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Bridging gaps between environmental flows theory and practices in China

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Abstract

In recent decades, a series of policies and practices for environmental flows (e-flows) have been implemented in China, with the sustainable development goal of balancing the utilization and protection of water resources among social, economic, and ecological needs. The aims of this study were to determine the main challenges and issues in e-flows implementation at different scales by analyzing policies and practices for e-flows in China, and to propose some recommendations for bridging the gaps between the science and implementation of e-flows. The gaps between the science and implementation of e-flows were found after review of literature, policies, and practices, and it was found that ecological flow was a more widely used term by the government, rather than e-flows, in implementation. The plans and effects of e-flows implementation are discussed in this paper and challenges of e-flows implementation are recognized: (1) limited water resources and uneven spatial and temporal distribution, (2) a weak scientific basis for e-flows implementation, (3) poor operability of e-flows science, and (4) ineffective supervision and guarantee measures. The recommendations are (1) to strengthen the scientific foundation of e-flows, (2) to improve effectiveness in application of e-flows science, and (3) to propose operable and effective supervision and guarantee measures. This paper elaborates the current understanding of e-flows science and provides practical recommendations for implementing e-flows and for improving the effectiveness in e-flows implementation. To bridge the gaps between science and implementation of e-flows and improve the operability of policies in future practices, more scientific research on practices is recommended through adaptive management.

Keywords: Environmental flows; Ecological flow; Integrated water resources management; Adaptive management; Sustainable development

1. Introduction

Human freshwater needs and our dependence upon the ecological goods and services supported by healthy freshwater ecosystems present a major challenge for water managers and scientists alike (Xue et al., 2018). Hydrological alteration caused by river damming represents one of the most prominent human impacts on freshwater ecosystems (de Jalón et al., 2019; Xue et al., 2017; Lai and Wang, 2017). Scientists need to develop tools and models to facilitate water resources management and sustainable development of ecosystems, thereby balancing human and ecological demands for fresh water in complex, dynamic, and changing environments

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(Arthington et al., 2010). The most promising strategies for integrating freshwater management into the broader scope of ecological sustainability is the provision of environmental flows (e-flows). E-flows implementation and management require the application of methods to defining the e-flows requirements, which are further integrated into water resources management (Opperman et al., 2018). This strategy was endorsed by the *Brisbane Declaration* in 2007 and revised in 2017. There are different e-flows definitions (e.g., instream flow, ecological flow, and ecological base flow), though they are similar for healthy rivers. Regardless of the definitions, they depend upon the responsibilities of authorities, and show temporal, spatial, and functional diversities across segments and sites.

E-flows are the basis for maintaining the health and sustainability of river ecosystems during exploitation of hydropower and water resources. While the ecological effects of flow regulation have been extensively documented, much less research has investigated the hydrological effects of dams and reservoirs in quantitative terms. Meanwhile, construction of small hydropower plants is booming worldwide, exacerbating ongoing habitat fragmentation and degradation, and further causing biodiversity loss (Lange et al., 2018). A better understanding of the impacts at dam site, reach, and basin scales is key for e-flows implementation.

In China, hydropower has developed increasingly in recent decades and the total installed hydropower capacity will be 380 million kW by 2020 according to the 13th Five-Year Plan for Hydropower Development. In addition, an 80% compliance rate of water quality in important rivers and lakes will be accomplished by 2020, in order to improve aquatic ecosystem health according to the 13th Five-Year Plan for Water Resources Reform Development. 172 large water conservancy projects have been planned from 2016 to 2020, and adverse impacts of their construction on river ecosystem will appear after operation. Due to over-engineering of rivers in China, barriers and cutoff segments have appeared in most rivers. Degradation of aquatic ecosystems and destruction of water cycles persist, and e-flows have been recognized as critical to mitigating the adverse impacts of these activities. E-flows are usually determined in the periods of environmental impact assessment (EIA) (Caissie et al., 2015), water resources management plan (WRMP), and watershed protection and restoration plan (WPRP) (Chen et al., 2014a, 2014b). Determination of e-flows release has been one of the primary issues during the past 30 years in China (Chen et al., 2016b). Scientists have focused on the theory and methods of e-flows assessment while the government has paid more attention to e-flows release, guarantee, and supervision. Although the policies have provided the basis for administrative management, there are still many issues when e-flows science is applied.

The aims of this study were to bridge the gaps between the science and implementation of e-flows by recognizing the main challenges and issues in e-flows implementation at different scales and to analyze the e-flows policies and practices in China. The history and development of e-flows in China, and relevant e-flows literature, policies, and practices are reviewed. The plans and effects of e-flows implementation are discussed and challenges of applications of e-flows science are presented. Recommendations for better e-flows implementation in China are proposed.

2. Scientific basis for e-flows implementation

Over decades, e-flows approaches have been developed successfully and applied in developed countries. The same frameworks will not ensure increasing acceptance for e-flows application in developing countries in the face of new, emerging challenges (Matthews et al., 2014). The definition of e-flows was introduced to China in 2007, and it was applied in the Yellow River Basin based on the China-Europe Water Platform (Liu et al., 2008). The application originated with the minimum flow determination in northwestern China and then expanded to the Yellow River Basin because of frequent river cutoffs (Chen et al., 2016c; Sui et al., 2015).

Many countries have recognized the role that e-flows should play in water management and have incorporated e-flows provisions as they have updated water policy. Their experience sets out generic recommendations for governments and other stakeholders regarding factors that e-flows implementation is likely to be scaled up if it is reflected in policy frameworks (Harwood et al., 2018). However, there are still many difficulties in e-flows management and implementation. The gaps have been recognized through review of the relevant definitions and analysis of the differences (Chen et al., 2016a; Chen, 2019). Ecological water demand has nearly the same implication as e-flows, but does not take the water requirements for human culture and livelihoods into consideration. Ecological base flow and sensitive-object ecological water demand are the two important parts of instream ecological flow, which comprises of low flows, floods, high flood pulses, etc. These flow components can be computed by the Indicators of Hydrologic Alteration (IHA) software (Fitzhugh, 2015). Ecological base flow is the flow necessary for maintaining the basic structure and functions of river reaches, especially in cutoff segments, and it is simply determined as the minimum flow value. The value is 20%−30% of annual average flow in southern China. In contrast, it has been assigned two values, depending on the periods in northern China, generally 10% of annual average flow and 20%−30% of annual average flow during special periods, such as the fish spawning period. Sensitive-object ecological water demand is the flow necessary for maintaining flow-sensitive objects (Zhu et al., 2011). The objects may include important wetlands; rare and endangered fish species and their spawning, feeding, and wintering grounds; sediment transportation demands; and migratory avifauna.

Because of poor operability, e-flows have not been accepted by management authorities. Instead, instream ecological flow has been found to be more acceptable in implementation, as it focuses on maintaining the downstream aquatic ecosystem rather than the whole watershed ecosystem. Expanding the content and scope of various methods increases their relative reliability but requires much more expertise, money, and time

(Karakoyun et al., 2018). Therefore, ecological flow is being used instead of e-flows by China's governmental management authorities. It was first defined in the official guide, *Technical Guide for Environmental Impact Assessment of River Ecological Flow, Cold Water, and Fish Passage Facilities for Water Conservation Construction Projects (Trial) EIA Letter [2006] No. 4* (*Guide 2006*) (Chen and Wu, 2019). The ecological flow, including human needs and ecological demands, has become the most operable definition in China. The definition emphasizes the importance of natural flow regimes and describes the minimum flow requirement. The value described by the Montana Method in 1976 is as follows: "10% of the average flow is a minimum instantaneous flow recommended to sustain short-term survival habitat for most aquatic life forms" (Tennant, 1976).

Above all, ecological flow is an alternate tool for management, covering and synthesizing the relevant definitions of e-flows. The definition is more operable in China and provides a scientific basis for e-flows implementation. An agreement has been reached that ecological flow is nearly the same as e-flows in science and management. The implementation of ecological flow enriched the connotations in past decades.

3. Policies and practices

3.1. National scale

E-flows at the national scale have been implemented through policies and regulations of the responsible authorities. In order to improve effectiveness and efficiency of e-flows implementation at different levels of authorities, a series of policies have been issued and published. Fifty-one relevant documents have been identified according to the statistics by the end of 2017 (Chen and Wu, 2019). In general, a very strict management system for e-flows implementation has been set. Eleven of these documents were issued by the central government, 34 of them were issued by the responsible authorities of the central government, and six documents were issued by local authorities. Among them, 21 regulations were issued by the Ministry of Water Resources (MWR). The policies have usually come into being along with the emergence of water scarcity events. For example, a cutoff of the Yellow River in the 20th century promoted the water allocation plan of the Yellow River. A national project, Water Resources Evolution Mechanism and Renewable Maintenance of the Yellow River, was launched in 1999. The Yellow River Basin and the Huaihe River Basin were chosen as two pilot sites for e-flows scientific research and practice in a plan for prevention and control of water pollution (Zhang et al., 2017).

The total amount of water resources allocated for e-flows in China was limited, and the water requirement for irrigation and human livelihoods has generally been fulfilled. According to the National Water Resources Master Plan (Zhang et al., 2017), the minimum water volume for instream ecology and environment is 867.4 billion m^3, while 1918.1 billion m^3 is preserved for flood control. The total allocated water for e-flows will be 2271.9 billion m^3 by 2030. However, guaranteed e-flows present significant variations due to uneven spatial and temporal distribution of water resources and populations. The total amount of water resources is 2740 billion m^3 in China, but the total amount of water per capita is only 2098 m^3, accounting for 27% of the world's per capita amount. Water use intensity is an indicator that shows the intensity of water resources used and the level of water scarcity to meet human water demand. It is defined as the percentage of total available water resources of a country. The ratio is obtained by dividing the annual water withdrawal by the total annual renewable water resources. As one of 13 water-scarce countries in the world, the effectiveness of e-flows implementation in China is at the average status level, based on the comparison of water use intensity with other countries (Fig. 1).

3.2. Basin and regional scale

E-flows at the basin and regional scale have mainly been implemented through water allocation plans. It was proposed in 2010 that for implementation of the e-flows plan at the national scale and at the basin and regional scale, the maximum limitation of national total water usage by 2030 accounted for 25% of the total water resources in China, meaning that 75% of the total water resources was planned to be reserved for the ecosystem. The strict water resources management system was proposed in 2012. As a result, the efficiency of water usage has increased every year since 2011,

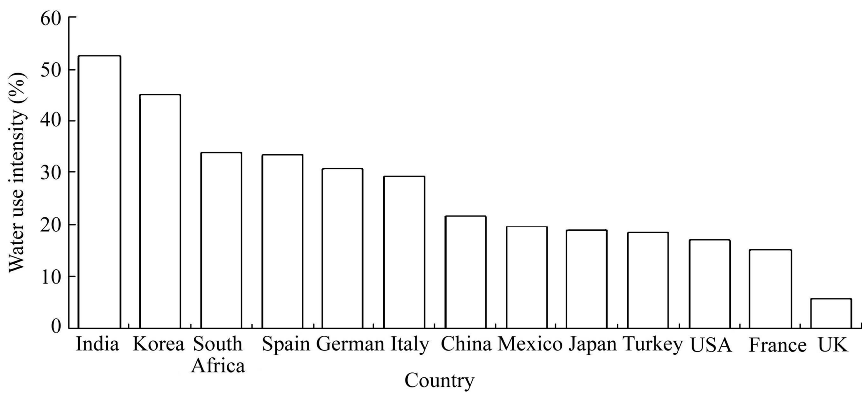

Fig. 1. Comparison of water use intensity in 2014.

and the qualification rate of water functional areas has gradually increased. E-flows implementation plans for each basin were designed in 2013, and e-flows in very important sections were determined and assessed for reservation. In the Yellow River, integrated water and sediment regulation has been implemented for cutoff prevention in the lower stream. E-flows management in the Tarim River, Heihe River, and Shiyang River basins was successfully conducted. There have also been a number of scientific reports and technical standards published and applied during the period of implementation (Chen and Wu, 2019).

In order to assess the effects of e-flows implementation at the basin scale, 180 rivers and 43 lakes and wetlands in China were chosen and 308 sections, including 265 sections of rivers and 43 sections of lakes and wetlands, were identified for assessment. The effects of e-flows implementation were analyzed from the perspectives of both ecological base flow and sensitive-object ecological water demand. The guaranteed rate of e-flows, based on whether daily e-flows requirements were met, was calculated.

In the implementation of e-flows at the regional scale, geographic variation was the main difficulty for e-flows assessment. Most rivers in northwestern China are seasonal rivers. Flow in these regions is mainly from the snowmelt in spring, and is very low in other seasons. Hydrological variation is significant in northern China, and runoff in most rivers has been heavily declining for decades because of climate change and human activities. E-flows release at barriers in these regions has mainly been dependent on reservoir inflows. The flow of rivers in southern China is much larger than in northern China and the minimum natural flow in southern China is higher than 10% of the annual average flow. The diversity of species is rich in southwestern China, and the key issue of e-flows implementation in these regions is to select the flow pulses for aquatic organisms.

E-flows implementation has shown varied effectiveness in watersheds and sub-regions. The guaranteed rate of e-flows in southern China was higher than in northern China, and implementation in main streams was better than in tributaries. For 125 sections of 77 rivers and 11 lakes and wetlands in southern China, the satisfactory ratio of ecological flow was 95%. The satisfaction ratio of ecological base flow was high while the ratio of sensitive-object ecological water demand was low. For 235 sections of 135 rivers and 35 lakes and wetlands in northern China, the satisfactory ratio of ecological flow was 75%. The satisfactory ratios of ecological base flow and sensitive-object ecological water demand were both low. Ecological base flow guarantee in tributaries in northern China was very difficult to meet. Compared with southern China, sensitive-object ecological water demand in northern China was not high. Ecological flow guarantee in northwestern China was a big problem because of water scarcity and conflict between ecological demand and human water demand. In recent years, ecological base flow of 80% of sections in northwestern China was improved through watershed water resources regulation. Most sensitive-object ecological water demands of downstream ecosystems were fulfilled by flood peak regulation. However, 20% of sections of rivers can hardly maintain ecological base flow and cutoffs appear, even though cascade reservoirs operate (e.g., the Heihe River, Shule River, Danghe River, Shiyanghe River, Tarim River, Kaidu River, and Peacock River).

3.3. Dam site scale

E-flows assessment at the dam site scale was improved and enforced in the management system. The first technical guide, *Guide 2006*, was issued for e-flows assessment of construction projects in 2006. E-flows release was specified in this guide for dams with less water or cutoff segments downstream. After that, e-flows guarantee measures became an important indicator in the management process and the e-flows implementation continuously improved (Fig. 2). The e-flows assessments are more scientific, and the downstream ecosystems of most projects have recovered through e-flows implementation.

Dam projects in China are divided into water conservancy projects and hydropower projects. E-flows implementation in the projects are determined by the authorities. In this study, e-flows implementation in 43 water conservancy projects from 2014 to 2017 and 105 hydropower projects from 2011 to 2017 were used to analyze the effects of e-flows implementation at the dam site scale (Chen and Wu, 2019). From the temporal perspective, e-flows release measures were enhanced after 2006 and the implementation was much more effective than before. E-flows implementation at hydropower stations was relatively effective, while it was not so effective for water conservancy projects because of insufficient funds. At the project scale, e-flows implementation in large projects was effective, while the efficiency of e-flows implementation in small projects needs to be improved.

E-flows implementation for water conservancy projects was different because they were of various types. According to statistics, 187 large water conservancy projects were built from 2009 to 2017, including six embankment projects, 32 flood control projects, five water supply projects, 18 irrigation projects, 31 waterway regulation projects, 31 river and lake renovation projects, 46 reservoir projects, and 18 water

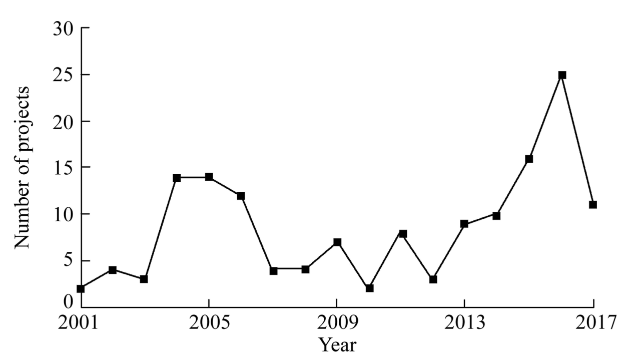

Fig. 2. Temporal distribution of e-flows implementation of dam projects from 2001 to 2017.

transfer projects. Only 23% of them launched e-flows assessment, including 34 reservoir projects.

With regard to hydropower projects, e-flows release was mainly implemented in run-of-river hydropower stations because there were water-reducing or cutoff segments downstream of these hydropower stations. E-flows were not considered for most projects before 2006, but were mandatory for all hydropower projects after 2006. E-flows implementation was mainly based on *Guide 2006*, according to the Tennant method, 7Q10, R2cross, the habitat simulation method, and eco-hydraulic methods. The minimum flow was generally higher than 10% of annual average flow, and the flow was higher for downstream ecological objects. After 2006, guarantee measures were built in 97% of the projects, and the flow improved after optimization (Wu and Chen, 2017).

For small hydropower projects in China, the efficiency of e-flows was much lower compared with other projects, because the density of small hydropower stations was very high in the small tributaries in northern China, and most of them were run-of-river hydropower stations. For example, there are 31 small hydropower stations along the Datong River, and cutoffs occurred downstream of most dams. There are over 150 small hydropower stations in the Qilian Mountains, of which 42 are located in the reserve. Ecological base flow and sensitive-object ecological water demand could not be fulfilled because of lack of e-flows release facilities.

4. Challenges and issues

4.1. Water resources and distribution

Spatial and temporal variations of precipitation and runoff are related to allocation of e-flows. Spatial distribution of groundwater resources is discordant with food productivity. Over 60% of precipitation is in flood seasons in southern China, while this value is over 70% in northern China (Xia et al., 2007). Thus, water needs for irrigation and urban users in drought seasons are in conflict, and environmental water is scarce. Half of the total economic water demand is met by 19% of total water resources in northern China. The carrying capacity of water resources in northern China is under intense pressure, especially in the Yellow River Basin, which accounts for 7.7% of total water resources and sustains 26.1% of farmlands (Xia et al., 2007). E-flows face challenges from climate change and its impacts on hydrological variations. Traditional e-flows theory and methods have not been adapted to the uncertain changing environment and are based on steady hydrological state hypotheses, which state that the hydrological series distribution is unchanged (Liu et al., 2016). The uncertain changing trends of climate and hydrological conditions have inestimable impacts on both macro and micro riverine ecosystems (McCluney et al., 2014). Since hydrological regimes and river ecosystems have changed significantly, it is not reasonable to use natural flow regimes as e-flows. The impacts of human activities on river ecosystems are significant in comparison with climate change (Xu et al., 2016).

The density of dams on the Yangtze River is very high. It might be much higher in tributaries of other rivers in China because of the construction of small hydropower projects. According to statistics from the government, there were 98002 dams and 46699 hydropower stations at the end of 2011 (MWR and NBS, 2013). Considering that water demands for population and economic development are increasing in China, it is very difficult to allocate more water for the environment. E-flows would not be guaranteed at dam sites, without scientific assessment and implementation, and that would directly result in river ecosystem degradation.

4.2. Scientific basis for e-flows implementation

Ecological flow is the most commonly used definition in water resources management systems in China, but its concepts have not been clear for implementation. There is no accurate definition of ecological flow in current technical regulations and guidance. Various definitions have been used based on specific objective in implementation. Research of e-flows mechanisms, such as eco-hydrological relationships, ecological water demand, and evolution mechanisms of wetlands, are still under discussion and in the initial phase. There are many factors that need to be considered in e-flows implementation, such as river characteristics, reservoir functions, ecological protection objects, and more scientific assessment. However, designers usually set 10% of annual average flow as e-flows due to lack of enforcement seriousness in the dam operation period. In recent years, more complex methods have been used in the e-flows assessment in the design period, but practices have still been based on the minimum flow value.

The differences and similarities between the segments in the main stream and tributaries, and between dams in different reaches were not fully considered. E-flows implementation conflicted with the environmental management framework. The diversity varied greatly with time in aquatic ecosystems. The spawning time varied from March to September, and it was also related to spatial differences. Endangered fishes were mostly located in the Yangtze River and in the southwestern rivers. For the life cycle of fish species, environmental water was insufficient. For reservoirs and dams with multiple uses, the differences in e-flows release were not considered. There were many protection objects, mainly including water quality, sediment transportation, basic structures and functions of river courses, water demand for hydro-salinity balance, wetland water demand, water demand for aquatic ecosystem balance, and water for aquatic organisms. The relationship between flow regimes and ecological processes was not given enough attention, and most studies were focused on the variation range of one hydrological element only, such as the discharge requirement for riverine ecosystems (Wang et al., 2013).

4.3. Application of e-flows science

There are many difficulties in the application of e-flows science in management systems. The main difficulty is that e-flows implementation involves multiple authorities and basins. Indicators are set for satisfactory evaluation of ecological base flow and sensitive-object ecological water demand. E-flows implementation and management are mainly based on *Guide 2006*, which focuses on the flow downstream of the dam. E-flows have gradually increased from the minimum ecological flow threshold value to the e-flows components, and then to the flow for sustenance of the whole river ecosystem.

There have been too many methods recommended in the guidelines, and too many guides in different periods of activities. E-flows implementation involves multidisciplinary intersection, and it is necessary to establish eco-hydrological relationships based on surveying and monitoring. However, the funding in some river basins has not been enough for this work. There are few qualified indicators for e-flows assessment in the management system. Even though the determination of e-flows involves rules, the reality is that most of the qualitative rules have not been operable and practicable for implementation. The minimum flow value is still the most effective way, though it is not feasible for all rivers in China.

Operation plans for important dam projects have not been reasonable with regard to e-flows implementation. In populated areas, e-flows are lower in comparison with human livelihoods and irrigation requirements. In water-scarce areas in northern China, the safety factor of water storage for different years is relatively high for some large and medium reservoirs. Annual flow regulation or multi-year flow regulation is used for urban and rural water supply and irrigation water. In water-rich areas in southern China, the operation mode of dam projects is less of a concern in environmental water needs. There is ecological regulation for most reservoirs except large reservoirs. For example, the Three Gorges Reservoir implemented e-flows regulation and flood pulse simulation considering the spawning of the four major Chinese carp species (Wang et al., 2014). The main ecological protection objects of inland rivers in northwestern China are the valley forests, downstream oasis, and wetlands, depending on e-flows in the flood season for the maintenance of their unique ecosystems. However, the satisfactory ratio of e-flows is very low in these rivers and environmental water cannot be guaranteed.

4.4. Supervision and guarantee measures

The main measure for supervision is monitoring of e-flows release, which has been widely used in large dam projects. There is insufficient consideration of ecological response monitoring and improvement, though there are improved monitoring programs in the Murray-Darling River Basin in Australia (King et al., 2015). Clearly identifying ecological responses to flow alteration is a significant challenge because of the complexity of river systems and other factors that may confound the response (Summers et al., 2015). The implementation has lagged far behind the river ecosystem alteration. A screening framework for dams and ecological impairment has been developed and applied in California (Grantham et al., 2014). There is still no common ecosystem monitoring system for the projects in China. Some large projects and companies have established ecosystem monitoring systems. For example, the Three Gorges Corporation has established a reservoir ecosystem monitoring system to supervise the four major Chinese carp species' spawning response to the operation of the Three Gorges Dam (Wang et al., 2014).

E-flows will fail in implementation if e-flows guarantee measures are not demanded strictly. E-flows release and drainage facilities were deficient in some early hydropower projects, since the facilities were not designed in the beginning. E-flows guarantee and release measures were examined and it is concluded that unscientific designs of ecological flow facilities have resulted in failure of e-flows implementation. There have been other causes: e-flows facilities and schedules have not been integrated in the operation plan of reservoirs; supervision in the construction period of dam projects has been weak; supervision in the operation period has been nearly absent; e-flows facilities have not been built as designed; and there have been no effectively operational measures since operation of the projects. Many projects have been approved by the local governments. The river division management system has led to the segmentation of a comprehensive protection system. It is estimated that only 10% of dam projects have been monitored by the online monitoring system for e-flows release.

E-flows are directly related to the hydroelectricity benefits. Allocating more water for the environment means less usage for economic activities. Research results have shown that the proposed shares with a dynamic flow licensing system would protect river flow more effectively than the current static minimum flow requirements during a dry year, but that the total opportunity cost to water abstractors of the environmental gains is 10%−15% loss in economic benefits (Erfani et al., 2015). Static minimum flow policy and dynamic flow duration curve have both been put into practice. However, economic incentive measures for discharging more environmental water during dry seasons are needed. For example, the installed capacity of the Jinping-II hydropower station is 4.8 million kW, and there is a 119-km long cutoff segment downstream. The minimum flow release is 45 m^3/s, which accounts for an annual hydroelectricity reduction of 1 billion kW·h. Assuming that the online price is 0.25 CNY per kW·h, it equates to a reduction of 250 million USD per year in generating income.

5. Recommendations

5.1. Strengthening scientific foundation of e-flows

Based on the challenges and issues described above, a scientific foundation of e-flows implementation is in need. It is necessary to propose a unified definition and interpretation of ecological flow. The scientific foundation of e-flows needs to be strengthened based on the diversity of rivers and lakes, protection objects, and sensitive periods. It has been found that increasing the scale of decision-making improves the efficiency of trade-offs (Roy et al., 2018).

More national scientific funded projects in China will support the research mechanisms of ecological and hydrological relationships, eco-basin assessment methods, dynamic evolvement of river ecosystems, fish habitat protection, ecological water demand for wetlands, and coordinated development of ecological-economic-social systems. As two important aspects of the management system in China, ecological base flow and sensitive-object ecological water demand should be assessed after a complete and scientific analysis based on various objects downstream. Since e-flows depend upon water resources allocation, water for irrigation, urban human livelihood needs, aquatic ecosystem stability, minimum dilution of water quality, water for sediment scouring and siltation balance, water for the fresh and salt water balance of the estuary, water for the dynamic groundwater level, water for evapotranspiration, and water for shipping should be considered at least. E-flows release should be raised when there are more water requirements, and the minimum value should be determined according to different rivers, regions, segments, and dams. E-flows should be considered first in implementation in important sections of rivers, lakes, and sensitive areas (e.g., reserves). Assessment of the guarantee rate of e-flows could be more scientific after research and consideration of different flow components, such as flood control, power generation, shipping, and irrigation. E-flows could be determined based on consultation with all stakeholders, such as watershed management organizations, hydropower station owners, and water resource users.

5.2. Improving effectiveness of e-flows implementation

E-flows are currently implemented according to published guides. There are too many methods in the guidelines and proper methods should be used according to the actual conditions, funds, and technical availability. The best solution is to determine the flow in the planning and design periods of dam projects. A list of dam e-flows implementation in environmental water plan and implementation of inventory management should be made based on regional diversity. Implementing a comprehensive survey of e-flows from main streams to tributaries in China will be helpful in understanding the protection objects of aquatic ecosystem. After determination of the main use and protection objects, the national e-flows database and monitoring network for e-flows implementation can be established. Appropriate e-flows release plans of each dam and e-flows for each river could be obtained.

Based on comparison with e-flows management in developed countries, relevant laws and regulations are recommended. For management of the whole process, e-flows should be integrated into sustainable hydropower management systems in planning, design, construction, and operation periods. Ecological operation should be planned for operating projects that have no e-flows release facilities. The planned and designed projects should ensure that e-flows implementation and release measures are synchronized with the main project. E-flows release plans and facilities should be made and integrated with operation plan of dam projects.

For small hydropower projects, compensation mechanisms should be strengthened in order to finish green small hydropower reconstruction. Many small hydropower stations built in the last century have no e-flows drainage facilities. Transformation and reconstruction of these small hydropower stations, as a matter of policy, can lead to social, ecological, and power generation benefits.

5.3. Operable and effective supervision and guarantee measures

E-flows supervision should be improved, and it is better to use measures of permanent e-flows release facilities. E-flows cannot be released when power generation flow of a single unit is less than 40%. Therefore, ecological generation units are not recommended to mitigate the impacts of reservoir regulation and operation. Meanwhile, release measures should be synchronized with the main project, and should be assessed as one of the environmental protection measures. The conflict between the e-flows release and power generation should be given attention to. The e-flows regulation should be integrated with a plan for single reservoir regulation and cascade reservoir regulation, which are the two main goals in e-flows implementation.

At the basin scale, cascade e-flows regulation can be promoted to improve the guarantee rate, so that e-flows release can be fully guaranteed. The insufficiency of run-of-river hydropower stations can be compensated by large annual impounding reservoirs through cascade reservoir regulation. At the dam site scale, ecological regulation and e-flow release from a single large annual impounding reservoir supply instream environmental water needs for maintaining the aquatic ecosystem, and the combined operation of cascade reservoirs and ecological operation. At the regional scale, after the implementation of the most stringent water resources management system, local governments and departments should strictly enforce e-flows. The basic principle is to integrate regional water resources regulation with integrated water resources regulation, and with hydroelectric power, water supply, shipping, and other objects that are also integrated with the National Water Resources Master Plan. A dynamic regulation management mode is effective in e-flows management. Considering the uncertainty and difficulty in verifying the results of e-flows assessment, e-flows should be continuously improved through adaptive management. Currently, there are not enough ecological monitoring data that can be used for building ecological and hydrological relationships.

In order to improve supervision of e-flows implementation, an automatic monitoring and long-distance transmission system downstream of e-flows release facilities should be established for authentic e-flows data acquisition. The hydroplant owners should regularly summarize the discharge monitoring data, synthesize the results of water quality monitoring and aquatic ecological monitoring, analyze the ecological protection of the river course, and optimize e-flows release plan in time. The administrative department responsible for environmental protection should strengthen the supervision of e-flows release measures and put forward e-flows optimization requirements by monitoring the operation of the facilities regularly. With provision for incentive and punishment, annual reports of e-flows of major rivers and lakes in China should be released to encourage public participation and supervision.

6. Conclusions

Past implementation of e-flows in China has been relatively imperfect, even though much scientific research and application have been done. There have been some achievements of past implementation, and the current e-flows status has improved much. The general plan of e-flows implementation has been deployed at multiple scales, including the national scale, basin and regional scale, and dam site scale. The effects of the implementations differ significantly across dams, regions, and basins. The greatest challenge of e-flows implementation in China is the spatial-temporal variations of runoff and precipitation. Though common effects are discussed in this paper, there are still many challenges in e-flows implementation due to limited water resources, weak scientific foundation, ineffectiveness of the management system, guarantee measures, and supervision. Online monitoring measures have been used in practice, but unified monitoring guidelines have not been formed. Since ecosystem functions and their equivalent flows are difficult to quantify, e-flows monitoring systems and effectiveness assessment have been recommended to improve the guarantee flow rate and supervision. Administrative measures are still most important in e-flows implementation. For better implementation in the future, there is still much work to do. Scientific research of e-flows needs to be strengthened, and the results need to be applied in practice to realize efficient management.

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