Basic theories and methods of watershed ecological regulation and control system

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ABSTRACT

Watershed is an important existing form of water, with various functions such as water supply, irrigation, fishery, tourism, and flood prevention, playing a major role in the daily production and lives of residents and regional social and economic development. As a brand new management objective, watershed development is a significant means for supporting and ensuring the sustainability of social, economic and environmental development. This paper elaborates the importance of preserving the ecological and hydrological connections of river systems to sustain their healthy life cycle, as a harmonious relationship is essential for the current and future watershed management. By emphasizing the importance of the watershed ecological and environmental management and restoration, on the basis of the existing research results, this paper sums up the basic concepts and connotation of the ecological operation of reservoirs, analyzing the research achievements and existing problems of ecological operation study, and resulting in a fundamental framework of ecological operation model based on the multiscale coupling mechanism, objective coordination mechanism, generative mechanism of characteristic flows and operation scheme of the rolling correction mechanism.

Key words | ecological control, ecological control model, ecological environment management and restoration, ecological operation, watershed management

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INTRODUCTION

Watershed is an important form of water, with various functions such as water supply, irrigation, fishery, tourism, and flood prevention, playing a major role in many aspects, including the daily production, lives of residents and regional social and economic development (Cadieux & Taylor 2013; Gudimov *et al.* 2015; Hipsey *et al.* 2015; Lu *et al.* 2016a). Watershed development is significant for supporting and ensuring the sustainability of social, economic and environmental development, and water environment management focuses on the ecology management. Since the 1990s, with the increase of human activities related to water pollution and ecological disruption, issues such as water eutrophication of lakes and rivers are prominent.

With the fast development of economy and society, people have better knowledge of the ecosystem and pay more attention to ecological operation. Chon (2011) proposed to lessen or eliminate the ecological and environmental effects of large and medium-sized reservoirs by changing reservoir operation. Frey & Rusch (2013) emphasized that ecological operation was put forward during the water resources allocation and operation, so during the planning, construction and operation of hydraulic works, social and economic benefits shall be considered, and ecological benefit also should be optimized. Gudimov *et al.* (2012) pointed out that compensating the demand of river ecosystem for water quantity, water quality and water temperature is the primary target, so scientific methods shall be adopted to effectively reduce the threat raised by the artificialization of downstream flow capacity, discharge of water with low temperature and supersaturated

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gas. Deng *et al.* (2016) believed that ecological conservation is also of great importance for reservoir operation to achieve multi social and economic goals. Ha *et al.* (2015) believed that reservoir ecological operation is available for handling the unevenness of the temporal and spatial distribution of runoffs. Mayer *et al.* (2014) believed that the ecological benefit of hydraulic projects is of equal importance as social and economic benefit, which needs to be upgraded to reduce the ecological and environmental impacts of dams. McClain *et al.* (2003) proposed that reservoir ecological operation refers to, during the process of controlling the water flow of reservoirs, fully considering the comprehensive utilization requirements of reservoirs while fulfilling the ecological and environmental water demand of rivers downstream of the reservoir and the requirements of water environment and quality of reservoir preservation.

Until now, even though the definition of reservoir ecological operation is not unified, all kinds of researches are emphasizing the ecological elements of reservoir operation by comprehensively considering the regional water demand of the ecological reservoir environment, coordinating ecological environment water demand and social and economic water utilization, and maintaining the health of the river ecosystems.

With the economic and social development in China, water demand is growing. Nowadays profit-oriented human activities deduce that the river eco-hydrological system is deteriorating. The operation of dams has changed the hydrological cycle of the natural river system and adjusted the intrinsic eco-hydrological relations. As a result, many living organisms have died or degenerated, as it was too late for them to adapt to the abrupt ecosystem change (Conrad & Hilchey 2011; Clark 2012; Plieninger *et al.* 2013; Lu *et al.* 2016b).

It is evident that most water-related ecological and environmental problems are closely linked to the changes of the river eco-hydrological relations. Thus it is of great theoretic value and practical significance to reconstruct, restore and maintain the ecological and hydrological relations of the river system and build a harmonious human–water relationship.

Currently, scientists have paid great attention to the response process of the river ecosystem and taken it as an important research subject in river ecological studies, trying to find effective methods to protect the river ecosystem restoration (Brinkley *et al.* 2010; Danielsen *et al.* 2010; Daniels *et al.* 2014; Lu *et al.* 2016c). During the continuous research period, ecologists and hydrologists have realized that the river eco-hydrological process is the key to the effect of hydropower projects on the river ecosystem, and in order to achieve sustainable management of water resources and renew the river ecosystem, it is important to maintain the organic connection between the river hydrologic and ecologic process and conduct ecological regulation in a feasible manner. This paper elaborates the importance of preserving the ecological and hydrological connections of river systems to sustain their healthy life cycle, as a harmonious relationship is essential for current and future watershed management.

CONNOTATION OF ECOLOGICAL OPERATION

'Ecological regulation' or 'ecological operation' is a new concept that has drawn much attention. The connotation of this concept is interpreted differently. 'Ecological operation' has no exact definition abroad. It has long been viewed as using an integrated operation to solve eco-environment problems. In China it is a common issue, with various approaches proposed. The difference lies in the setting of ecological goals and the priorities. Christin *et al.* (2014) think that the multi-objective ecological operation of dams is a method of reservoir regulation where multiple objectives, such as flood control, power generation, water supply, irrigation and shipping, are met and also takes into account the needs of the river ecosystem. Daniell *et al.* (2013) think that under the ecological reservoir operation, functions of the reservoir such as flood control, power generation, irrigation, water supply, shipping and tourism will be fully exploited on the basis of the protection of the downstream ecosystem and the water environment in the reservoir area, so that the negative impact of the reservoir on the ecosystem and the water environment in the downstream reach is kept within a tolerable limit, allowing renewal of the ecological and environment system gradually. Dickinson *et al.* (2010) state that ecological reservoir operation, by taking full consideration of reservoir's regulation behavior and river transportation characteristics, utilizes the storage capacity to store or discharge runoff, coordinate the natural flow and sediment to improve the water environment conditions in the reservoir area and the downstream areas, thus promoting river's health. Dietz *et al.* (2010) point out that ecological reservoir operation, based on such restricting factors as flood control, power generation, shipping, ecological water demand, irrigation, water supply, breeding, tourism and recreation and sewage flush, aims to achieve combined equilibrium and optimization through coordination of these economic factors, and reasonable reservoir operation is carried out to minimize the negative effect of the reservoir on the river ecosystem. At the same time, the reservoir's ability to regulate water content is utilized to help the complex river ecosystem develop in the direction of ecological succession. Rieman & Wallenburn (2015) think that ecological reservoir operation aims to basically realize the ecology environment objectives and then harness the social and economic benefits, but the precondition is that people's life and property are guaranteed. Van Delden *et al.* (2011) propose the ecological and environment operation, stating that the environment and ecology should be separated in the operation when studying the methods to minimize the eco-environmental impacts. The objective of environment operation is to improve water quality while ecological operation aims to make eco-compensation for the construction and operation of reservoir projects. The two are related but with different focuses. Based on the above-mentioned ecological operations, it can be found that the fundamental of ecological operations aims to incorporate the ecological factors into existing reservoir operations to match other reservoir functions, which in turn is regarded as the core function of the reservoir and used as the guidance for its operation practices. Ecological operation is a new stage of reservoir operation that addresses the ecological and environment problems from the start to the end so as to meet the objectives of water resource optimal allocation and river ecosystem health. In view of this, the author combines various definitions of reservoir ecological operation and now proposes the concept of ecological operation as follows (Agarwal *et al.* 2002; Brown *et al.* 2012; Vovik 2014; Zehe *et al.* 2014; Lu *et al.* 2017): ecological operation is to coordinate the relation between ecology and other reservoir functions to minimize the impact of reservoir operation on the downstream ecosystem on the basis of meeting human's basic needs of the rivers.

By definition, ecological operation can be defined in a broad or a narrow sense. The broad sense refers to reservoir combined regulation with the ecological requirement taken into account, while the narrow sense refers to reservoir regulation operation for a single purpose. Both approaches aim to improve the hydrological, hydraulic and water environment conditions in the reservoir air and the downstream areas, and safeguard river ecosystem health and safety (Maes *et al.* 2012; Crossman *et al.* 2013; Kandziora *et al.* 2013; Lu *et al.* 2018). Their difference lies in the broad sense that belongs to an integrated operation characterized by multiple dissensions, layers and objectives by which ecological protection is only one of the objectives pursued. In comprehensive application of reservoirs, the basic needs of flood control and water supply should be satisfied first, and then other goals are coordinated so as to protect river ecological functions. Whereas ecological operation in the narrow sense is one conducted to achieve a specific goal or at a certain stage, which has supreme priority among other functionality objectives, this approach is normally a method or a step in the combined operation, aiming at alleviating the ecology environment problems in some degree or within a short period, including the emergency response operation. Research and discussion of this article are focused on ecological operation in the broad sense.

STATUS QUO AND PROBLEMS CONCERNING ECOLOGICAL OPERATION

In related studies and practices abroad, the ecological operation is always considered a main river ecosystem renewal method, inclined toward the narrow sense. The work has been carried out in many countries. For example, the United States has conducted ecological operation in the Tennessee Valley and adaptive management in the Colorado River Glen Canyon; Australia has conducted ecological regulation in the Murray-Darling River (Pagella & Sinclair 2014; Ibisch *et al.* 2016; Mandle *et al.* 2016). The research in developed countries such as America and Australia is more advanced at the practical study stage (De Groot *et al.* 2010; Pahl-Wostl *et al.* 2011; Parker & Crona 2012;

Shang *et al.* 2016). In China, ecological operation is basically at an experiment stage. Due to the limits of current economic development level as well as the infrastructure, current research conditions and environment are immature in China and there is a huge gap in terms of research level. Many scholars in China have engaged in a series of studies and obtained original results. However, in order to arrive at a set of ecological operation theories and methodologies suited to Chinese conditions, the author believes that there are several problems which need to be solved urgently.

Insufficient basic data

Except for some special reserves, ecological monitoring is still quite backward in China. Many regions and rivers are not backed up with ecological monitoring data which has made ecological operation and ecological restoration research difficult in such areas. Therefore, improving the ecological monitoring network to enable real-time acquisition of ecological environment data is the key to further ecological restoration and regulation.

Ecological control objectives

The ecological reservoir operation aims to improve the drain conditions, restore the river's ecological and hydrological relations, and protect ecosystem health. To achieve the goal, it is necessary to understand the response mechanism between the flow conditions and the ecosystem, which is accompanied by a viable ecological control objective. Research results regarding ecological control objectives are mainly concentrated in the area of ecological water demand and are dominated by hydrological and hydraulic methodologies (Polasky *et al.* 2008; Ruckelshaus *et al.* 2015; Ellison *et al.* 2017), it has the following weak points. (1) Macro research scale. Due to the limits of operation level for ecological water demand, much of the ecological water requirement researches focus on water volume and thus there is no detailed description of the requirement process of the ecological system, such as the flow shape, the extreme changes and the flood pulse. (2) Undefined response relationship with the ecological system and lack of a physical foundation. Due to the limits of experiment research, many ecological objective researches lack macro experimental results as the base. The hydrological and ecological functions have unclear mechanisms which makes the feasibility and effect of ecological operation open to challenge.

Coordination of ecological goals and socioeconomic goals

Influenced by the social and economic system, Chinese reservoirs perform multiple functions, such as power generation, flood control, irrigation and water supply. Therefore, other functions should be coordinated when the ecological efficiency of reservoir is considered, e.g. coordination between ecological goals and the flood prevention plan and the regional network loads, and coordination between ecological functions and the water diversion process. However, as these matters are related to national flood control safety, energy safety, water supply safety and food safety which concerns national economy and people's livelihoods and involves a wide range of departments, the practical operating level is extremely complicated and challenging, and it is imperative to carry out the research work on the response mechanism of ecological operation in different areas.

Moreover, as water demand varies with time and space, ecological operation is time-dependent in the process of coordination with other objectives. It is therefore necessary to combine different water uses with multi-time scales and establish a principle of prioritizing time and space functions so as to develop a set of characteristic water flow generating techniques that feature multiple objects and multi-scales and adapt to other concurrent needs.

Complexity of basin ecological operation

The ecological operation at the basin level is no longer regarded as a simple issue that used to be considered the rise and fall of reservoir level and flow discharge, but an issue that concerns the whole river basin (Abson *et al.* 2014; Popescu *et al.* 2014; Vreese *et al.* 2016). At the current stage, an ecological control point or monitoring section is generally chosen for river or basin ecological control. However, the control flow for these points is always determined by the combination of the discharge amount of the reservoirs in the upper reach. In particular, the discharge accumulation of the mainstream and tributaries is relatively complicated in terms of time and space.

Maintaining a healthy river ecosystem is a systematic, complicated and multi-dimensional regulation problem, in which the ecological reservoir operation is only a link. After the operation is in place, it is still necessary to review river ecological health and its characteristics so as to further gauge the effect of the implementation of ecological operation. The results are used as reference for ecological feed-back regulation in order to build a well-established river eco-health regulation system and to provide long-term security for river health and life through ecological operation. In other words, it is necessary to set up a post-evaluation and rotational correction mechanism.

As ecological operation reference may impact the flow at control points, the ecological operation in the cascade reservoir on a basin-scale is too complicated to be solved easily.

Long-term effectiveness of ecological operation

The impact of ecological operation on river ecological and hydrological systems should be assessed in a broader sense, or the concurrent impact will be neglected. However, as current hydrological-ecological data is insufficient, there is a lack of insight into the hydrological-ecological relation, or there is diversity of the ecological goals caused by the diversity of river functions and biological communities, so people's perception of the health status of river ecological-hydrological differs from each other, or the understanding of the mechanism for the degeneration or restoration of river ecosystem caused by hydrological changes is incomplete. Therefore, it is very important to set up a widely accepted, river-specific and quantitative post-evaluation system with a view to providing a long-term mechanism for ecological operations.

KEY TECHNOLOGIES FOR ECOLOGICAL OPERATION

Ecological operation is a new stage of reservoir operation and aims at addressing ecological and environmental problems and promoting optimal water resource allocation and ecological health of rivers. By the sphere of action, the ecological reservoir operation can be divided into reservoir area ecological operation and downstream area-oriented ecological operation. As its name implies, the former focuses on the reservoir area by using the discharge flow process at different hours, different discharge positions and different flows to improve and maintain the health and stability of reservoir area ecological system, while the latter focuses on the protection of the downstream ecological environment system, covering a number of problems such as flow discharge magnitude, frequency, duration, occurrence time and rate of change, as well as water quality, temperature and sediment content. Depending on the object and goal of ecological reservoir operation, the ecological operation can be divided into five categories (Weaver *et al.* 2008; Berkes 2009; Bond *et al.* 2012, 2015): (1) ecological water demand regulation; (2) ecological flood regulation; (3) sediment regulation; (4) water quality and volume regulation; and (5) ecological factor regulation. Ecological factor regulation mainly refers to regulation of ecological factors, such as water temperature, flow rate and flow. The ecological operation proposed by this article is mainly concerned with ecological water demand regulation, e.g. ecological operation based on the ecological objective of ecological water requirements.

Based on the concept, connotation of ecological operation and the key problems in the study, the ecological reservoir operation should tackle the major problems in ecological operation research through four mechanisms (Cash *et al.* 2003; Adger *et al.* 2009), i.e. multi-scale coupling mechanism, objective coordination mechanism, characteristic flow generation mechanism and rotational correction mechanism.

Multi-scale coupling mechanism

Water demand for river ecosystems in different periods is different and the duration is different, too, so ecological water demand has multi-scale characteristics, that is to say, there is a difference in time-scale between the time scales (Alexander *et al.* 2015; Booth *et al.* 2016). For example, the minimum flow rests with the monthly scale and the impulse flow applies to daily scale. Therefore, important ecological information may be neglected if a monthly, ten-day or daily method is simply used as the operation period. Ecological operation modeling must cover different time scales by producing characteristic water flow of different time scales. Based on the experience and practice of reservoir operation, the author sets forth three time scales to carry out ecological operation, i.e. medium- and long-term operation, short-term operation and in-plant ecological operation. The medium- and long-term operation is suitable for yearly, monthly and ten-day scales and addresses the water needs for continuous flow, minimum flow and optimum flow; the short-period operation applies to daily and hourly scales and concentrates on problems such as bank-flush discharge, impulse flow and artificial floods. In-plant ecological operation, on the other hand, is responsible for detailed tasks or emergency or undefined tasks that other models cannot tackle, such as water temperature adjustment, improvement of water quality, aeration and supplementary nutrients. The three operation models use long- and short-term nesting and condition-triggered methods to generate characteristic water flow of different scales. Long- and short-term nesting refers to nesting of medium- and long-term ecological requirements and short-term ecological requirements. Water demand with minimum flow and optimum flow and other larger-scale requirements can be considered when developing medium- and long-term operation plans. However, when drawing up short-term plans, bank-flush discharge, pulse flow and artificial flood can be generated according to the time and condition-trigger mechanism. Other requirements for water temperature adjustment, improvement of water quality, aeration and supplementary nutrients can be controlled within in-plant operations in more detail and activated in response to monitoring data or ecological feedbacks.

Objective coordination mechanism

It is well known that reservoir operation is a complicated multi-dimensional, multi-objective and multi-layer project. Effective and stable strategies and methods have been developed over a long period of practice (such as the operation graph and rules). If ecological environment problems are to be solved by reservoir operation, its functions such as flood control, water supply and power generation must be considered. How should we develop a reservoir operation scheme that combines ecological requirements and human needs? It is imperative to conduct research on the coordination mechanism between ecological requirements and flood control objectives. Through coordination, the ecological environment along the river or in the basin can be improved to the largest extent within tolerable limits of human needs.

However, since human needs and ecological water requirements are whole-process behaviors, it is very difficult to realize so-called optimization at the operation level (Bangash *et al.* 2013; Serpa *et al.* 2015). The author believes that setting of priority targets according to the time, or objective-first approach, can be employed. Functionality objectives in different periods (at the same scale or different scales) can be arranged in sequence of importance, such as flood control priority in the flood season, irrigation objective priority in spring and summer irrigation season, power generation objective priority in the post-irrigation period, ecological objective priority in the important life cycle of organisms. The period of time can be divided according to the hydrological characteristics, water resource utilization and native species' water needs. Table 1 illustrates this using the Lanzhou section of the Yellow River.

As shown in Table 1, selection of key objectives is not necessarily all-inclusive and only those that need coordination are listed. For example, in the swelling period before the flood, we consider the pulse flow, irrigation and power generation objectives. It does not include water consumption for domestic use, though the factor may be important or should be treated as a priority. It is owing to the fact that water is abundant in such a period with no conflict with domestic consumption that it is not taken as a major consideration. This treatment can reduce the number of coordinated objects and the complexity of the coordination. At the same time, as key objectives vary greatly in different periods, they should be considered separately.

Mechanism for generation of characteristic water flow

Influenced by reservoir operation and water diversion, many original characteristic water flows have degraded and even disappeared, triggering a series of ecological environment problems (Bateman *et al.* 2013; Dong *et al.* 2015). Factors such as ecological flood, pulse flow and the restoration of bank-flush discharge and over-beach discharge, key to the ecological system, are very important to the living organism inside and outside the river. However, these characteristic flows normally occur in a particular period and under special inflow conditions, so manual intervention must be resorted to in order to form such flows. For example, upstream water and future rainfall factors can be combined in such considerations and the reservoir discharge and supply mode can be used to generate characteristic water flow required by downstream areas.

Flood pulse is generated in two parts: the time and the magnitude of the pulse discharge. When the inflow of downstream tributaries exceeds a limit value, a pulse discharge event will be activated, namely meeting the following conditions.

$$Q_T > T \tag{1}$$

where *T* is the limit value (m^3/s) produced by preset pulses. To avoid too frequent pulse event occurrences, the interval between two pulses can be set as a minimum of 5 days. When the flow falls to under the preset value or the flow decreases for *n* days successively (generally *n* is the preset pulse interval), a pulse event is over. Since flood pulse produces a pulse effect in the downstream areas through reservoir discharge, the reservoir must compensate and control pulse discharge. See the specific setting as follows:

$$Q_P = Q_R - Q_T + C \tag{2}$$

where Q_P is the discharge flow of the reservoir (m^3/s); Q_R is the target base flow (m^3/s); Q_T is the inflow rate (m^3/s) of downstream tributaries; *C* is the compensating factor that can be a positive value or negative value and it can be used to calculate the variations of the peak values when the flood peak floats downstream (including the decrease caused by evolution or increase from tributary inflow). When the tributary flow that triggers the discharge attenuates before the discharge period is over, the compensating factor can maintain the flow so that it reaches the required level at a given contact point. In an ecological operation model, as the number of flood pulses is very important, the mode of man–machine interaction can be adopted to manually select the pulse contact.

Table 1 | Mechanism for coordination between ecological goals and flood control and public-good objectives in the Lanzhou section of the Yellow River

		Flood season (June–September)				**Dry season (December–March**	
Name	**(Pre-flood swelling period (August–June)**	**Non-flood season**	**Medium and small flood season**	**Large flood season**	**Water falling stage after flood (October–November)**	**Ice flood season**	**Non-ice flood season**
Key operation objectives and prioritization	Pulse flow Irrigation Power generation	Flood control Power generation High flow capacity	Flood control Flood pulse Power generation Irrigation Bank-flush discharge	Flood control Sediment Over beach discharge Power generation	Power generation Irrigation Suitable discharge	Ice prevention Irrigation Suitable discharge Power generation	Life Irrigation Ecological basic flow Power generation

Rotational correction mechanism of operation scheme

The ecological system is a varying system. Water demand varies apparently with time and appears unstable in long-term evolution processes. Therefore, when an ecological operation scheme is developed, the operation strategy should be adjusted according to the response of the ecological system in order to achieve adaptive management goals.

A cybernetic model can be introduced to build a rotational correction mechanism for the operation scheme. Take the reservoir as a controlling system, as shown in Figure 1. It serves the function of control and receives the feedback. The downstream ecological system is used as the controlled system that receives control and supply feedback.

The controlling system model is combined with the controlled system model. The controlling system model enables the experienced operation, regulation and management staff to send control information to experts based on objective coordination results and control the controlled system. The controlled system, after receiving the control, acquires the feedback of downstream ecological system through ecological monitoring and evaluation system. After receiving the information, experts will analyze the information, republish the control information, exert real-time control and then form a rotational correction mechanism. However, since it is difficult to acquire ecological data and the timeliness of the response is poor, it is difficult to realize real-time operation, and the scheme can be corrected on a regular basis.

CONSTRUCTION OF THE ECOLOGICAL OPERATION MODEL SYSTEM

Based on existing research results and the analyses and discussions of key technologies involved in the modeling, a basic framework for ecological reservoir operation based on the scale nesting mechanism, objective coordination mechanism, characteristic water flow generation mechanism and operation scheme rotational correction mechanism is presented in Figure 2.

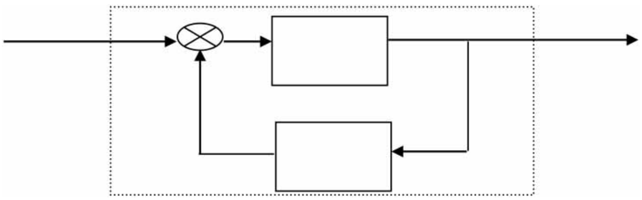

Figure 1 | Control theory model.

The ecological operation model system has the following characteristics:

1. The objective of ecological operation model system is to improve and maintain river ecological-hydrological relation and restore river ecosystem health.
2. The ecological operation model is a water resource multi-objective regulation model that takes into account the ecological requirements. It is designed to find a balance and compatibility between the ecological goals and human needs to improve and restore the health of the river ecosystem to meet basic human requirements (or with lesser influence).
3. The model system, through medium- and long-term operation, short-term operation and in-plant ecological operation, can effectively adapt to the scale difference existing in ecological requirements by producing or generating required characteristic water flow through the operation models of different scales.
4. The model system uses a key objective priority method for different periods based on multi-objective coupling (Danielsen *et al.* 2013; Clark *et al.* 2016). The reservoir operation objectives for different periods are prioritized according to importance while conflicting objectives are coordinated according to precedence. Such a multi-objective approach avoids too strong optimum solution theories existing in the multi-objective precedence method which lacks physical meaning and has poor operability. At the same time, the time-divided method can better approach the operation reality and make it easy to draft operation rules and schemes.
5. Operation itself is only a step in maintaining river eco health. To improve the health status of the ecological system, it is necessary to set up an ecological post-assessment mechanism. Rotational corrections are exercised over ecological operation through ecological monitoring information and evaluation results so as to maintain the scientific nature and effectiveness of the ecological operation.

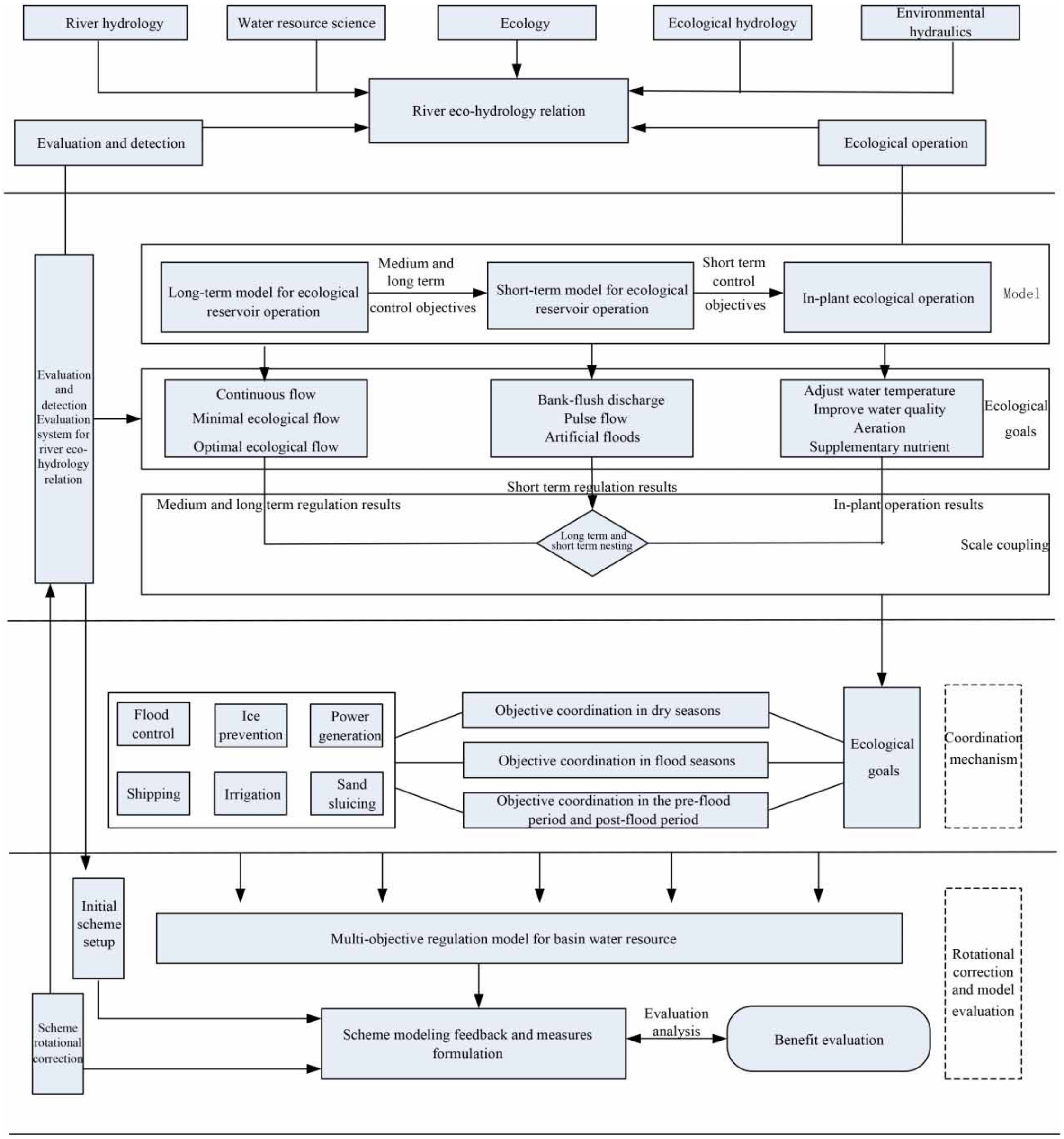

Figure 2 | Research framework for ecological operation.

AREAS THAT NEED DETAILED STUDY

Ecological reservoir operation is a frontier science in water resource study that involves hydrology, river dynamics, environmental science and ecology (Cortner & Moote 1994). It is a cross-field and complex discipline. As China is still in the exploration stage in terms of the practice of river ecological operation, many concepts exist in the operation of ecological reservoirs. Experiments have simply proposed single ecological requirements into water resource multi-objective models. There is a lack of consideration for the complexity of ecological objective's time scale and the optimal objective coordination mechanism, as well as insufficient combination of theories with practice. Therefore, based on related discussions and model framework for ecological operation, the author believes that future ecological operations should focus on the following aspects for detailed and effective research.

Improvement of ecological monitoring network

Ecological data are the basis for all river ecological studies. Due to the limits of economic conditions and development stage, the ecological monitoring network in China remains imperfect. A monitoring network is absent or has been disused for a long time in many rivers. Collectable data are too outdated. Take the Yellow River as an example. *A Preliminary Study Report on the Biological Foundation for Fishery in the Yellow River*, published by the Institute of Zoology at Chinese Academy of Science, and the *Fishery Resource in the Yellow River System*, written by the Yellow River Fishery Resource Work Group, are relatively complete surveys about the fish in the Yellow River (Fishery Resource Research 1987). Related surveys and research in this regard are small in number since 1990. Due to insufficient data, hydrological and ecological research on the Yellow River basin and the research on the evolution of its ecological system and its mutation mechanism have remained stagnant. It is evident that ecological data are the key to river ecosystem research. Perfecting an ecological monitoring network and improving the monitoring ability of the ecological system are crucial for deeper understanding of the ecological environment problems associated with rivers and the promotion of the rivers' health and life.

Study of ecological safety evaluation system

Evaluation of river ecological safety status is the premise of ecological operation, and also an important method and base for assessing ecological operation effects. Currently, related ecological safety evaluation is mainly based on biological population number, birth rate and habitat environment (Daw *et al.* 2011). It can reflect the overall situation of the ecological system, but the support it provides for ecological operation research is inadequate. Because it cannot determine the available operation factors on the basis of the evaluation results, the evaluation results cannot play a guiding role and there is actually no practical value for it. Therefore, optimum selection should be made based on the evaluation index and factors relating to the water flow, water quality and sediments should be used as the evaluation indicators as much as possible to strengthen the guidance of evaluation results.

Study of ecological objective identification

Ecological goals are vital to ecological operation theories. Selection of the objective can determine the impact of ecological operation. Existing research results at home and abroad contain varied ecological goals, including biological indicators such as fish, shell fish and alga. Some focus on hydrological indicators, mainly the hydrological regime (Geneletti *et al.* 2016). Ecological objective is a representative of the ecological system and is difficult to select. On the one hand, ecological objective must represent variations of the system, otherwise the effect of ecological operation is impractical; on the other hand, ecological goals must be concrete and easily quantifiable, or it will be difficult to activate ecological operation. Therefore, determination of ecological goals is a difficult job with a strong regional quality, and should be demonstrated and researched completely.

Study of the coordination mechanism between ecological goals and other reservoir objectives

Though this article presents a coordination mechanism between ecological goals and other reservoir objectives, the question is not solved completely. The time-based key objective precedence method can be used to address the conflict of objectives of a single reservoir. However, as for the ecological operation of a cascading reservoir or basin scale, its complexity is multiple. Issues such as optimization of flood control capacity and the hydrological relation and power transmission between cascading reservoirs have posed serious problems to the realization of ecological goals. Therefore, the objective coordination research between cascade reservoirs remains the core content of future river ecological operation research.

Study of ecology-oriented reservoir operation graph

To normalize ecological operation, it is necessary to draw up related operation rules or graphs. Ecological water requirements have multi-scale characteristics and do not match the conventional scale of the operation graph, so many ecological water requirements cannot be fulfilled by conventional operation graph. Therefore, it is important to study the operation graph that can reflect more detailed operating rules so that it can be used to guide the practice of ecological operation as a vital step from theoretical study to practical application.

Design of ecological hydraulic structure

Hydraulic structure is the physical base for ecological operation. However, the limits of the current stage, the ecological requirements in the reservoir areas or the downstream areas are not considered in the design process, so many ecological operation measures are difficult to implement, such as water temperature adjustment and aeration (Gleick 2000). They are not easy to manage because there are no facilities to support this. Related ecological hydraulic architectural design must be conducted to ensure ecological operation capability on the physical basis.

Supporting system of reservoir operation decision that considers ecological requirements

The operation scheme rotational correction mechanism is a man–machine interaction process. To realize such interactive rotational correction, it is necessary to set up a decision support platform. This platform can be used to release decision information, receive and summarize feedback information, and organize experts to discuss and formulate decisions and opinions so as to ensure scientific and accurate decision making on ecological operation. It can be predicted that the ecological operation decision support system will be the integrated body of associated research results for future ecological operation as an important safeguard of ecological operation process, therefore, focus should be placed on it in future studies.

CONCLUSIONS AND PROSPECTS

Watershed ecological operation is a major event that has a huge impact on the whole watershed, especially the regional ecology of waters downstream of the dams. Therefore, the operation shall be carried out in accordance with the preservation requirements of watershed biological resources.

Good river protection can maintain the basic biological process and life support system, protect gene diversity, and ensure the sustainability of species and the ecosystem. This paper mainly describes how important it is to maintain the eco-hydrological relation and build a harmonious man–water relationship in current and future river basin management. From the perspective of the importance of river ecological environmental management and the restoration process, this paper has summarized the existing research results, concluded the basic conceptions and connotations of ecological reservoir operation, analyzed the current situation and problems of ecological operation research, and presented a basic framework for ecological operation models based on multi-scale coupling mechanisms, objective coordination mechanisms, characteristic water flow generation mechanisms and operation scheme rotational correction mechanisms. Based on the model structure and research orientation, the subfields and themes for future prioritized research are proposed to lay a theoretical basis for further research of river ecological operation.

Watershed ecological operation is a multidisciplinary and complicated systematic engineering issue. Even though achievements have been made as elaborated in the paper, due to the complexity of the issue, deficiencies may be detected and much further research is still needed.

Currently, there lack monitoring systems and networks related to the evaluation of watershed ecological effects, the void of actual observation materials before and after the hydraulic engineering also brings a great deal of difficulty. We should improve the ecological environment data collection work, set up the original data base, proceed with ecological monitoring and analyzing works before and after the impact of human activities on the environment, so as to build an effective supervision and management system, which will facilitate the smooth completion of the evaluation work.

The flow capacity of watershed ecological environment needs to be further boosted. To achieve the reasonable allocation of water resources and to ensure the flow capacity of the ecological environment of river courses, it is necessary to conduct hierarchical analysis of water utilization, so as to coordinate the relationship between ecological environment water demand and social and ecological water demand.

Relevant models need further perfection. It is necessary to enrich the operation model and methods of hydraulic engineering, and fully consider the pulse discharge, nutrient concentration and other ecological elements, all of which will provide technical support for promoting the efficiency of ecological operation.

Economic evaluation is missed out during the consideration of operation strategies. The evaluation is delivered centering on water supply guarantee rate, annual rate of water shortage, depth of water shortage, and periods of the maximum continued shortage, which has mainly taken social benefit and evaluation into consideration and missed out the evaluation of ecological benefit. Therefore, while optimizing the objective function setting of the ecological operation of hydraulic engineering, aside from the maximum water supply (minimum water shortage) index, ecological indexes (such as power benefit) shall also be put on the table, so as to select the operation strategy comprehensively.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest in this work.

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