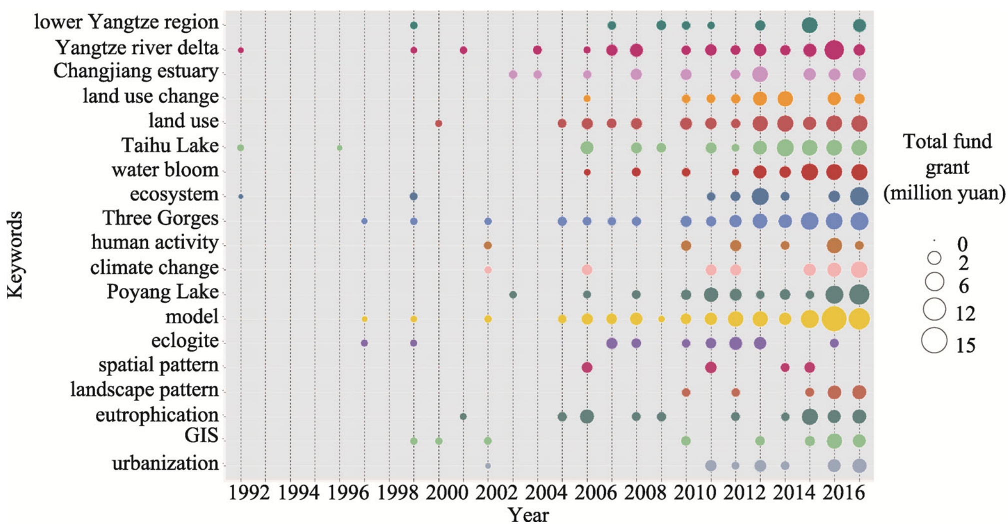

Figure 2 Interannual variation in NSFC funding related to hot research topics in the YRB. The color of the bubbles in the figure was only used to distinguish different keywords.

2.2 Research hotspots in the YRB supported by the MST over the past 20 years

For the YRB projects supported by the Ministry of Science and Technology (MST) of the People's Republic of China, we further compared relationships between the YRB research and investments from national science and technology (Figure 3). Keyword frequency distribution for these projects indicated that environmental pollution, ecological security, technical regulation, and watershed ecosystem were the main themes of the YRB projects that were subsidized by the MST. The main difference was that "environmental pollution" and "model simulation" were dominated by NSFC funding, while the proportion of technology regulation for projects funded by the MST was relatively high, highlighting that MST funding projects focused on aspects of technology that were subsequently applied to basic research.

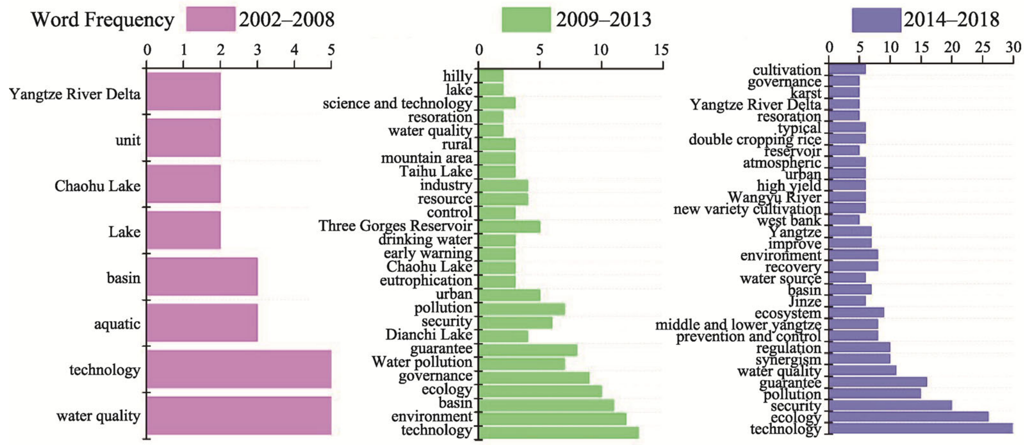

Figure 3 Time series changes associated with the YRB research topics funded by the MST in 2002–2018

2.3 Changes in research status and hot topics of the YRB

In accordance with research result cluster analyses in the YRB from the China National Knowledge Infrastructure (CNKI) over the past 20 years (Figure 4), geoscientific research hotspots were mainly reflected by: 1) The utilization of sediments, soils, and water bodies in eco-environmental fields, accounting for the core contribution in the YRB, such as nutrient and water quality monitoring, lake eutrophication, hydrodynamics, soil erosion, among which sediments were the primary focus; 2) the importance that the CNKI attaches to studies related to the application of agriculture in the YRB, particularly studies on rice yields, corn, and wheat; 3) the biogeochemical studies that continue to be a focus of research in the YRB, such as community structure and biodiversity, phytoplankton, and microcystins; 4) the concentration of YRB research on ecological security over the past decade, wherein the keywords "ecological footprint" and "ecological risk" having received more attention in Taihu Lake; 5) the main focus in the exploration and exploitation of rock and oil in mining areas in geology and chemistry fields in the YRB; 6) studies that have paid greater attention to regional issues in the YRB, mainly comprising of Taihu Lake, Dianchi Lake, Chaohu Lake, the Three Gorges Reservoir, the Yangtze River Estuary, and certain karst areas. From the time series, it can be seen that the YRB research initiatives over the past two decades have focused on fields associated with environmental pollution, such as those related to sediments, heavy metals, soil runoff, and environmental factors. From 2010 onwards, research hotspots have gradually transitioned to biogeochemical fields (i.e., community structure and phytoplankton) and ecological security, while factors associated with shallow lakes, hydrodynamics, and eutrophication were hot research topics during the previous decade in the YRB.

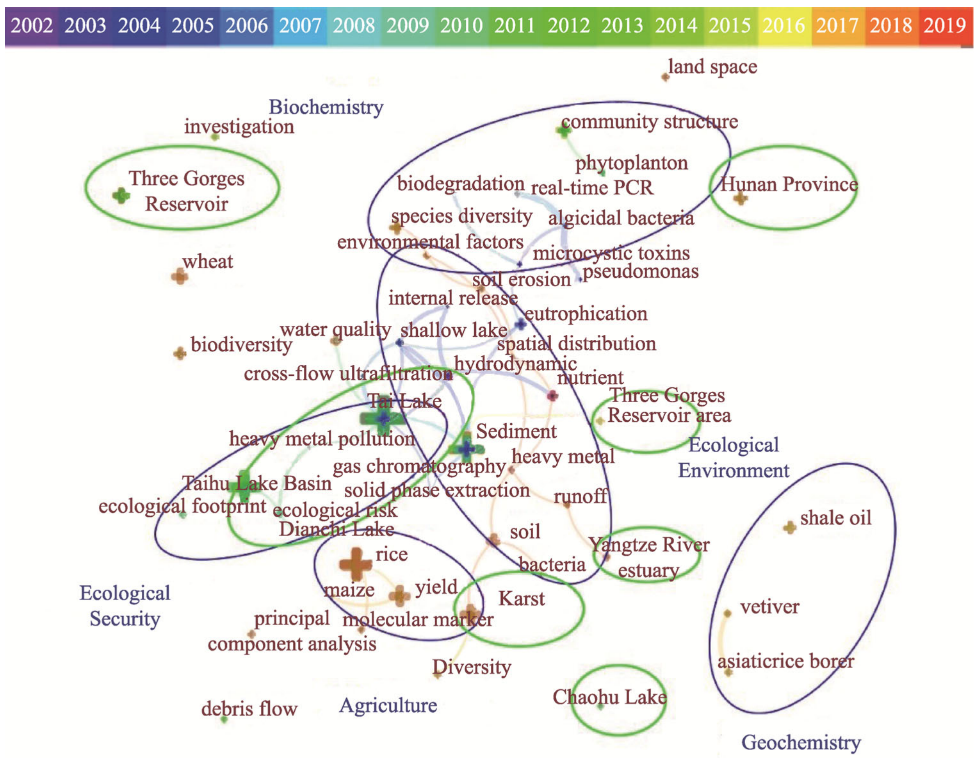

Figure 4 Co-occurrence relationship of CNKI keywords in the YRB between 2002 and 2019

Papers on the YRB published by Chinese scholars on the Web of Science in the past 20 years were used to conduct co-citation analysis. The results were clustered, showing cluster labels by log-likelihood, labeling clusters with indexing terms (Figure 5). Cluster #1 to Cluster #3 were clusters with multiple outbreak points (citation tree-rings were red), and their nodes were located on the right side of the timeline visualization. Therefore, “Poyang Lake”, “tidal range”, “rainy day” and “extreme precipitation” were deemed hot words. The nodes of Cluster #4 to Cluster #10 were located on the left side of the timeline visualization, which meant that these studies were more prevalent to the 2000s, and thereafter gradually declined. Many nodes in Cluster #0, Cluster #1, Cluster #2 and Cluster #9 were surrounded by purple circles, indicating that these documents have high betweeness centrality. In general, in the past 20 years, the frequency of citations of English papers published by Chinese scholars has become higher and higher in the scientific research on the YRB.

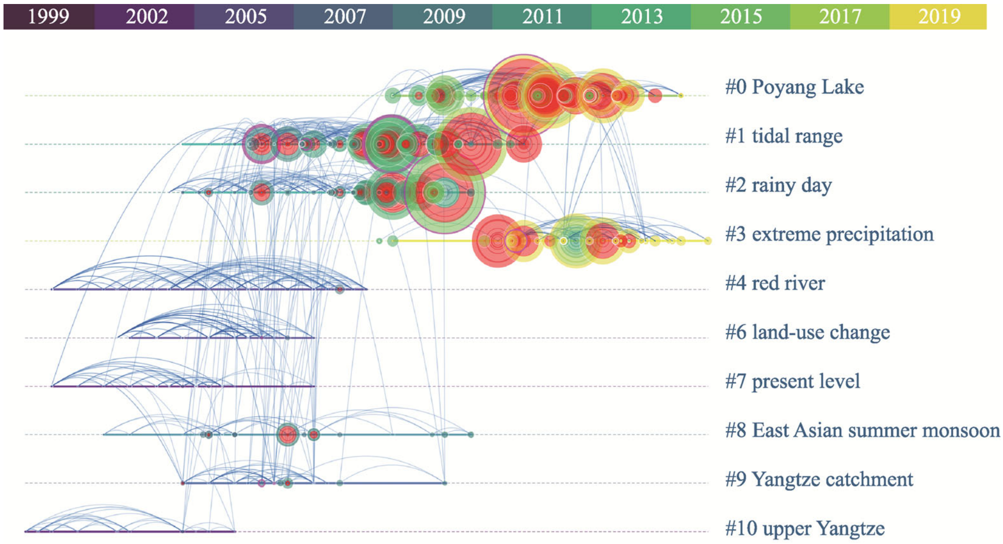

Figure 5 Timeline visualization of co-citation network in literature associated with YRB. The size of the node represented the cited times of the literature, and the color of the ring represented the cited time. The red citation tree-rings represented that the number of citations in this year is increasing explosively. The appearance of pink ring indicated that the literature has a high betweenness centrality.

3 Physiographical and national ecological security strategies of the YRB

Under a holistic and historical perspective, using basin as a unit, emphasizing the natural attributes of the basin, its human trajectory, historical evolution, and rules respective to its dynamic development are important in understanding the basic conditions of sustainable development in different watersheds and in providing a scientific basis for the regional research response to global change (Fu *et al*., 2014 and 2018). Under a background of global climate change as well as the profound impacts associated with human activities, ecological environmental changes in geographical processes have accelerated geographical process-based studies to move toward process-based geo-ecological coupling studies (Fu *et al*., 2006; Zhu *et al.,* 2018), which mainly include structures and processes as well as synthesis and integration, involving structures, functions, dynamics, driving forces, processes, mechanisms, factor integration, process integration, and regional integration, focusing on scale–structure– process interactions and nature–socioeconomic interconnections, geomorphology–hydrology–ecology process coupling, and geography–ecology processes in combination with resource and environmental effects (Gao *et al*., 2019b, 2020).

3.1 National appeal for research in the YRB in the New Era

To resolve ecological and environmental problems in the YRB on a national scale, it is paramount to strengthen multidisciplinary intersections and to view this as the core of geoscientific research as well as providing a strategic scientific design of a future watershed system approach. This will fundamentally improve our understanding of the YRB as well as scientifically-based research in the region, while it will also allow us to come to terms with the necessity of investigating the joint prevention and control aspect associated with ecological problems in the YRB. Key scientific issues and techniques that must be addressed include: 1) Those based on long-term observation system data under holistic, system-based, and multi-scale spatiotemporal perspectives, namely, the study of watershed behavior, regulatory aspects associated with evolution, and system interactions between water cycles and the ecological environment within critical zones of watersheds; 2) the means by which to scientifically evaluate cyclic material changes in interfaces and environmental effects as well as their impact on biodiversity under a scenario of dam fluctuation; 3) the regulation of eco-hydrological and geochemical processes as well as achieving and controlling purification measures associated with compound pollution in the watershed under a connective river–lake system strategy; 4) the integration of big data, extensive platforms, and system observations, while establishing an early-warning system along with the comprehensive management of the YRB.

Furthermore, regional observation platform networks that account for material and energy flux in ecosystems throughout the world have become the most valuable geoscientific tool as well as providing the most abundant data source on global climate change. The role of a network platform is unique in tackling global climate change, providing scientific and technological support for sustainable development, developing earth observation systems and scientifically-based global climate change research initiatives, while recognizing regional patterns and long-term changes in material and water cycle processes. Geoscience has entered the research era of big data and big science, which poses new challenges and opportunities in geoscientific development. Therefore, to satisfy China's strategies on ecological environmental construction projects and regional sustainable development in the YRB, new technologies, methods, and perceptions are necessary from the perspective of disciplinary development in the prospective development of frontier research fields as well as new directions in geoscience that promote large-scale and comprehensive scientific research based on big science and big data, while also developing a quantitative, predictable, early-warning system under expedient conditions associated with spatial management and control.

3.2 Key issues under national appeal in watershed physiographical research

Respective of the aforementioned research hotspots on watershed physiography, current trends in development, and major research goals in geography, this study proposes a series of key geographical research topics for the YRB: 1) Determining both developmental and historical evolutionary processes in the YRB, investigating erosion and environmental evolutionary processes in the YRB (Kong *et al*., 2015; Miao *et al*., 2016), ascertaining relationships between biological productivity and biodistribution patterns in the YRB as well as structural, functional, and morphological watershed dynamics, groundwater effects, and associative changes in the terrestrial environment, while also determining interactive interface evolutionary processes between groundwater and surface water (Xie, 1995; SFC, 2003); 2) ascertaining interactive structural, functional, and morphological mechanisms in the YRB as a unit, while determining interactive structural, functional, and morphological dynamics in watersheds at different scales, while investigating whether spatial and temporal scale patterns and processes affect corresponding patterns and processes at other scales, watershed resource capacities, environmental assessments, and carrying capacities, and understanding the impact and response of ecological environmental change to landscape patterns in the

YRB (Yang *et al*., 2008; Lai *et al.,* 2020); 3) determining the rules associated with the occurrence and evolution of man–land regional systematic relationships and associative spatial and temporal differences and regulatory mechanisms in the YRB, namely, the manner in which land-use and water-use changes affect man–land relational processes in the YRB and their correlation to global change, as well as evolutionary processes of riparian buffer strips in the YRB and relationships between watershed ecology remediation and human activities and socioeconomic development, environmental background values, and the environmental carrying capacities of water systems, and a comprehensive evaluation of water resource engineering, the assessment and the development of an early-warning system to forecast natural disasters, the development of agricultural industrialization in the YRB, namely, introducing new technologies as well as providing demonstrative and applicable optimization structures within a forestry–agriculture–fishery composite system (Cai *et al*., 2010; Wang and Zhang, 2009; Zhang *et al*., 2011).

3.3 Earth system science and the implementation of ecological security research in the YRB

There is a great need for the application and utilization of a national field monitoring platform, the synthetization of multidisciplinary intersections, the exploration of new technologies, new methods, and new concepts within a prospective design of frontier research fields as well as determining the direction to take in ecological security and governance in the YRB. Furthermore, it is also necessary to understand holistic behavior, regulatory evolutionary processes, and interactions between watershed intersystems using an ecologically-based big data platform while scrutinizing the design of the platform with respect to the YRB. Also, there is a pressing need to establish an early-warning system and the spatial management and control of resource allowances in the YRB. Lastly, we determined that four aspects related to earth system science must be strengthened in the YRB, namely, integrating C-N-H_2O coupling and energy cycles (see Figure 6).

(1) Long-term observation data, integrating data from literature on the YRB, strengthening the comprehensive study of C-N-H_2O coupling and energy cycles

The integration and analysis of long-term observation system data on the YRB, as well as understanding scientific problems associated with long-term changes and regional pattern research on coupling cycles of carbon, nitrogen, water, and energy in the YRB should be proposed (Gao *et al*., 2019a, 2016). At the same time, we should strengthen the analysis of the historical documents of the YRB, discuss the existing research and the scientific problems that need to be solved urgently under a scenario of dam fluctuations, and put forward the key scientific problems of carbon, nitrogen, water and energy circulation in terrestrial and aquatic ecosystems under a connective river–lake water system strategy (Baldocchi, 2003; Noormets *et al*., 2010; Liu *et al*., 2016).

(2) Proposing key technologies and frontier designs in resolving urgent issues in the study of processes associated with land–river habitats

The most crucial issues that must be resolved using digital hydrological tools and water quality monitoring platforms in the YRB, while promoting the national development of and the strategic appeal for research. We should also propose incorporating critical technologies that are necessary to resolve water cycling issues in the YRB under a changing environment, improve the ability to reconstruct and analyze processes associated with historical changes in river water quality and water quantity versus nutrient flux in the YRB, and determine the role of natural factors and human activities in river water quality and water quantity versus nutrient transport, while conducting coupling studies on water quality and water quantity versus nutrients at different scales (Zhou *et al*., 2016).

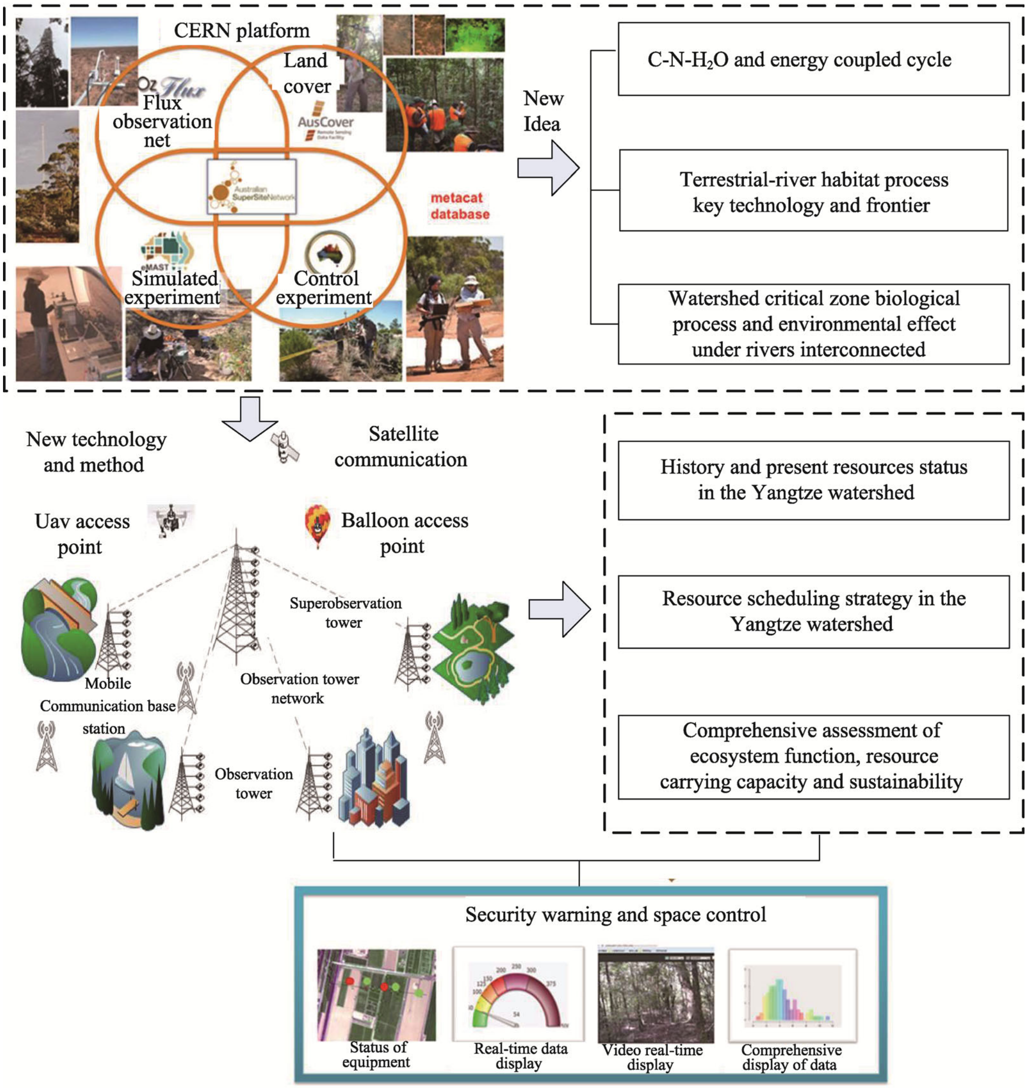

Figure 6 Technical directions of earth system science and ecological research in the YRB

(3) Comprehensive investigation of biological and pollution processes in critical zones of the YRB under connective river–lake systems

This study focused on issues related to migration and transformation processes associated with biological elements and pollutants in the critical zones of the YRB under a scenario of dam fluctuation and also scientifically evaluated the absorption and purification of pollutants and their impact on biodiversity under a scenario of dam fluctuation. This study also focused on determining the ecological red line of ecological water security in the YRB, while formulating conservation zoning of biodiversity in the YRB using the Yangtze River Bioinformatics Data Platform Strategy.

(4) Comprehensive study on the resource status, scheduling, and ecological security in the YRB

By determining each element in detail as well as regional network observations and experiments in combination with the application of new technologies, such as ground–satellite stereoscopic observations, laser and radar detection technologies, unmanned aerial vehicles, and information and automation technologies, the aim of this study was to strengthen comprehensive observations and experimental research of a three-dimensional surface–air network, to determine current conditions in the YRB, to comprehensively evaluate ecosystem functions, resource carrying capacities, and the sustainable management and utilization strategies in the YRB, while also proposing watershed resource scheduling strategies suitable for multi-space and multi-time scales. The aim was also to establish real-time predictions, warning systems and assessments, while optimizing ecological security management and measures by which to serve the national eco-environmental strategy of the YRB.

4 The inspiration of CERN to geographical research in the YRB

The objective of CERN is to implement a national strategy and provide important measures required by the Central Committee of the Communist Party of China, providing a prospective design for comprehensive multi-factor and multi-scale observations of processes in terrestrial ecosystems in China as well as a stereo-observation system combined with near-surface and remote sensing imagery. The great advantages of CERN to scientific research in earth system sciences primarily include the following three factors (Yu *et al*., 2006a and 2016): 1) to systematically understand evolutionary rules of material cycle and service functions in Chinese ecosystems, to promote field observations of ecosystems and to provide an observation network; 2) to provide experimental field stations and a scientific infrastructure for national ecosystem protection and scientific research on climate change; 3) to establish research stations and scientific data that support platforms in the development of earth system science, geographical science, ecology, and environmental science in China.

The impact of global climate change is becoming increasingly severe. The development of earth system science and solutions to problems associated with ecological environmental degradation will undoubtedly depend on scientific and technological progress in the field of earth system science. Accordingly, new technological applications and long-term comprehensive observations and experiments associated with a three-dimensional ground–air network have become the mainstream in the promotion of geoscientific and technological innovations and progress. The establishment of CERN is indispensable in resolving scientific problems associated with network monitoring data, simulation experiments, and numerical laboratory simulations for long-term earth system science research. Furthermore, based on regional network observations and experiments, ground–satellite stereoscopic observations, newly-developed technological applications (such as laser and radar detection technology as well as information and automation technology), which can detect individual elements of ecosystems in minute detail, have become the main developmental trends in scientific and technological innovations and progress in earth system science research. To resolve ecological issues on a national scale, the promotion of scientific and technological advancements and comprehensive capabilities in field observations and experimental research as well as the integration and the sharing of field observations and experimental technological resources are urgently required (Yu *et al*., 2006b, 2013a, 2013b, 2014).

5 Summary

(1) The unique geographical location and the natural environment of the YRB, the contradictory nature associated with its long history of human activities, and the current relationship between humans and the land, which increases national competitiveness during economic transition periods, have all provided a broad platform and a significant regional superiority to conduct geographical research on a regional scale in the YRB.

(2) Long-term observations, experiments, and simulations are an impetus to today's mainstream scientific and technological innovations and progress in earth system science, while geography and fields that study global climate change have largely curtailed potential discoveries, rules of interpretation, and mechanistic clarity in the past, which now attaches great importance to ecosystem function maintenance and sustainable management.

(3) Frontier scientific issues of concern include: basic relationships between changes in ecosystem material cycles, service functions, environmental resources, human well-being, impacts and feedbacks of global climate change on ecosystem material cycling, and relationships between ecosystem degradation or restoration and regional sustainable development and ecological security.

(4) The response and adaptation of environmental carbon–nitrogen water cycles to global climate change is considered a frontier field in geoscientific and ecological research. The National Academy of Sciences and the Ecological Society of America have clearly stated that carbon–nitrogen–water cycles and their associative coupling processes that both respond and react to climate change provide new opportunities in future geoscientific development.

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