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Evidence-Based Indicator Approach to Identify Environmental Impacts of Cascade Dam Projects: A Case Study of Cascade Dam Projects on the Yangtze River

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Abstract: Policies for promoting sustainable development of dam projects in the world have always been an argument due to the negative impacts on ecosystems. How to improve the efficiency of identifying the impacts and main indicators in the environmental impact assessment (EIA) process and post environmental impact assessment (PEIA) process is a common topic. Since the rapid dam construction in the past decades, most dam projects in China have turned to operation period. In order to identify the main impacts and provide scientific bases for the decision-making process, we optimized and applied the decision-support prototype (DSP) toolkit on the cascade dam projects on the Yangtze River. Through the optimization of the module and tools, the modified DSP was more applicable for China's dams. Though the modified DSP cannot replace large-scale assessments for dam projects, it would assist the EIA and PEIA process by identifying the most relevant environmental concerns and knowledge gaps at early stages of negotiation, so that more attention can be focused on subsequent studies and evaluative processes. On the other hand, some new limitations were found in our practice. In response to the limitations, we propose several suggestions: (1) SBQ: to introduce a factor to balance the proportion evaluation result of new developed dams and existing dams in the study; (2) SBQ: to consider more about interactions between cascade dam projects and their impacts on different spatial scales; (3) EEM, extend the parameters for generating EEM from dams in areas outside of the U.S.

Keywords: environmental impact assessment; evidence-based indicator; hydropower; dams; river function

1. Introduction

To serve as water use, electricity, flood control, irrigation, shipping, and other purposes use for human beings, more and more dam projects are being constructed. Though it is a low-cost and low-carbon way to produce clean energy and has multiple uses, policies for promoting sustainable development of dam projects in the world have always been an argument [1–3]. The construction and operation of dam projects provide energy with long-term effects. Before the construction of projects, an environmental impact assessment (EIA) that relies upon environmental studies is required as common policy in many countries. However, sometimes it is not effective in rejecting projects with dubious justification, significant impacts, and little social utility [4]. Potential impacts and mitigation of construction and operation of the project are proposed after study, and then mitigation facilities and measures will be implemented. However, the effectiveness and effects of the mitigation are merely assessed for most projects and comprehensive data of mitigation facilities is lacking [5–7]. Costs of mitigation improvement can become a new decision variable for dam projects development in the U.S. due to the small scale of most of the remaining potential and the increasing stringency of environmental requirements [8–11]. Until now, there is no common policy for assessing the operation of dams, which guarantee

the sustainable development of the projects. In the U.S., a time and resource-intensive regulatory process Federal Energy Regulatory Commission (FERC) license was applied for project re-license [12]. While standard EIA may were enough in the past, at least six more detailed guidelines are prescribed by many international institutions (e.g., FERC, LIHI, EAWAG, GHC, HSAP, IEA, and EBRD), and three guidelines are under or prepared for implementation in China (e.g., LIHI, HSAP, and GHC) [13–15]. Most of them use a consolidated set of metrics to help balance competing demands and achieve stakeholder goals in a timely and affordable manner, while others use a time and resource consuming method to cover all the effects [16]. In order to scientifically assess the impacts of operation, China proposed guidelines of post environmental impact assessment (PEIA) framework based on the three guidelines. However, a subset of indicators may not adequately address all components of sustainability, while complete covered indicators spend uneconomic cost and delay the assessment to several years.

To be effective in evaluating the environmental impacts of dams' comprehensive cost-benefits, a decision-support prototype (DSP) toolkit was presented for determining the most relevant indicators to understand environmental impacts of dams [17]. The toolkit aims to increase the efficiency of the EIA process and assist the EIA process by identifying the most relevant environmental concerns and knowledge gaps at early stages based on the science-based questionnaire (SBQ), so that more attention can be focused on subsequent studies and evaluative processes. Furthermore, the toolkit can be applied to PEIA, and it can be used for determining the most relevant indicators of cascade dam projects after modification. Based on a database of environmental metrics collected from a series of studies, an Environmental Metrics of Hydropower that contains many indicators is proposed in six categories including biota and biodiversity (BB), water quality (WQ), geomorphology (GM), connectivity and fragmentation (CF), water quantity (HD), and land cover (LC). Moreover, then SBQ was built on the premise of eco-evidence approaches [18,19].

With rapid dam construction in the past decades, most dam projects in China have turned to operation period. Nearly half of the large dams of China have been built in the Yangtze River basin and the environmental impacts of the dams' operation remain uncertain [20]. In order to evaluate the impacts of operation, we chose the first dam project, Gezhouba Dam Project (GZBP), and the largest dam project, Three Gorges Dam Project (TGP), on the mainstream of the Yangtze River as objects to identify the preliminary critical indicators. This is mainly because most dams in the mainstream of the Yangtze River are under construction or put into operation in the past ten years. Moreover, there lacks a comprehensive investigation of environmental processes in the project operation. Identifying the most relevant environmental concerns is the most important preliminary work before the implementation. Since GZBP has been in operation for four decades, and it has been nearly 30 years since the construction of TGP, it is needed to implement a post environmental impact assessment of GZBP and to determine the preliminary critical indicators of the cascade dam project. We modified the DSP toolkit by evaluating a single dam project to adapt the cascaded dam projects, and applied it to finish the evaluation. Moreover, many regional contents were added in the modified DSP and the toolkit is more adaptable for dam projects in China through this study.

2. Materials and Methods

2.1. Method

The DSP was developed by McManamay and Oak Ridge National Laboratory. The overall development of the DSP and connections among the three tools are introduced in McManamay's paper. All three tools within the DSP were developed within Microsoft Excel with macro-enabled interactive features so it is very convenient to use and modify for a specific purpose. In this study, we modified the DSP for re-evaluation and post evaluation of cascade dam projects in China.

2.1.1. Science-Based Questionnaire (SBQ)

The first of the tools in the DSP is the science-based questionnaire (SBQ), which uses a question-driven weight-of-evidence approach to determine which river functions have been impacted by dam project construction and operation. A total of 52 river function indicators (Table 1, more details in Supplementary Table S1) were selected through a checklist study of Environmental Metrics for Hydropower (EMH). In the SBQ, two versions of the spreadsheet tool were provided for different projects: one for evaluating existing projects and a second for assessing potential impacts of new development projects.

Through a series of structured questions, the SBQ aids in identifying knowledge gaps and selects which river function indicators may be worthy of further investigation, either through documentary analysis or field investigations. In this study, we modified the structured questions based on China's reality and added some regional specific questions (Table S2). To structure the 140 questions in the SBQ, each of the questions was formulated to identify common environmental effects of dam projects implemented within a variety of contexts. Of these, 92 questions were reformatted to be applicable to new development projects. For both existing and new development projects, questions were organized into five major categories related to different spatial considerations and 18 subcategories aimed at more specific details (Table 2). Within the spreadsheet programs, answers to questions are summarized by river function indicators representing the dimensions of the terrestrial–aquatic environment potentially affected by cascade dam projects.

Table 1. River function indicators used to develop the science-based questionnaire presented in this paper (indicators and table taken and modified from Parish et al., 2019; Pracheil et al., 2019 and McManamay et al., 2020).

Category	ID	Name
Biota and Biodiversity (BB): Shifts in aquatic, riparian, and terrestrial populations and communities have been linked to several aspects of hydropower construction and operation and impacts to aquatic and terrestrial habitats. Accurate assessments of population and community are required to assess the health of the ecosystem.	F1	Abundance, density
	F51	Algae/primary productivity (BB)
	F5	Behavior, movement, colonization, extinction
	F6	Demographics, age, sex, size
	F7	Fitness, survival, growth, condition, reproduction, mortality
	F8	Functional group, or species or trait composition
	F9	Genetics, mixing, meta-population
	F10	Habitat, critical habitat, or surrogates of such
	F11	Internal composition nutrient abnormalities
	F2	Life history trait characteristics
	F3	Presence, absence, occupancy, or detection
	F4	Species diversity
Water Quality (WQ): Water quality characteristics can be directly or indirectly affected by hydropower development and operation. Changes in water quality can adversely affect the health of humans and wildlife	F40	Algae/primary productivity (WQ)
	F41	Buffering capacity
	F42	Dissolved gasses
	F43	Dissolved oxygen
	F44	Ecosystem function
	F45	Gas emissions
	F46	Key elements
	F47	Macro-molecular pollutants
	F48	Nutrients and organic material (C, N, P)
	F49	Solid transport, turbidity, and conductivity
	F50	Water temperature
Geomorphology (GM): Hydropower development can disrupt a river system's geomorphologic equilibrium through altered sediment and flow regimes, which influence the availability and quality of habitat for plants and animals within the system	F15	Catchment and basin attributes
	F16	Channel
	F17	Floodplain valley
	F18	Sediment and substrate

Table 1. *Cont.*

Category	ID	Name
Connectivity and Fragmentation (CF): Dams and reservoirs disrupt aquatic, riparian, and terrestrial connectivity, all of which can directly affect the habitat quantity and quality for organisms in an ecosystem	F12	Basin area
	F13	Dendritic network and riverscape
	F14	Fish passage
	F52	Spillage and turbineentrainment
Water Quantity (HD): Hydropower development can alter the hydrologic cycle by impounding free-flowing water, increased evaporation, and altered groundwater recharge. Because dam operations may serve many purposes, temporal changes to water quantity affect human and wildlife populations through altered water availability	F24	Basin attributes
	F25	Diversion
	F26-31	Downstream discharge
	F26	Downstreamdischarge duration
	F27	Downstream discharge frequency
	F28	Downstream discharge magnitude
	F29	Downstream discharge periodicity
	F30	Downstream discharge rate-of-change
	F31	Downstream discharge timing
	F32	Groundwater
	F33-39	Upstream hydrology
	F33	Reservoir hydrology
	F34	Upstream inflow duration
	F35	Upstream inflow frequency
	F36	Upstream inflow magnitude
	F37	Upstream inflow periodicity
	F38	Upstream inflow rate-of-change
	F39	Upstream inflow timing
Land Cover (LC): Land cover influences many other environmental properties ranging from river and floodplain sedimentation rates to fragmentation of habitats and wildlife populations. Land cover changes can include increases in wetted surfaces from reservoir formation, and fragmentation of the surrounding landscape by infrastructure (e.g., transmission lines, roads).	F19	Area impacted, project area
	F20	Floodplain or riparian vegetation
	F21	Land cover class
	F22	Protected land
	F23	Reservoir inundation

Table 2. Number of questions within each section of the spreadsheet tools ("Existing" refers to the spreadsheet program for existing dams whereas "New" refers to the program for new development) and their relationship to each river function indicator category.

Categories	Subcategories	Questions		Applicable River Function Categories					
		Exist	New	BD	CF	GM	LC	HD	WQ
Basin Context	Project location and orientation	4	4	●	●	◎	◎	◎	◎
	Upstream human activities	6	6	●	●	◎	◎	●	●
	Regional water quality considerations	8	8	●	◎	●	●	◎	●
	Surrounding landscape and geology	6	6	◎	◎	●	◎	●	◎
	Regional biological considerations	5	5	●	●	◎	●	◎	◎
Project characteristics	General information	8	8	◎	●	◎	●	◎	◎
	Operations and Infrastructure	12	12	●	●	●	●	●	●
	Other considerations	5	1	●	◎	◎	◎	◎	●
Reservoir properties and conditions	General information	8	7	◎	◎	◎	●	●	●
	Sediment, organic matter, water quality	8	3	●	◎	●	●	●	●
	Surrounding land use considerations	4	0	◎	◎	◎	●	●	◎

Table 2. *Cont.*

Categories	Subcategories	Questions		Applicable River Function Categories					
		Exist	**New**	**BD**	**CF**	**GM**	**LC**	**HD**	**WQ**
Downstream properties and conditions	Flows and water quality	9	6	●	●	●	◎	●	●
	Channel geomorphology	9	2	◎	◎	●	●	●	●
	Floodplains	6	2	◎	◎	●	●	◎	◎
Biological Considerations and Biodiversity	Biological conditions downstream	17	7	●	●	●	◎	●	●
	Migratory organism considerations	7	5	●	●	◎	◎	◎	◎
	Fish passage and injury	9	2	●	●	◎	◎	◎	●
	Biological sampling considerations	9	8	●	◎	◎	◎	◎	◎
	Total	140	92	●	●	●	●	●	●

Note: ● means exit; ◎ means none exit.

All questions were structured in a way that "yes" answers provided evidence of potential effects of dam projects on a given function. All questions must be answered "yes", "no", "uncertain", or "not applicable". Five questions were targeted per function in order to elicit enough information about each function while also providing a "tiebreaker" question. The questions were organized into a series of primary categories and subcategories. Primary categories of organization related to the spatial scales (basin, project-level, reservoir, or downstream). For biologically relevant questions, options were also provided for a user to specify which taxa groups were relevant (fish, amphibian, bird, mammal, reptile, crustacean, bivalve, insect, and plant).

2.1.2. Environmental-Envelope Model (EEM)

The second tool is environmental envelope model (EEM) to predict the likelihood of river functions being affected by dam projects based on several variables. In cases of new development projects, answering questions about environmental impacts may be difficult as development has yet to occur and environmental responses are not observable. Information required to determine the potential impacts of a new project on river functions is generally limited by using the SBQ. Thus, the EEM was developed based on data envelopment analysis (DEA), by using EHM database of more than 3000 environmental metrics derived from global literature of several types.

DEA is a non-parametric mathematical method measuring relative performance or efficiency within a group of homogeneous decision-making units (DMUs) with multiple inputs and multiple outputs [21]. The Charnes–Cooper–Rhodes (CCR) DEA model and the Banker–Charnes–Cooper (BCC) DEA model are two standard DEA models. The CCR DEA model is a model of constant returns to scale. The BCC DEA model is a model of variable returns of scale. In this study, the CCR DEA model was used.

Let a set of DMU_j be in the evaluation system. Define x_{ij} as the input vector of DMU_j with the input weight vector v_i, and define y_{ij} as the output vector of DMU_j with the output weight vector u_i. Assume that each DMU_j consumes x_{ij} amount of input i to produce y_{rj} amount of output r, and that the input and output of DMU_j being evaluated are as in Equation (1).

$$
\begin{array}{c}
\begin{array}{ccccc}
 & 1 & \cdots & j & \cdots & n
\end{array}\\
\begin{array}{ccccc}
v_1 & \cdots & 1 & \rightarrow & x_{11} & \cdots & x_{1j} & \cdots & x_{1n}\\
\vdots & v_i & \vdots & & \vdots & \ddots & x_{ij} & \ddots & \vdots\\
v_m & \cdots & m & \rightarrow & x_{m1} & \cdots & x_{mj} & \cdots & x_{mn}
\end{array}
\end{array}
\tag{1}
$$

$$
\begin{array}{ccccccccc}
y_{11} & \cdots & y_{1j} & \cdots & y_{1n} & \rightarrow & 1 & \cdots & u_1\\
\vdots & \ddots & y_{ij} & \ddots & \vdots & & \vdots & u_i & \vdots\\
y_{r1} & \cdots & y_{rj} & \cdots & y_{rn} & \rightarrow & s & \cdots & u_r
\end{array}
$$

In this study, 10 indicators of dam attributes (Table 3) were selected as the input vector v_i of DMU_j and predictive variables of EEM, and their influence on 52 river function "occurrence" probability was selected as the output vector u_i, and the possibility of being impacted was selected by EEM.

Table 3. Indicators of dam attributes as input vector of DMU and predictive variables used in developing the environmental envelope model (EEM), their description.

Variable	Unit	Description
Installed Capacity (MW)	Megawatts (MW)	Generating capacity as an indication of the size of the facility
Dam Height (Height_m)	m	Height of the dam
Discharge Flow (Flow_cms)	cms	Discharge of dam
Reservoir Storage (Stor_ml)	Megaliters (ML)	Storage of the reservoir
Surface Area	km^2	Surface area of the reservoir
Fish Species of Concern (FSOC)	n	Number of fish species of concern occurring in watershed containing dam project
Total Number of Aquatic Species of Concern (TASOC)	n	Total number of aquatic species of concern occurring in watershed containing dam project
Number of Terrestrial Species of Concern (TSOC)	n	Number of terrestrial species of concern occurring in watershed containing dam project
Critical Habitats (CritHab)	Y/N	Spatial intersection of national endangered or threatened species' critical habitats with project reservoir or proximate downstream environment
Conservation Land (ConsLand)	Y/N	Spatial intersection of protected lands with project reservoir or proximate downstream environment

For unit j_0 ($1 \le j_o \le n$), the input-oriented DEA model has the form of Equation (2). The goal of the input-oriented DEA model is to minimize the virtual input, relative to a given virtual output, subject to the constraint that no DMU can operate beyond the production possibility set and the constrain relating to non-negative wights. While the optimal efficiency rating h_{j0} of P is 1, then j_0 is considered 100% efficient.

$$
(P) = \begin{cases}
\max h_{j0} = \dfrac{\sum\limits_{r=1}^{s} u_r y_{rj}}{\sum\limits_{i=1}^{m} v_i x_{ij}}\\[2ex]
s.t. \left(\dfrac{\sum\limits_{r=1}^{s} u_r y_{rj}}{\sum\limits_{i=1}^{m} v_i x_{ij}}\right) \le 1, j = 1, 2, \cdots, n\\[2ex]
u = (u_1, u_2, \cdots, u_n)^T \ge 0\\
v = (v_1, v_2, \cdots, v_n)^T \ge 0
\end{cases}
= \begin{cases}
\max h_{j0} = \dfrac{u^T y_0}{v^T x_0}\\[1ex]
s.t. \left(\dfrac{u^T y_j}{v^T x_j}\right) \le 1, j = 1, 2, \cdots, n\\[1ex]
u \ge 0\\
v \ge 0
\end{cases}
\tag{2}
$$

To construct the non-linear envelop relationship between the 10 predictor variables and 52 river function indicators, the Generalized Reduced Gradient algorithm was used to maximize log likelihoods in Microsoft Excel. Moreover, two scenarios of river function indicator envelope curves were developed to determine the individual influence of each predictor variable on the probability of impacting each of the 52 river function indicators. In this study, the upper limit threshold where predictor variables' values 25th percentile equals the maximum P is 1, and where percentiles of 0.05, 0.1, 0.15, and 0.2 equal P values of 0.2, 0.4, 0.6, and 0.8, respectively. The lower limit threshold where 50th percentile of predictor variables' values equals the maximum P is 1, and where 0.1, 0.2, 0.25, 0.3, and 0.4 percentiles equal P of 0.2, 0.4, 0.5, 0.6, and 0.8, respectively (Figure 1). After that, the individual influence of each predictor variable on the probability of impacting each river functions indicator can be determined.
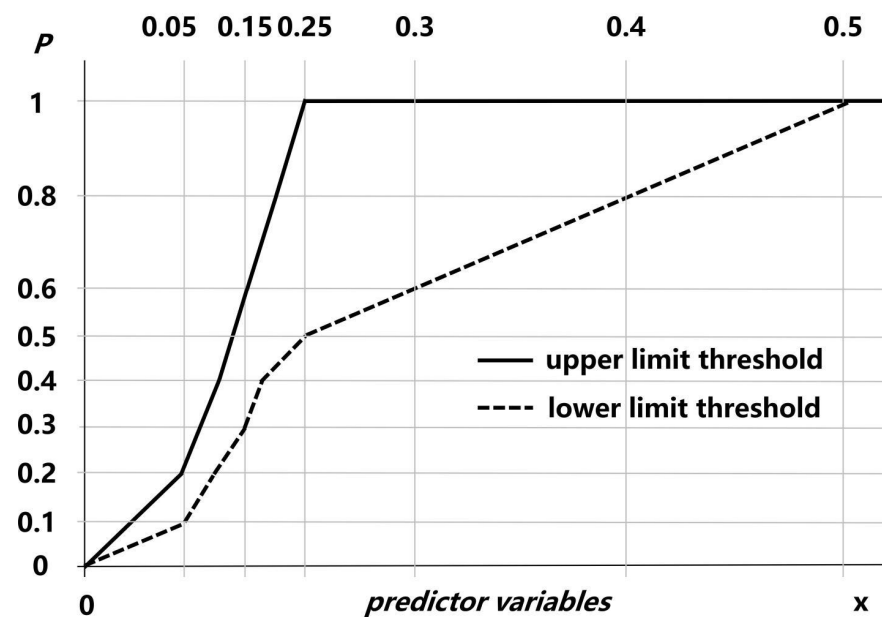
Figure 1. Upper and lower threshold envelopes predicting the probability of each predictor variable on each river function indicator.

Furthermore, an indicator suitability scores (*SS*) was constructed to describe the individual influence of a dam project on the probability of impacting each river functions indicator (Equation (3)). *SS* consist of 10 individual influences of each predictor variable on the probability of impacting each river functions indicator u_i. Based on the upper and lower limit threshold, max(SS_j) and min(SS_j) can be calculated. Moreover, the 52 max(SS) and min(SS) provide the individual influence range of new dam projects on the probability of impacting river function indicators.

$$SS_j = \frac{\sum\limits_{i=1}^{n} u_i^j w_i^j}{\sum\limits_{i=1}^{n} w_i^j} \tag{3}$$

where SS_j is the individual influence of a dam project on the probability of impacting j^{th} river functions indicator, j = 1, 2, ... , 52. u_i^j is the individual influence of ith predictor variable on the probability of impacting j^{th} river functions indicator, and i = 1, 2, ... , 10. w_i^j is the relative weight of the individual influence of ith predictor variable on the probability of impacting j^{th} river functions indicator, $0 < w_i^j < 10$.

2.1.3. River Function Linkage Assessment Tool (RFLAT)

The third tool is the River Function Linkage Assessment Tool (RFLAT) for drawing graphical networks to visualize inter-dependence among river functions and indicators. A binary matrix of pair-wise directional hypothetical relationships between river functions was formed, where 1 indicates a viable relationship and 0 indicates no likely relationship. Visualizing network-type relationships required decomposing the matrix into node and edge datasets. The "node" dataset represented river functions as hubs of the network whereas the "edge" dataset represented the relationships (i.e., 'from-to' linkages) among river functions. The strength of relationships between indicators can further be informed using evidence from the SBQ, particularly the proportion of questions answered "yes" for each indicator participating in a relationship. Bayes' theorem was used to infer causality between indicators (Equation (4) to Equation (6)), where the probability of causality is conditioned based on the probabilities that each indicator is independently affected. The RFLAT tool also requires the use of the R programming code to develop network visualizations. In this study, we extended the linkage from functions categories to function indicators in order to describe the details of the cause-and-effect relationship. Moreover, network visualizations were described by a "Circos" graph instead of a network type relationship graph.

$$p(I\,y|\,I_x) = H\left(\frac{p(I_x|I_y)\,p(I_y)}{p(I_x|I_y)\,p(I_y) + p(I_x|\sim I_y)\,p(\sim I_y)}\right) \tag{4}$$

$$p(I_x|I_y) = p(I_x)\,p(I_y) \tag{5}$$

$$p(I_y|\sim I_x) = \frac{(1 - p(I_y)) + (1 - p(I_x))}{2} \tag{6}$$

where $p(I_x|I_y)$ represents the strength of causal relationship of indicator I_x and indicator I_y, it is the conditional probabilities of I_y being influenced by indicator I_x. H is the hypothesized relationship, as indicated by binary values of 0 and 1. $p(I_x)$ and $p(I_y)$ are the proportions of questions answered "yes" for indicator I_x and indicator I_y. $p(\sim I_y)$ is the probability that I_y is not impacted, and $p(I_x|\sim I_y)$ is the probability of I_x being impacted when I_y is not impacted. There is a hypothesis in the RFLAT development that some indicators I_y cannot be affected by dam projects, the minimum value of $p(\sim I_y)$ is set 0.2; thus, if $1 - p(I_y) \leq 0.2$, then $p(\sim I_y) = 0.2$, or, $p(\sim I_y) = 1 - p(I_y)$.

2.1.4. Evaluation for Cascade Dam Projects

For under evaluation cascade dam projects, the target objects can be regarded as an entirety. Any elements or impacts of one project can be regarded as the entirety's elements or impacts. As cascade dam projects in a basin might range from upstream to downstream, the nearest integrated dam project and re-regulated dam project were mainly considered in this study. Therefore, the evaluation period can be divided into several periods:

The first period is the predicative re-evaluation of planning dam projects. SBQ is used for the new DSP and EEM for the modified DSP to re-evaluate the predicative impacts of an individual dam project.

The second period is the post or review evaluation of a single dam project. SBQ is used for an existing project in modified DSP to evaluate the impacts of an individual dam project.

The third period is the post or review evaluation of cascade dam projects. Using SBQ for an existing project in modified DSP to evaluate the impacts of cascade dam projects.

For more than two cascaded projects, more periods need to be considered based on their contribution to joint operation.

2.2. Study Area

2.2.1. General Information

The study area is the Yangtze River basin in China (Figure 2). It is the world's third longest river, with a length of 6300 km. The Yangtze River basin is a major development area for China, drains an area of 1.8 million km², and has experienced rapid socioeconomic development in the past decades. There are more than 50,000 dams and reservoirs in the basin under the influence of both climate change and human activities. The basin is already home to 40% of the country's total GDP. Most of the water use in the basin is for irrigation, primarily for water-intensive rice production. The dam project has made great contribution to water use. However, most of the dams are on the tributaries, the dams on the mainstream of the Yangtze River are mainly on the very upstream. The lowest two dam projects are GZBP and TGP.
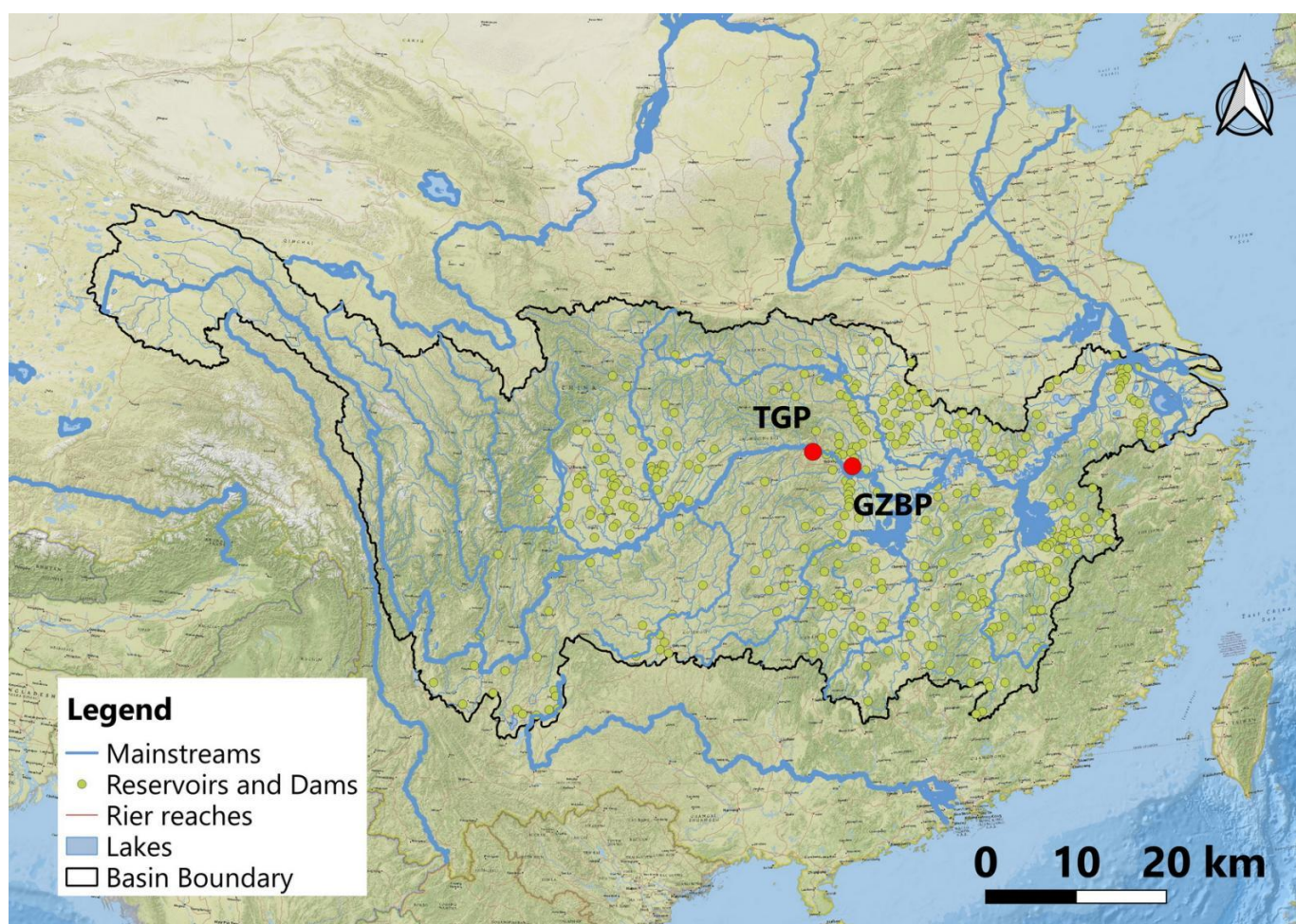
Figure 2. Yangtze river basin and cascade GZBP and TGP location.

GZBP is located in Yichang City of Hubei Province in China, 38 km away from the dam of TGP on the upstream of the Yangtze River. It is the first dam and first large-scale water control project on the mainstream of the Yangtze River, which started construction in 1970, generated in 1981, and finished construction in 1988. The project is the most downstream dam in the upper stream and water catching area is merely 1 million km², which is about 56% of the Yangtze River basin area. It consists of two hydroelectric power stations with an installed capacity of 2715 MW, three navigation locks, and several sluice gates, some of which are used for accumulating water in dry seasons. There is a total storage capacity of 1.58 billion m³, and a maximum discharging capability of 110,000 m³/s.

TGP is on the upstream of the GZBP. It is the largest dam project in the world, which started construction in 1993, generated in 2003, and finished construction in 2015. The install capacity of TGP is 22,500 MW.

2.2.2. Temporal Limits

The main purpose of GZBP development is mainly for electricity, shipping, re-regulating, etc., while the main purpose of TGP development is flood control, electricity, shipping, and water replenishment. After TGP started generating in 2003, the two projects of TGP and GZBP started to operate in combination. Therefore, to identify the critical impacts of GZBP, the evaluation period was divided into three periods.

The first period is the natural period. Before 1981, there were no dam barriers on the mainstream of the Yangtze River, and the mainstream was free flowing. We need to predict and identify the main impacts of GZBP.

The second period is the individual dam period. From 1982 to 2002, there was only one dam barrier on the mainstream of the Yangtze River, GZBP was independently operated. We need to review the main impacts of GZBP in this period to identify the individual impacts of construction and operation.

The third period is the integrated operation period. Since 2003 until now, there are several dam barriers on the mainstream of the Yangtze River, GZBP, and TGP are the nearest two project in integrated operation. At the beginning, there were no other dam projects on the mainstream. Then, more and more cascade dam projects joined the cascade joint operation of the Yangtze River basin. Currently, there are six large dam projects on the mainstream of the Yangtze River, that are jointly operated.

2.2.3. Spatial Limits

The general spatial extent is mainly from the tail area of the TGP reservoir to the 80 km downstream below the GZBP dam. This spatial extent covered the main parts of GZBP and TGP, and the two dams are the boundary section of the concerned area, which is divided into three parts: upstream of the TGP dam, TGP dam to GZBP dam, and downstream of the GZBP dam. For some specific evaluation purpose such as basin context and biodiversity, the spatial scale extended to a wider range.

2.3. Data

The data sources are mainly peer-reviewed articles online from Web of Science, Google Scholar, China National Knowledge Infrastructure (CNKI), scientific reports, and files from official websites. These open source data were mainly used for providing answers evidence for SBQ and EEM.

Moreover, there are some basic data from preliminary investigation such as hydrological data, hydro-environment data, hydro-biological data, remote sensing, and Geographic Information System (GIS) data, etc., (Table 4). These basic data were mainly used for indirect analyzing to answer questions. For example, hydrological data analyzing was used for for Q_70 "Does the project changes any downstream monthly flows larger than 20%?"; land use data analyzing was used for Q_126 "Does agricultural landcover occupy at least 10% of area in upstream watershed above facility?".

For regional biological considerations, there was no natural barriers to fish migration in the downstream of project. For this cascade project, we chose protected fish in the "List of key protected wild animals in China (2021)" as species of concern. There are two fish species (*Acipenser sinensis, Psephurus gladius*) and two amphibian species (*Lipotes vexillifer, Neophocaena asiaeorientalis*) found adjacent to project waters. There are no invasive species found in project lands or waters [22].

Table 4. Data category and sources for evaluation.

Category	Sources	Note
Articles	Web of Science, Google Scholar, China National Knowledge Infrastructure (CNKI)	Keywords are Yangtze River; TGP; GZBP; Changjiang, etc.
Reports and news	EIA reports; HSAP reports; official websites of dam related industries and government	Ministry of Ecology and Environment, Ministry of Water Resources, etc.
Hydrological data	Daily flows, sediment, water temperature of Yichang gauge station	Flow data: 1950–2014; sediment data: 1970–2016; water temperature data: 1962–2016
Hydro-environment data	4 hours water quality data with 9 indicators of 16 national surface water quality monitoring sections on the mainstream of the Yangtze River	Data from website of Ministry of Ecology and Environment, http://106.37.208.243:8068/GJZ/Business/Publish/Main.html (accessed on 1 July 2018). Among 16 sections, 14 sections in Chongqing (Zhutuo, Jiangjindaqiao, Fengshouba, Heshangshan, Cuntan, Qingxichang, Yangdu, Sujia, Wuling, Shaiwangba, Tian'ecun, Baidicheng, Peishi) and 2 sections (Huanglashi, Nanjingguan) in Hubei. 9 monitoring indicators are (1) water temperature, (2) pH, (3) dissolved oxygen, (4) conductivity, (5) turbidity, (6) permanganate index, (7) ammonia nitrogen, (8) total phosphorus, (9) total nitrogen
Hydro-biological data	Historical investigation data including fish, plankton, benthos, aquatic vascular plants and other aquatic organisms in 2015; considering that Chinese Sturgeon is the main flagship species existing in the Yangtze River, the scale and structure of Chinese Sturgeon were analyzed	Investigation by Changjiang Institute of fisheries, Chinese Academy of fishery Sciences
RS and GIS data	Land use data of China from Geographical Information Monitoring Cloud Platform (www.dsac.cn, accessed on 1 October 2012)	Time series: 1980, 1990, 1995, 2000, 2005, 2008, 2010, 2013, 2015, 2018, 2020; Resolution: 15 m, 30 m, 100 m, 250 m, 500 m, 1 km

3. Results and Discussion

We applied the modified DSP tools to cascade dam projects, representing three periods from new developed project, existing project, to cascade existing projects. Moreover, the results varied dramatically among predictive period and post period, and among individual project and cascade projects.

3.1. Impacts of Individual GZBP

The evidence of the EEM result and SBQ result associated with predictive GZBP showed major differences among different river function categories (Figure 3, details in Figures S1–S3). The EEM result displayed the impact ranges of possibility between 0.5 and 1, and the major impact of possibility was water quality, while the SBQ result displayed major impacts on biota and biodiversity. After post evaluation of GZBP using SBQ, the predictive SBQ for the new developed project was proven effective. The highest number of questions answered "yes" with evidence of affects by GZBP were 107 of 157 and 153 of 239 for predictive and post period, respectively.
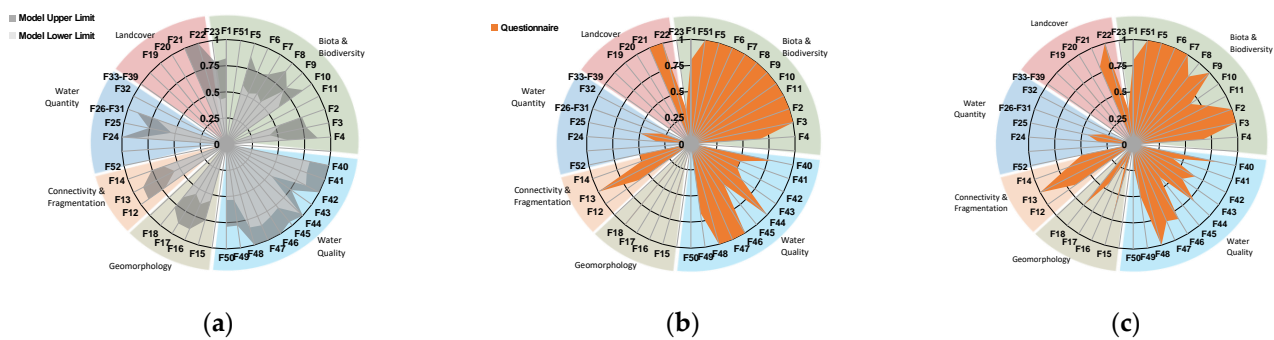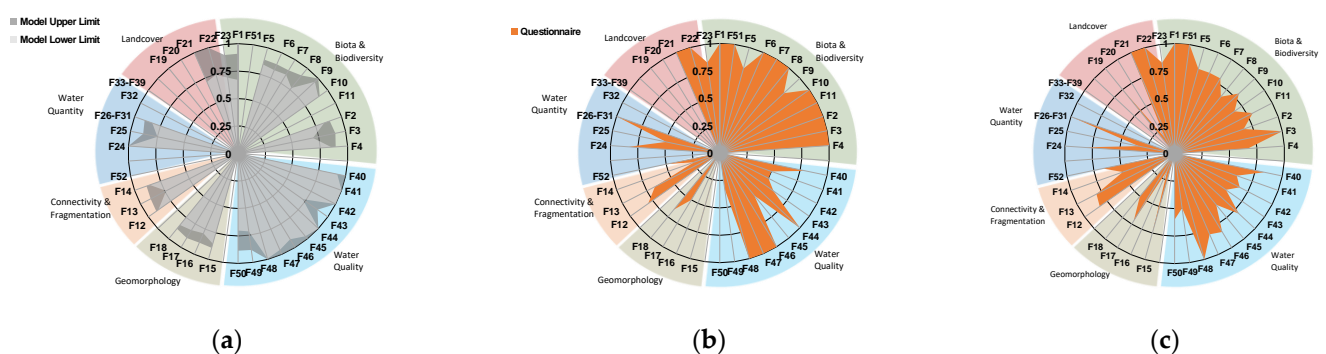
Figure 3. Spider diagram for GZBP (**a**) EEM result of new developed GZBP, (**b**) SBQ result of new developed GZBP, (**c**) and SBQ result of existing GZBP.

Because of the size of the project and extent of land assets, river functions with evidence of the impacts of construction and operations spanned multiple spatial scales and measures of terrestrial and aquatic taxonomic diversity (Figures S4–S7). In the predictive period, the basin scale functions were more estimated to be affected. However, project scale functions were more directly affected by construction or operations. The impacts on relevant specific taxonomic groups displayed obvious differences of water quality functions between predictive period and post period. Impacts on fish species were the main concern in post period.

3.2. Impacts of Cascade GZBP and TGP

The evidence of the EEM result and SBQ result associated with predictive cascade GZBP and TGP showed major differences among different river function categories (Table S3. Figure 4, details in Supplementary Figures S8–S10). The EEM result displayed the impact ranges of possibility between 0.7 and 1, and the major impacts of possibility was water quality, while the SBQ result displayed major impacts on biota and biodiversity and water quality. After post evaluation of cascade GZBP and TGP using SBQ, the predictive SBQ for new developed projects was proven effective. The highest number of questions answered "yes" with evidence of affects by cascade GZBP and TGP were 120 of 157 and 167 of 239 for predictive and post period, respectively.

Figure 4. Spider diagram for cascade GZBP and TGP, (**a**) EEM result of new developed cascade GZBP and TGP, (**b**) SBQ result of new developed cascade GZBP and TGP, (**c**) SBQ result of existing cascade GZBP and TGP.

Because of the size of the project and extent of land assets, river functions with evidence of the impacts of construction and operations spanned multiple spatial scales and measures of terrestrial and aquatic taxonomic diversity (Figures S11–S14). In the predictive period, the basin scale functions were more estimated to be affected. However, project scale functions were more directly affected by construction or operations. The impacts on relevant specific taxonomic groups displayed obvious differences of water quality functions

between the predictive period and post period. Impacts on fish species were the main concern in post period.

3.3. River Function Linkages

We applied the modified RFLAT tool on GZBP and cascade GZBP and TGP. Information explained by various graphical network sizes were used to determine the optimal sizes of networks (Figure 5). Higher network complexity is expected for cascade GZBP and TGP based on the size of that cascade projects and number of environmental concerns. This linkage provided a sub-selection of relationships to consider when evaluating the most important river function indicators, and their relationships with other components of the river ecosystem.

(**a**)   (**b**)
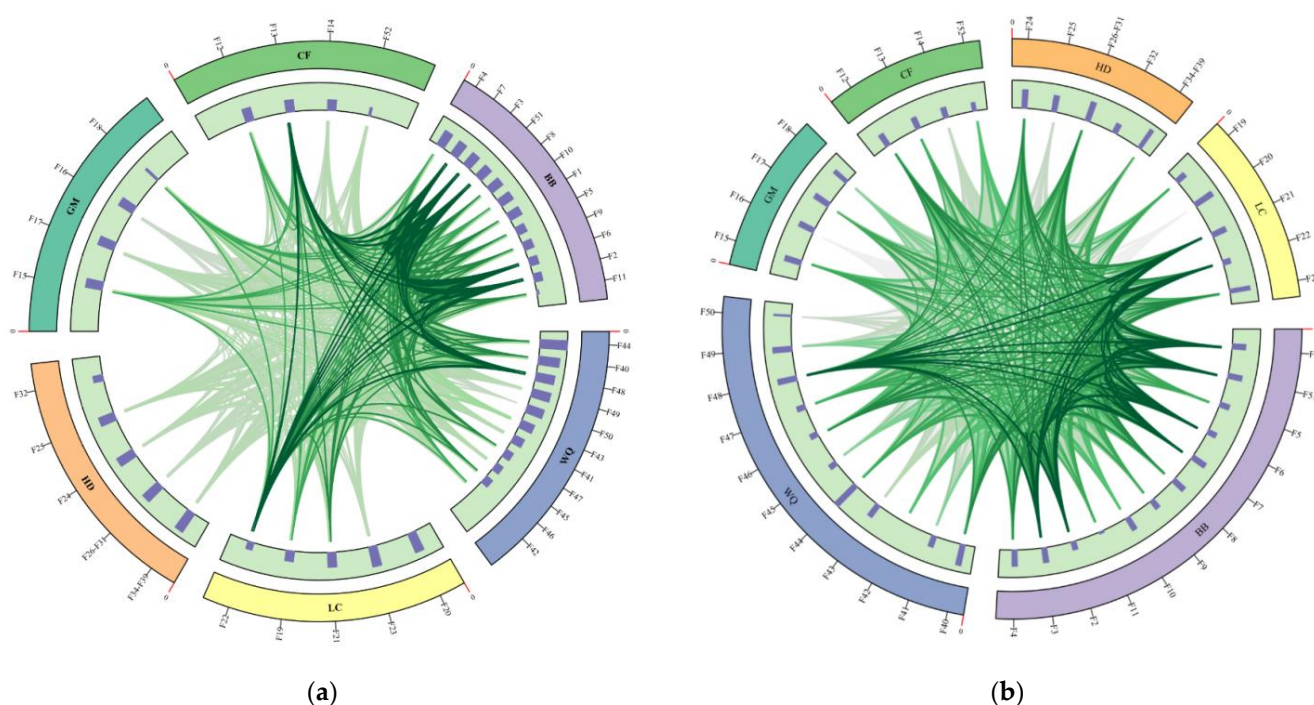
Figure 5. Application of the River Function Linkage Assessment Tool (RFLAT) (**a**) results of individual GZBP, (**b**) results of cascade GZBP and TGP.

The linkages of GZBP displayed that the impacted sequences of function categories were BB, WQ, CF, LC, HD, and GM, while the sequences of cascade GZBP and TGP were BB, HD, WQ, CF, LC, and GM. For individual GZBP, the relationships of BB, WQ, and LC function categories were obvious. For cascade GZBP and TGP, the relationships among BB, WQ, and CF, and among WQ, LC, and HD were obvious. To evaluate the impacts of cascade projects, there were some main function indicators to be concerned. In the biota and biodiversity category, we need to focus on F1, F51, F6, F7, F2, and F3. In the WQ category, we need to focus on F43, F 46, and F50. In the LC category, we need to focus on F20 and F21.

3.4. Optimization of Modified DSP Toolkit

The GZBP is located on the mainstream of the Yangtze River with multiple developments, while the TGP is 40 km on the upstream of GZBP. The GZBP construction was finished in 1988, thus the reservoir is relatively old. Moreover, the TGP construction and project acceptance was finished in 2020. Because of the long time span of the cascade projects, three periods were divided to separately evaluate the individual dam project and cascade dam projects. This is a new modification and innovation of the method that has not been proposed before. After this study, the modified DSP toolkit generally proved

useful for applying in the study area. However, the different tools of the toolkit need to be optimized if used in China and other regions outside the U.S., because of too few parameter data in the current database. Moreover, if the toolkit is being used for cascade dam projects instead of an individual dam project, the higher complexity of cascade dam projects should be taken into consideration.

3.4.1. SBQ

SBQ provides a new way for stakeholders to make a decision through science-based questions. This method simplified the professional knowledge bases of stakeholders and bridged the gap between different aspects. From this study, we modified some questions to make it adapt to China's reality. From the comparison of a new developed project and existing project, we found the similarity of predictive SBQ results and post SBQ results for both individual dam and cascade dams. However, because there were less questions for new developed dams, the proportion of "yes" for new developed dams might be larger than existing dams. We considered introducing a factor to balance the proportion evaluation result in a future study. Moreover, the cascade projects displayed a high number of river functions with evidence of effects. Setting a question to comprehensively describe the cascade dam projects was very difficult. The interaction between cascade dams was very complex, the current four spatial scales of questions need to be reconsidered especially for project scale and reservoir scale.

3.4.2. EEM

Parameters for generating EEM were mainly data from dams in the U.S., and it was not applicable for Chinese dams. There were 283 global dams' data in the EEM, and 121 U.S. dams' data, while only 5 Chinese dams' data were in the EEM. According to China's new investigation result of national dams and reservoirs, there were nearly 100,000 dams and reservoirs in 2021. The parameters of China's dams need to be extended to provide a new envelop curve for determination. Moreover, a larger problem is that many parameters of dams were missing such as 153 blank (null) dam height data out of 283 and 89 blank (null) mean annual flow data out of 283. Though it is hard work, more participation and contribution of dams' data and preliminary evaluation are in need (e.g., GRanD database).

3.4.3. RFLAT

This study provided a sub-category relationship of river functions to consider the river function linkages of under-evaluated dams and under-evaluated cascade dams. The methodology of RFLAT was not modified in this study, except the display form of the relationship. In the new "Circos" display graph instead of network type graph, the contributions of the function impacted by other functions were more clearly and easily identified.

4. Conclusions

Because of the size of the cascade projects and extent of land assets, river functions with evidence of the impacts of operations spanned multiple temporal and spatial scales. The majority of impacts were associated with the construction and operation of the original facility. The cascade GZBP and TGP are the most downstream dams on the mainstream of the Yangtze River. Moreover, the projects have no facilities located in close proximity up- or downstream. It is uncertain whether there is a free-flowing river habitat in the upstream or downstream of the project or between developments within the project. In the upstream basin, there are intense human activities that can influence hydrology and operations at the facility. Therefore, it is difficult to develop causal relationships between stress and ecosystem responses, which requires understanding interconnections among ecosystem components for the cascade projects. We introduced and modified the DSP to be used to isolate the most important hierarchical relationships among river function indicators, and to identify impacts of cascade projects in multiple periods. Moreover, the results varied dramatically among predictive period and post period, and among individual project

and cascade projects. Though the modified DSP cannot replace large-scale assessments for dam projects, it can assist the EIA and PEIA process by identifying the most relevant environmental concerns and knowledge gaps at early stages of negotiation, so that more attention can be focused on subsequent studies and evaluative processes. When we applied the toolkit, some new limitations were found in the three tools:

(1) In SBQ, because there were less questions for new developed dams, the proportion of "yes" for new developed dams might be larger than existing dams. We suggest introducing a factor to balance the proportion evaluation result in future study. Moreover, the cascade projects displayed a high number of river functions with evidence of effects. How to set the question to comprehensively described the cascade dam projects was very difficult. The interaction between cascade dams was very complex, the current four spatial scales of questions need to be reconsidered especially for project scale and reservoir scale;

(2) In EEM, parameters for generating EEM were mainly data from dams in the U.S., and were not applicable for dams in other areas. Moreover, a larger problem is many parameters of dams were missing. We suggest more participation and contribution of dams' data such as GRanD database;

(3) In RFLAT, the new "Circos" display graph instead of network type graph was clearer and easier for users to identify the main functions being impacted.

5. Ethical Statement

The authors declare that:

(1) They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper;

(2) This paper has not been published in whole or in part elsewhere;

(3) This paper is not currently being considered for publication in another journal;

(4) All authors have been personally and actively involved in substantive work leading to the manuscript, and will hold themselves jointly and individually responsible for its content.

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