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Review on hotspots, challenges, and the future of river management strategies in China

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Abstract

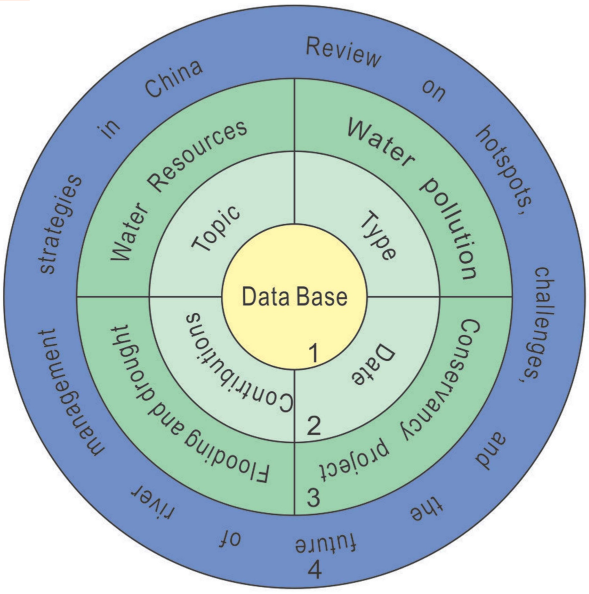
Aim : Review of the new research on medium- and large-sized rivers in China and its impact to develop more rational management strategies for medium- and large-sized rivers.

Methodology : Papers on rivers-related research in China published over the past 15 years (2004–2018) were summarised through statistical analyses. The main topics, data sources and contributions were also summarised, and representative papers were presented to illustrate milestones and contributions.

Results : The management strategies of medium- and large-sized rivers shifted remarkably from traditional agricultural utilisation of floods and water resources to ecological protection. Water resources and pollution, conservancy projects and flooding and droughts were the four most focused research areas.

Interpretation : Chinese economy significantly contributed to the change in river management strategies over the last two decades.

Key words: Ecological protection, Hotspots, River management



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Introduction

There are more than 22,000 rivers with a basin area of more than 100 sq. km and 2,221 with a basin area of more than 1000 sq. km in China. The quality and quantity of water in rivers and the related channel management systems play a vital role in maintaining the urban socio-economic development (Yang *et al.,* 2019). Economy development, urban expansion, and pollution intensification have motivated the research on Chinese rivers and their study as abundant water resources. Despite great economic development support, huge issues such as flooding, draughts, pollution and biodiversity degradation still have to be addressed (Han *et al.,* 2016; Wang *et al.,* 2017). In general, the Chinese government has made great achievements in river management, mainly in terms of flooding, drought, agricultural irrigation and pollution control. Dikes, reservoirs, channel dredging, flood detention and non-engineering measures, including forecasting, dispatching, detention area management and emergency relief and flood control systems, have been developed, and frequent floods have been under control (Lai and Wang, 2017).

However, problems related to water resources, including in homogeneous distribution, water pollution, water scarcity and aquatic ecosystem degradation, are significantly limiting the sustainable development of some rivers (Chang *et al*., 2016; Li *et al.,* 2018; Yang *et al.,* 2019). Additionally, sediment erosion from both basin and channels also introduces many problems to flooding control, water conservancy and hydropower projects management (Li *et al.,* 2014). Approximately, 20 papers are published annually on three Gorgesdam (TGD), covering topics such as flooding control and management (Lai and Wang, 2017), water quality (Wang *et al.,* 2018), water resources (Deng *et al.,* 2016), sediment erosion, and wetlands evolution (Han *et al.,* 2018). The south-to-north water diversion (SNWD) project was applied to decrease the risk of scarcity of water resources for domestic, agricultural, industrial and ecological purposes in the north using transferred river flow, reclaimed water and rain water resources (Proje, 2016; Zhao *et al.,* 2015).

Furthermore, research has also been published on the safety of drinking water in rural areas (Cai and Liu, 2011), reconstruction of large irrigation areas (Chen *et al.,* 2014), water-saving technologies (Blanke *et al.,* 2007), treatment of small- and medium-sized rivers, construction and reinforcement of small and medium-sized reservoirs, soil and water conservation (Li *et al.,* 2014), water environment and ecology protection, water resources management systems (Sha *et al.,* 2012) and sponge city construction (Shao *et al.,* 2016). However, problems of river flooding, water pollution (Han *et al.,* 2016, 2018; Li *et al.*, 2016), biodiversity and aquatic environment degradation, urban water logging (Lin *et al.,* 2018), and water resources scarcity (Wang *et al.,* 2017) are becoming more serious than ever due to inefficient environment management, unfettered expansion of urban areas, and climate change. Although flood prevention systems have been greatly improved, the current research is mainly focused on hydrological forecasting and hydrological project construction. Meanwhile, the increasing soil erosion, shrinking river bed habitats and in-channel sand, and gravel excavation have caused higher flood water levels and elevation of embankments (Fang *et al.,* 2017). The scarcity and inefficient utilisation of water resources has also caused a series of problems, such as lakes drying, rivers disconnection, ground water over exploitation and ecology deterioration (Long and Pijanowski, 2017). Despite China's industrialization and achievements, serious environmental pollution and ecological deterioration have attracted great attention from all over the world (Han *et al.,* 2016; Wang *et al.,* 2018). In addition, many projects are addressing other problems including aging, lower economic benefits and lack of efficient management strategies.

However, a review on the progress of Chinese rivers management-related research is still missing. Extensive research has been conducted on pollutant transport (Ji *et al.,* 2007; Ji *et al.,* 2012), hydraulic systems engineering (Chen *et al.,* 2013) and environmental pollution monitoring in rivers and lakes (Ji *et al.,* 2010; Lu *et al.,* 2010). In recent years, more ecosystem indicators, including fish and benthonic organisms (Dong *et al.,* 2019), vegetables (Ji *et al.,* 2018), and paddy rice (Ji *et al.,* 2017), have been chosen to evaluate the environmental behaviour of pollutants (Zhang *et al.,* 2018 a; Zhang *et al.,* 2018 b and the aquatic ecological risk in fresh lakes and their upstream rivers under hydrodynamic interaction (Ji *et al.,* 2014; Ji *et al.,* 2017 (a); Ji *et al.,* 2017 (b)). In this review, we have focused on case studies, data, and topics from published papers and compare river-related research in China and developing countries to better understand the topics. Meanwhile, the most prominent research fields were presented by representative examples to clarify whether these areas were suitable for future Chinese river management strategies.

As shown in Table 1, based on the number of river management-related articles, it can be concluded that water resources and scarcity, water pollution, monitoring, conservancy project construction, groundwater, flooding issues, and aquatic ecology are still important issues in most developing countries. In this study, Origin 9.0 (OriginLab, Massachusetts, USA) and Microsoft Excel 2010 were used to perform a statistical analysis of the data. Origin 9.0 was also used to draw graphs.

Results and Discussion

Chinese Water Resources-Related Research: As presented in Table 1, the number of articles on river management-related articles in China is far higher than in other developing countries. Based on the frequency of keywords and consultation with experts from the Chinese Central Environment Protection Agency, the most valued research areas in China are water resources, water pollution, conservancy projects, and flooding and drought research. On comparing the research fields considered in China and in other developing countries, it is clear that water pollution received increasingly higher attention in China in recent decades, which is slightly different than in other developing countries. During past several decades, the economic development along with rapid industrialization in China has boosted the economy and caused higher pollution of water bodies, which has led to serious environmental degradation along the main rivers and fresh lakes (Hu and Cheng, 2013). Limited sewage treatment capacity, lower treatment standards, overuse of pesticides and fertilizers, and excessive pursuit of rapid economic development have created risk to water safety and aquatic ecology than ever before (Hu and Cheng, 2013).

Issues related to Chinese water resources are the main focus of river management articles, similar to the research in other emerging economies, as listed in Table 1. Since late 1970s, the mainland China has been experiencing a rapid economic and social development with a population of approximately 1.37 billion in 2010, which has caused a dramatic increase in the water demand (Chen *et al.,* 2013). Furthermore, the mainland China has a vast land area crossing several different geographic regions, resulting in significant spatial and temporal variations in the precipitations. Seventy percent of total water consumption in China is for agriculture (Geng *et al.,* 2019).

Low efficiency of industrial processes and discharge of sewage into rivers and lakes without treatment has further exacerbated the shortage of water resources (Yao *et al.,* 2018). For past 10 years, the Chinese government has implemented a unified management of water resources in the management system (Li *et al.,* 2018). It has also strictly limited the exploitation of water resources, increased their sustainability, reduced expenditure, and balanced supply and demand. At the same time, a reasonable compensation mechanism for lack of water resources was established to protect the interests of farmers in upstream areas and the areas with scarce water resources (An *et al.,* 2018).

Owing to global warming, sea level rising in, and water recycling, increasingly more researchers have been focused on the climate change and their effect on water resources (Zhang *et al.,* 2015; Xia *et al.,* 2017). Human activities and climate change have caused observable changes in the water cycle, including, precipitation quantity, intensity and distribution characteristics (Zhang *et al.,* 2015), which ultimately alter the water resources distribution and socio-economic development (Chahine, 1992). In addition, the land usage, deforestation, water resource utilisation, agricultural activities and urbanisation directly affect the runoff generation, evaporation and infiltration. As China is a developing country with the largest population in the world, the central and local Chinese governments have paid much attention to the research on climate change and its effect on the water resources (Zhang *et al.,* 2015; Zhu *et al.,* 2016).

Chinese Water Pollution-Related Research: Based on the published data, more than 11,000 water supply-related emergencies have been reported since 1995. A recent case was reported in Lanzhou, where the city water supply system was temporarily shutdown owing to contamination caused by benzene from a nearby petrochemical facility (Yan, 2015). Furthermore, according to the data released by the Ministry of Land and Resources, the State Oceanic Administration, and the Ministry of Environmental Protection, China was facing severe water scarcity and pollution crises, which seriously put the socio-economic development at higher risk and reduce the country's sustainability (Gleick, 2009). Despite some improvements in drinking water accessibility as reported in recently released documents, it is estimated that more than 200 million residents, especially in the country side, are still facing scarcity of clear and safe drinking water. Since 2006, the National Water Pollution Control and Treatment was set as one of the 16 major projects by the Chinese Central Government, which aimed at water pollution control and management and provided strong scientific and technological support. In 2015, the Chinese Central Government released the Water Pollution Prevention and Control Action Plan ("10-Point Water Plan"), which aimed at tackling groundwater and surface water pollution (Gleick, 2009; Shapiro, 2012).

According to the Environmental Quality Standard of Surface Water of China, more than 80% of rivers, lakes, and reservoirs have been polluted or have lost their ecological function. Generally, chemical and biological oxygen, nitrite, and ammonia-N are the most frequently used indicators that exceed standard levels by the highest amounts (World Bank, 2006). In recent years, the rapid development of mining and heavy metal processing industries and other industrial and urban sources of pollution have contributed to higher concentration of heavy metals in rivers, tributaries, mainstreams and lakes (Han *et al.,* 2017; Sun *et al.,* 2018; Tang *et al.,* 2018). Owing to their potential toxicity and ecotoxicity, the rivers contamination by heavy metals has led to serious effects on the local public health and the environment. China has implemented a national heavy metal treatment and control plan to achieve a satisfactory heavy metal contamination reduction (Han *et al.,* 2017; Liu *et al.,* 2018; Zhao *et*

Table 1: Numbers of river-management related articles of hotspot

Research area	China	India	Pakistan	Bangladesh	Indonesia	Brazil	Mexico	Russia	South Africa
Water resources	2620	712	130	160	86	432	336	66	432
Water pollution	1454	308	23	47	46	186	142	48	154
Conservancy project	1007	290	41	88	54	162	168	42	167
Flooding and drought	642	222	40	80	33	119	150	15	88
Risk assessment	613	80	21	27	21	57	47	18	40

Table 2: China river-related management theory application, theory building and research findings

Research areas	Theories or approaches application	Theories or approaches building	Finding or China river-related management
Water resources	◆ Improved water use efficiency model cooperated with vapor pressure deficit was proposed for water resources conservation in the Heihe River Basin, northwestern China (Zhou *et al.,* 2018). ◆ Hydrological modeling approach proposed by MIKE HYDRO model was applied to resolve water resources allocation issues among different users in a large basin scale along the oasis of Tarim River in Northwest China (Yu *et al.,* 2017).	◆ Integrated model derived from interval parameter programming and two stages stochastic programming framework was developed for agricultural irrigation planning in the Zhangweinan river watershed (Li *et al.,* 2010). ◆ Integrated method incorporated from interval mathematical programming, scenario analysis and two phase fuzzy programming was developed for water resources planning in a wetland ecosystem (Lv *et al.,* 2013). ◆ A three layer model in cooperated crop irrigation scheduling, crops water resources allocation and regional water resources allocation was applied in Yangling region, Plateau, China (Shangguan *et al.,* 2002).	◆ This paper revealed the water scarcity in northern river basins and potential result for irrigation areas reduction and food production fall (Wang *et al.,* 2017)
Water pollution	◆ Improved model was applied to predict nitrogen loads as well as the anthropogenic sources of nitrogen in watershed (Hu *et al.,* 2018). ◆ Well established SWAT model coupled with heavy metal transport and transformation module was successfully applied to simulate the transport of metals (Meng *et al.,* 2018). ◆ Integrated environmental decision support system combined simulation models and visualization system was applied in watershed scale (Zhang *et al.,* 2015). ◆ Investigation combined with principal component analysis-multiple linear regression model was applied to identify the distribution, source and risk of pharmaceutically active compounds (Lin *et al.,* 2018).	◆ Integrated water quality monitoring and management system combined sensor data, virtual technique and artificial neural technology was applied in Liming River basin (Yang *et al.,* 2008). ◆ Mechanistic model of water quality was established and linked to the Water Quality Analysis Simulation Program at the first time to support total maximum daily load in Taihu Lake Basin (Wang *et al.,* 2015).	◆ This research revealed the relationship between urbanization and pollutants discharge, aquatic ecosystem as well as water environment system in the Songhua River basin (Yu and Lu, 2018).
Monitoring	◆ Satellite altimetry data was used to monitor water levels of the Great Brahmaputra River sourced from the Tibetan Plateau (Huang *et al.,* 2018). ◆ Matter element analysis combined with numerical water quality model was used to resolve the temporal and spatial variations of the water quality for pollution control and sustainable management (Chen *et al.,* 2012).	◆ This presented a rehabilitation framework integrated fish habitat and new weighting calculation method to identify high-priority habitat factors (Zhao *et al.,* 2015).	◆ This paper summarized the pollution situation in rural, China, assessed the pollution economy cost and mentioned the reasons the implementation gap for environmental protection laws (Wang *et al.,* 2008).
	◆ An improved habitat model was used as an intermediate step to evaluate the impact of water conservancy projects on fish	◆ An eco-hydrodynamic model was established by coupling fish habitat module and hydrodynamic model to simulate and evaluate the effect of	◆ Adverse impacts of conservancy projects including fish migration, migration, ecological system, ecological base flow, fish habitat

Table continue

Conservancy project	habitats. (Wang et al., 2017) ◆ A self-adaptive GA-aided multi-objective ecological reservoir operation model was applied in the Xiangxi River watershed for water quality management (Hu et al., 2014).	Three Gorges Reservoir on fish habitats characteristics (Zhou et al., 2014).	protection and restoration were summarized in China over the past several decades (Chen et al., 2016).
Flooding and drought	◆ Integrated hydrological hydraulic model with SRTM DEM data verified by hydraulic correction method applied in Huifa River Watershed to simulate an extreme flood event (Chen et al., 2018). ◆ Site specific methodology combined flooding control and social development was applied in Mengwa, Huai he River Watershed to identify the potential wetlands construction sites and assesses the flood retention benefits (Zhang and Song, 2014).	◆ Integrated storm water management system combined by storm water collection, storage, reuse and treatment was implemented in Jinan City to resolve waterlogging, pollution and aquatic system (Yang and Cui, 2012).	◆ This paper summary the development of flooding control in China from the early flood control approach relied largely on structural interventions to flood risk management approach (Liu, 2016).

al., 2018). Furthermore, organic compounds have drawn worldwide attention for their effects on carcinogenesis, teratogenicity and mutagenicity. The Yangtze River, Yellow River, Pearl River, Songhua River, Haihe Rivern, Huaihe River, Liaohe River, Weihe River and Fenhe River have been seriously polluted by organic compounds, especially polycyclic aromatic hydrocarbons, polychlorinated biphenyls, organ chlorine pesticides, pharmaceuticals, and other semi-volatile organic compounds (Meng *et al.,* 2017; Yan *et al.,* 2018).

Chinese Conservancy Projects-Related Research

Large-sized dams, water diversion, hydropower generation, and reservoir capacity have been continuously enhanced in the past three decades (Liu *et al.,* 2013). There is no doubt that these water conservancy projects have significantly supported the Chinese economic development and food security and have also contributed significantly to the floods control, clean energy generation and amount of available water (Const, 2015). Today, China has approximately half of the world's dams, 20% of the world's hydropower plants and 21% of the world's irrigated farm lands. The TGD and south-to-north water transfer (SNWT) projects have received worldwide attention for their large scale investment and impact (Morgan *et al,* 2012). However, these large water conservancy projects have also introduced many problems, including soil and river erosion (Huang *et al.,* 2018), environment impacts (Tang *et al.,* 2018) and resettlement of large population.

Accordingly, much research has focused on the impacts of water conservancy projects on the environment and ecology and proposed different measures to alleviate these adverse effects (Han *et al.,* 2018; Tang *et al.,* 2018). Some aspects of the conservancy projects have received particular attention. These include the impact of TGD on ecological processes and biodiversity (Huang *et al.,* 2018; Tang *et al.,* 2018); the ecological and environmental effects of SNWT project (Tang *et al.,* 2014; Tang *et al.,* 2016); and the negative effects of dam construction on the complexity of suspended sediment dynamics and river discharge in the Yangtze River (Wang *et al.,* 2018), the Yellow River (Wang *et al.,* 2017), and the Pearl River (Dai *et al.,* 2009). However, Chinese Water Conservancy projects have to consider some trade-offs, and the Chinese government is making efforts to balance the needs of humans and nature. The experience of China can also provide valuable information for other developing countries.

Chinese Flooding and Drought-Related Research

Owing to uneven temporal distribution of rainfall, most of the Chinese rivers have experienced heavy floods with a frequency of approximately one in 10 years, which has caused disasters in flooded areas (Wang and Liu, 2018). The Yellow River has experienced more than 1500 levee bursts, which has claimed millions of human lives (Wang and Liu, 2018). The Zhengzhou region has been avulsed 26 times, resulting in numerous old channels and devastating calamities (Wang and Liu, 2018). In 1998, some major rivers, including the Yangtze River Basin and the Minjiang River, experienced catastrophic floods simultaneously, which had a serious impact on the economic and social development (Liu *et al.,* 2018). Today, more than half of the cultivated land, population, main cities, food products, commodities, and economies are located in the middle and downstream parts of major rivers, which are threatened by flooding (Wang *et al.,* 2016).

To control floods, in the past half century more than 85000 reservoirs with a total capacity of 518.36 billion sq.m have been

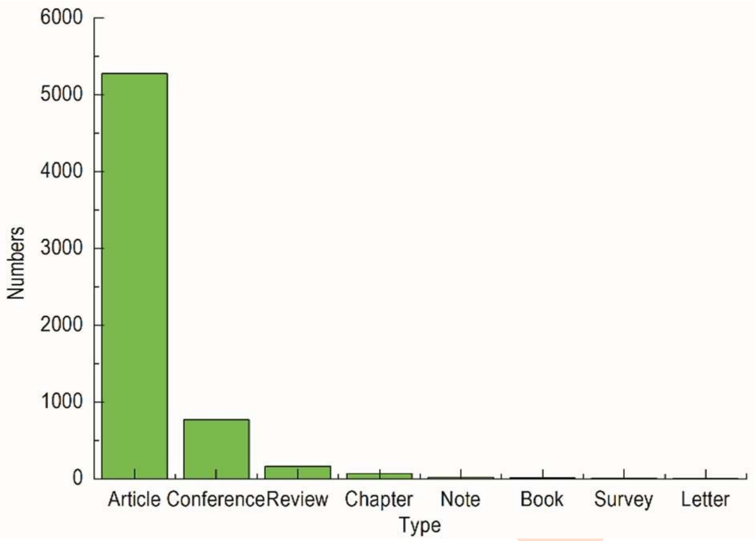

Fig. 1: Annual number for China river-related different type articlesfrom 2004 to 2018.

built. In addition, non-engineering measures, such as hydrological forecasting, communication and remote monitoring and flood control systems have also been beneficial in defence against floods (Wang *et al.,* 2016). As one of the non-engineering measures of flooding control, the hydrological information transmission, including data collection, processing, and distribution, has also helped to tackle flooding (Ji *et al.,* 2012). However, these non-engineering measures for flooding control of small and medium rivers are lagging behind and their ability to prevent floods is reducing, which is causing many casualties due to frequent occurrence of mountain torrents disasters. The urban flooding control is a prominent issue, and the construction of non-engineering measures for flood control is imperfect (Lo *et al.,* 2015; Su *et al.,* 2018). For a long time, the third step geomorphology and monsoon climate have caused droughts in China (Zhou *et al.,* 2017). Over the last 60 years or so, droughts have posed a serious threat to the China's grain production (Wang *et al.,* 2018; Zhang *et al.,* 2018). At the same time, urban droughts and water ecological degradation are also increasingly prominent (Zhang *et al.,* 2018). From 2003, drought disaster management systems have began to change from single agricultural and negative drought resistance to comprehensive and active drought resistance, respectively (Watts, 2011).

Fig. 1 shows eight different types of Chinese rivers-related articles that were reviewed in this study. Among them, the number of research papers using data from surveys, field studies, and government investigations increased from a few in 2004 to almost half a thousand in 2018, which accounted for more than 80% of all articles. Meanwhile, the number of review papers and short communications through summarizing the findings of others and the official reports also increased steadily from 0 in 2004 to approximately 50 in 2018. It is worth noting that the experimental method, which is usually accepted in physical and chemical research, has been used widely and has become increasingly prominent in Chinese rivers management-related studies (Zhang *et al.,* 2018).

Paper tried to distinguish the nationality of the authors that focused on the Chinese rivers management-related research. The statistical results indicated that the articles from Chinese authors accounted for approximately 90% of the total articles. The main reason was that data from the public services of the Chinese government, such as the Hydrology Bureau, the Wetland Administration, and the Environmental Protection Agency, were difficult to obtain. Although the survey method was mostly applied in Chinese rivers management-related research, in majority of these studies the data were usually collected from one respondent in one department rather than from multiple sources or using longitudinal data. Therefore, the findings of some studies have been questioned, and their results have not been accepted completely. Furthermore, for international researchers dedicated to Chinese rivers management-related research, there are lots of obstacles in utilising secondary data from Chinese organizations for social system reasons. Therefore, although there has been a prominent increase in secondary data used in Chinese rivers management-related research from 2004 to 2018, this methodology is still not widely used compared with other methodologies.

Contributions

Based on the articles' contributions, we divided the Chinese rivers management-related papers into three broad categories: DIE, containing papers that focus on description, introduction, or explanation of river management issues in China;

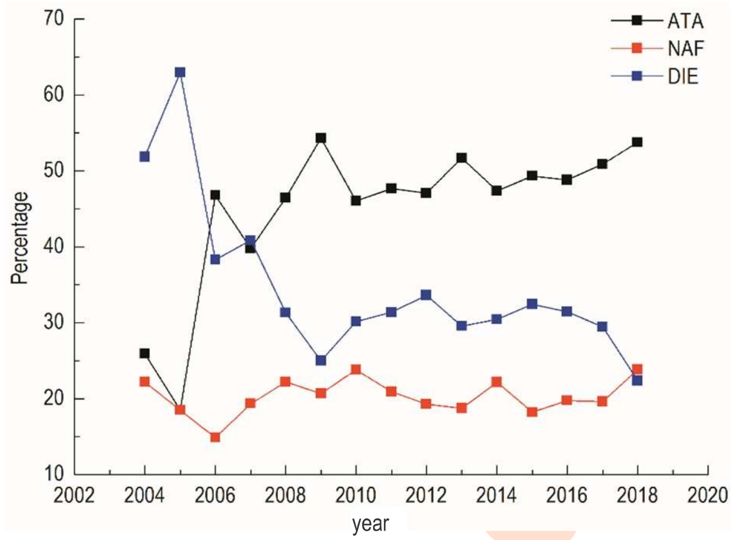

Fig. 2: Percentage of research contribution from 2004 to 2018.

NAF, containing papers that establish new approaches or frameworks to solve river management issues in China; and ATA, containing papers that apply theories or approaches to Chinese rivers management-related issues. As shown in Fig. 2, the number of DIE articles decreased from 50% in 2004 to less than 25% in 2018. In contrast, the number of NAF articles increased from 25.9% to more than 53.7% in the same period. The ATA articles remained relatively stable at 20%.

In Table 2, we listed some examples of articles on the main research fields, which accounted for more than 10% of all articles, to illustrate different types of contributions that benefited the researchers. In the field of water pollution, increasingly more attention has been paid to the problems of pollutant sources and pollutant migration processes. To effectively solve the randomness of pollution sources and uncertainty of observation points, mathematical models have been used to simulate the formation, migration and transformation of various pollution sources (Yang *et al.,* 2008; Wang *et al.,* 2015; Hu *et al.,* 2018). Combined with advanced technologies, such as SWAT model (Meng *et al.,* 2018), visualization systems (Zhang *et al.,* 2015), and sensor data (Yang *et al.,* 2008), mathematical models can also provide effective technical means for the quantification of pollution source control and management. In response to flooding and droughts, the construction and management of flood control facilities are strengthened continuously and flooding and drought emergency response mechanisms are continuously established (Liu, 2016). Based on hydrology physics theories and big data, hydrologic simulation and prediction technologies and flood forecasting and dispatching systems have been applied successfully and widely, providing a powerful method for flooding prediction and water resources planning (Yang and Cui, 2012; Zhang and Song, 2014).

In recent decades, China has made remarkable achievements in the field of water resources development, utilisation, allocation, conservation, protection and management, legislation, and system and technology development. Due to large scale and complex construction and numerous influencing factors, the research on modelling and simulation of water resources systems has become a hot spot in this field (Li *et al.,* 2010; Lv *et al.,* 2013; Zhou *et al.,* 2018). Object-oriented technologies and geographic information system (GIS) technologies have been gradually applied in watershed water resources simulation (Yu *et al.,* 2017). Water resources decision systems contain increasingly more independent but interrelated professional modules, thus forming a complex model system (Shangguan *et al.,* 2002). Massive water conservancy projects have brought tremendous social and economic benefits as well as adverse impacts on the environment and society (Zhou *et al.,* 2014; Chen *et al.,* 2016; Wang *et al.,* 2017). As a major flooding control measure, integration of dams, reservoirs and dikes (Hu *et al.,* 2014) have been connected and applied by the Chinese government. However, the environmental and ecological challenges posed by conservancy projects, such as changing the river temporal pattern and reducing downstream sediment fluxes have attracted wide attention (Yang *et al.,* 2011). Biodiversity degradation caused by flow manipulation, inundation and habitat fragmentation also make water conservancy more widely debated and researched.

Suggestions and future research directions

The establishment of modern water resources management systems require more reasonable laws and regulations for the water resources development and utilisation and the river water quality improvement in watershed scale. The effects of pollutants on aquatic organisms and short- and long-term effects of pollutants on human body through food chain and drinking water should also be included in the model simulation scope. With the development of big data computing ability, space remote sensing technology and GIS technology, integrated models are of pollutants one of the development directions to reduce the source in the watershed. Decision support systems combined with multiple technologies will become the development trend of water pollution model research in the future, which is suitable for many types of climate, hydrological conditions and pollutants. By combining pollution hydrodynamic, ecological, and eutrophication models with agricultural input and income assessment criteria, a multi-objective management optimization model could be established and used in scientific decision-making for the whole society to promote the sustainable development of whole watershed. Furthermore, multiple data collection methods, such as field surveys, longitudinal data, and observation and information collection can make the results more meaningful.

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