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Geomorphometric Assessment of the Impacts of Dam Construction on River Disconnectivity and Flow Regulation in the Yangtze Basin

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Abstract: Rivers are under increasing pressure from anthropogenic impacts with incremental dam construction, experiencing global and regional alteration due to river disconnectivity, flow regulation, and sediment reduction. Assessing the cumulative impacts of dams on river disconnectivity in large river basins can help us better understand how humans disintegrate river systems and change the natural flow regimes. Using the Yangtze basin as the study area, this study employed three modified metrics (river connectivity index, RCI; basin disconnectivity index, BDI; and the degree of regulation for each river section, DOR) to evaluate the cumulative impacts on river disconnectivity over the past 50 years. The results indicated that the Yangtze had experienced strong alterations, despite varying degrees and spatial patterns. Among the major tributaries, the greatest impact (lowest RCI value) happened in the Wu tributary basin due to the construction of cascade dams on the main stem of the tributary, while the lowest impact (highest RCI value) happened in the Fu tributary basin, which still has no dams on its main stem. Collectively, rivers in the upper Yangtze reaches experienced more serious disturbances than their counterparts in the middle and lower reaches. The BDI results displayed that a substantial part of the Yangtze River, especially the Wu, Min, Jialing, and Yuan tributaries, only maintain connectivity among one to three representative river systems. No part of the Yangtze connects all the 12 representative river systems. This study also revealed that small dams can also exert significant impacts in flow regulation on regional river systems through their sheer number and density. The study results can help promote more environmentally sustainable river management policies in the Yangtze basin.

Keywords: geomorphometric assessment; river disconnectivity; Yangtze River; hydropower dams; river regulation; anthropogenic impacts

1. Introduction

Rapid population growth and economic development are tightly coupled with a surge in demand energy and water resources. For example, world electricity production increased by 72% between 1993 and 2010 [1]. At present, there are approximately 50,000 large dams worldwide used for power generation, water supply, etc. [2]. Dam construction represents one of the most significant anthropogenic features on Earth [3]. It has exerted various influences on land–ocean processes, thereby triggering various adverse, often unwanted consequences both globally and regionally, including impacts on sediment retention and downstream sediment starvation [4,5], flow regulation [6], river disconnectivity [7], biodiversity loss [8], coastal erosion, and shoreline retreat [9].

China's Yangtze River basin (Figure 1), as a prominent case of the challenging balance between economic benefits and side effects related to hydropower development and dam construction, has experienced incremental pressure from greater hydropower production and other water-related developments, such as large-scale irrigation. In recent years, the main stem of the Yangtze and its major tributaries are being dammed at a dazzling pace. At present, there are approximately 43,600 reservoirs of different sizes in the Yangtze basin with a total storage capacity of approximately 290 km^3, among which 1358 reservoirs are large- and medium-sized, with a storage capacity greater than 1 x 10^8 and 1 x 10^7 m^3, respectively [10] (Figure 2). Due to reservoir construction, the Yangtze has been strongly altered, impeding not only the movement of river flows but also the delivery of sediments and other nutrients downstream. For example, after the construction of the Three Gorges Dam (TGD), the riparian ecosystem has also been significantly disrupted [11]: The latest survey shows that the population of finless porpoises in the Yangtze River basin has declined to approximately 1000, making them even rarer than giant pandas in the wild [12]. Furthermore, critical concerns about the issues caused by dam development in the Yangtze basin have been addressed in the international conservation community. The World Wide Fund for Nature (WWF) and the Chinese government have implemented more than one hundred conservation projects which focus on species, forest, freshwater, capacity building, policy advocacy as well as environmental education in the Yangtze River basin [12]. In this context, new assessments should be executed to optimize the management, configuration and operation of hydropower plants.

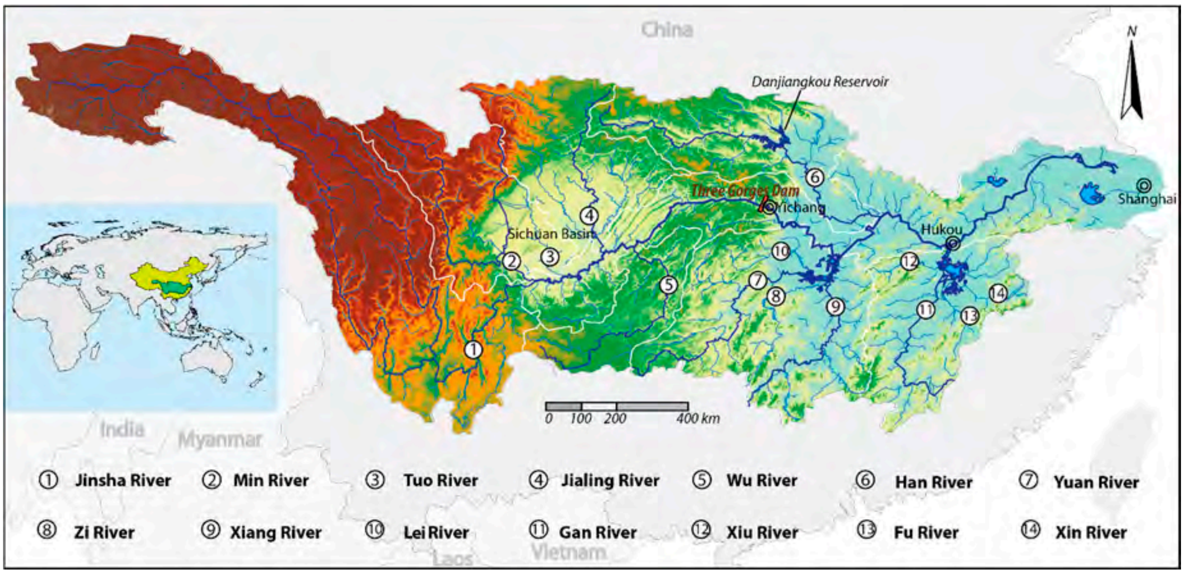

Figure 1. The geographical setting of the Yangtze River and its 14 major tributaries.

Investigations of the impacts on river disconnectivity have been done by various researchers in the Yangtze basin. For example, Fu et al. [13] as well as Park et al. [14] have studied the impacts of dams using data on migratory species based on observational movement studies, although such reliable observations are often unavailable for large rivers. Sindorf et al. [15] used an approach that used river ecosystems as an alternative to compensate for the lack of actual observations. The representative river ecosystems, as coarse-filter targets, can be obtained through river-system classification based on basin characteristics such as climate (e.g., precipitation, temperature), topography (e.g., slope, relief), and geology (e.g., karst geology). The classification results can then serve as a proxy for representative river systems or ecosystems [15]. The connection between river-system classes can be used as a proxy for the real sediment or nutrient exchanges via river network. Researchers also proposed various indices to measure such impacts at a global or regional scale. In summary, current studies [16,17] about river connectivity in the Yangtze basin focus on the middle and lower reaches (or the Yangtze River floodplain), especially the connectivity between Yangtze and the Dongting and Poyang lakes. Although the influence by dams has also been investigated [14,18–20], only several dams on the main stem (e.g., the TGD and Gezhouba Dam) were studied, the impacts by the vast majority of the dams in the Yangtze basin remain unknown.

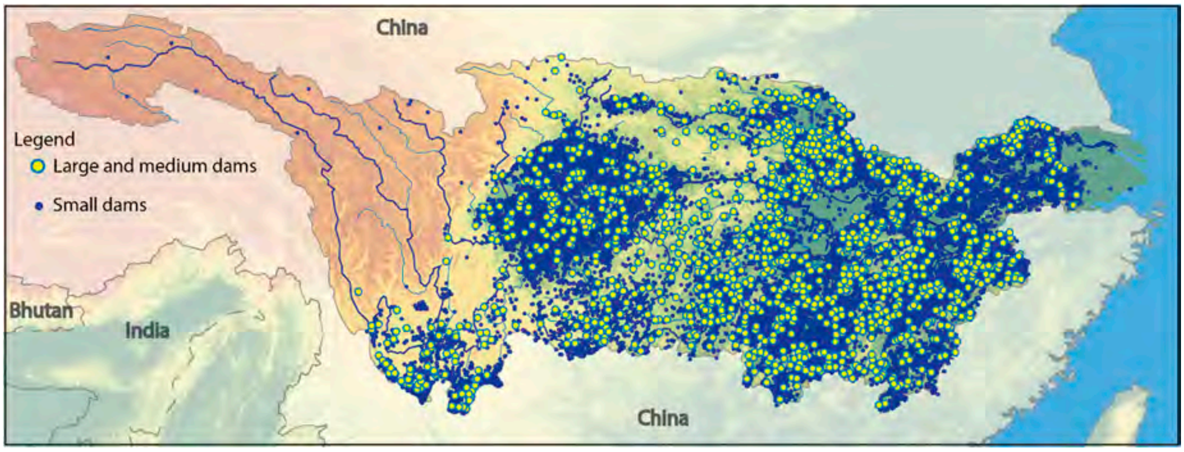

Figure 2. Spatial distribution of the 43,600 dams in the Yangtze River basin.

In addition, few geomorphometric assessments have been conducted to measure the impacts of dams on river disconnectivity from the perspective of geomorphometry and fluvial geomorphology. In fact, the changes in fluvial geomorphology, especially the variations in sediment load and flow discharge, are the first victims of the adverse impacts caused by dam construction because one of the major consequences of dam construction is spatial sediment disconnectivity [21]. In terms of the huge number of dams in the Yangtze basin, the impacts of dams on spatial sediment disconnectivity could be quite remarkable. The geographical characterization of the new disconnectivity configurations in the Yangtze basin will enable the prediction of the significance of a given tributary or river section as sediment source, as well as it delineates sediment routing paths. Thus, the evaluation of the impacts of dams on river disconnectivity from the perspective of geomorphometry and fluvial geomorphology, especially the consideration of sediment load change, is particularly important for river sustainability and water resources management in the Yangtze basin. Although, the concept of river disconnectivity in ecological function has been well fostered [22,23] and many indices, for example, the dendritic connectivity index [24], river ecosystem fragmentation index [15], moving-average spatial covariance model [25,26], habitat connectivity index [27], index of longitudinal riverine connectivity [28], patch-based spatial graph [29], and river connectivity index [30], have been presented to depict and measure the impacts, few studies have evaluated the impact of dams on river disconnectivity in terms of the variations in sediment load and flow discharge. In addition, river geomorphologic characteristics (e.g., river size and stream length) were not considered yet during the assessments, even though the roles for the rivers with different sizes are definitely different. For example, a large tributary can provide more diverse geomorphological and ecological functions than a small creek.

Despite the fact that most studies did not explicitly integrate sediment load change into the models for river disconnectivity assessments, numerous studies have demonstrated the relevance between the changes in sediment load and the degree of river disconnectivity through fluvially geomorphological field observations. Wang et al. [31] reviewed the relationship between sediment load change and river disconnectivity with examples from the major rivers in East and Southeast Asia. Additionally, the study by Jansson et al. [32] and Hancock [33] are very relevant to be mentioned as both confirmed the role of sediments in the maintenance of ecosystems and the contribution to keep river connectivity. Using remote sensing imagery, Vanacker et al. [34] also used sediment load as an indicator to depict the human-induced change in river disconnectivity. The computation of sediment-load-based indices with integrated GIS (geographic information system) analysis and imagery interpretation was also employed by researchers [35,36], but applications at large scale are still uncommon at present.

Besides, numerous small dams constructed in the Yangtze basin also intercept natural flows, which was initially delivered downstream where it is again available for river systems, but the magnitude of environmental changes to water resources resulting from more than 42,000 small dams are still not well evaluated. Although they tend to avoid the more obvious environmental and social disruption of large projects, their cumulative impacts on the Yangtze River are still unknown to the public. Unfortunately, few comprehensive studies in the Yangtze River basin have investigated the cumulative impacts of small dams. as information on small dams is extremely limited in China, where baseline environmental data, small-dam spatial information, and environmental assessments are less commonly available [37]. Gleick [38] suggested that many environmental impacts of small dams are comparable to or even worse than conventional large dams when measured on a unit-energy basis. Anderson et al. [39] also emphasized that one of the primary causes of change in river systems is flow reduction after the construction of small dams. However, few comprehensive analyses of this assumption have been done in the Yangtze basin. Hence, investigating the cumulative impact of flow reduction after the construction of small dams is also an applicable measure to examine the impacts led by small dams in the Yangtze basin.

The academic community has advocated for the protection of the Yangtze River for decades. As both the policies for the river development and the target to protect the integrity of the Yangtze River are put into practice at large scales, a sustainable river development framework is required for the Yangtze River basin in which the risks of dam development can be assessed and the impacted regions can be identified. Additionally, using this knowledge, it is possible to quantify the potential impacts of incremental dam development on the Yangtze River at the basin or sub-basin level in terms of environmental intactness. The knowledge will also make it easier to develop the Yangtze River basin with a relatively lower environmental footprint. Based on the above discussion, this study, using the Yangtze River case study, tried to (a) set up a basic framework for assessing the impacts of large dams on river disconnectivity based on changes in sediment load and water discharge, which can be considered as an initial attempt to investigate what can be done with simple and applicable river disconnectivity analyses; (b) develop a new model to quantify the cumulative impacts of small dams on water regulation in the Yangtze River basin; and (c) investigate the current condition of the Yangtze River and provide an important reference for policymakers for future dam development in the Yangtze River basin.

2. Materials and Data Processing

Data used in this study included dam information of 43,600 dams (Figure 2) obtained by Yang and Lu [10]; digital elevation model (DEM) data, which was used to derive river network, reservoir catchments, and catchment properties (e.g., mean slope, mean elevation); hydrological data providing water discharge and sediment load for each tributary; and land-cover thematic maps for river system classification and visualization.

The dataset of 1358 large- and medium-sized dams and approximately 42,000 small dams was obtained using remote sensing techniques. The study [10] initially delineated reservoirs by analyzing 94 cloud-free Landsat images using a supervised classification method by a support vector machine (SVM) classifier. After classification, water bodies were co-registered, correlated, and then were converted to polygons stored in a geodatabase. Small polygons with an area lower than 0.0036 km^2 were removed. Thus, a further study based on this dataset could yield relatively conservative assessments of the impacts of small dams. Based on the overlap between polygons and flow accumulation data derived from DEM, the outlet for each reservoir could be identified, which could be used as the dam location for the corresponding reservoir. The corresponding storage capacity for each dam was also estimated by on the method proposed by previous studies [10,40]. The dataset is the best available dataset that provides basic spatial information about dams in the Yangtze River basin. It; thus, enabled the assessment of the cumulative impacts of dams, as described later. Except for surface area and estimated storage capacity, other information (e.g., construction time) for 1358 large- and medium-sized dams was also collected from various sources (e.g., government reports and the Internet) but only the information that appeared in multiple sources was used in order to guarantee data quality.

The DEM data were obtained from the Consortium for Spatial Information of the Consultative Group on International Agricultural Research (http://srtm.csi.cgiar.org/). Through the C-Band synthetic aperture radars imagery of the Shuttle Radar Topographic Mission (SRTM), the DEM images are available between 60 degrees north and 56 degrees south latitudes. The SRTM satellite circled the Earth over a wide swath producing radar images that allowed for the reformation of the surface relief, generating the SRTM data. The global DEM product, with a horizontal resolution of 3 arc-second (90 m) and a vertical resolution of 5–9 m, which means that the resolution and the accuracy are good enough for studies in a large area. Based on the data, the river network and catchment properties were derived using ArcGIS with integrated ArcHydro tools. The threshold for river network extraction based on the flow accumulation grid is 500 pixels (~ 4.05 km^2); the catchments for almost all the small dams could; thus, be delineated.

The hydrological data were provided by an extensive hydrological monitoring program across the entire Yangtze River basin, which was established in the 1950s by the Changjiang (Yangtze) Water Resources Commission (CWRC) in accordance with national data standards. A detailed description of the methods for the measurements of river flow and sediment load can be found from the national standards [41,42]. The original records for each station provide information on station coordinates, catchment area, mean monthly and annual water discharge as well as sediment load, and the magnitude and date of occurrence of the maximum and minimum daily water discharge and sediment load. Annual precipitation data from 220 meteorological stations (163 stations located in the Yangtze River basin, 57 stations located outside the basin but in the vicinity of the basin) were extracted from a 728-station precipitation dataset released by the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/). Since these stations are not evenly distributed in space, basin-wide and sub-basin annual average precipitation was interpolated using Kriging Interpolation Tool within ArcGIS Desktop. A regression method was then used to predict river runoff for each ungauged river section. Previous studies [43,44] have reported the results obtained from regression methods are good enough for large-scale hydrological assessments. River runoff data from 223 gauging stations obtained primarily from the CWRC were collected to simulate runoff variations and establish the regression model across the Yangtze River basin.

3. Geomorphometric Assessment Methods

3.1. River Connectivity Index (RCI)

Depending on the probability that sediments can be delivered from an upstream point to a downstream point in a river network, we defined the river connectivity index (RCI) to assess river disconnectivity:

$$RCI = \frac{\sum_{i=1}^{n} w_i \times c_i \times s_i}{\sum_{i=1}^{n} w_i \times s_i} \times 100\% \quad (1)$$

where s_i is the length of section i; w_i is the weight or Strahler number of section i; c_i is the simulated cumulative mathematical passability depending on the number and passability (p) of dams in section i; assuming the passability of multiple dams is independent, if there are M dams on a river, then c_i is defined as:

$$c_i = \prod_{m=1}^{M} p_m \quad (2)$$

where p_m is the upstream passability for the m_{th} dam. Hence, RCI depends on how many dams are built between the two points, and the passability for each dam. Here, passability refers to the mathematical probability of sediments being able to cross a dam in the downstream direction, which is the difference between 1 and dam-associated reservoir's trap efficiency (TE) ($p = 1 - TE$). In this study we used the following equation from Brown [45] to calculate TE as only reservoir storage capacity (C in m^3) and drainage area (A in km^2) are known:

$$TE = 100 \times (1 - \frac{1}{1 + D \times (\frac{C}{A})}) \tag{3}$$

where D is a coefficient with values ranging from 0.046 to 1.0 [45] and a mean value of 0.1 was used in this study.

The RCI was inspired by Cote's graph-theoretic dendritic connectivity index (DCI) [24], but it is more applicable as it employed TE to define the passability p for each dam, which can be easily obtained based on reservoir storage capacity (C) and drainage area (A). The RCI can be calculated for any size of stream network, or portion of a stream network. This model also considers different river sizes in different sections. For example, the main stem section can usually sustain larger river ecosystems than its tributaries, even though they may have similar channel lengths. Thus, before calculating RCI values, each stream section was assigned a weight to indicate the relative stream size. Stream order [46], as a well-accepted way to define the size of a stream, was used as the weight of the stream (Figure 3).

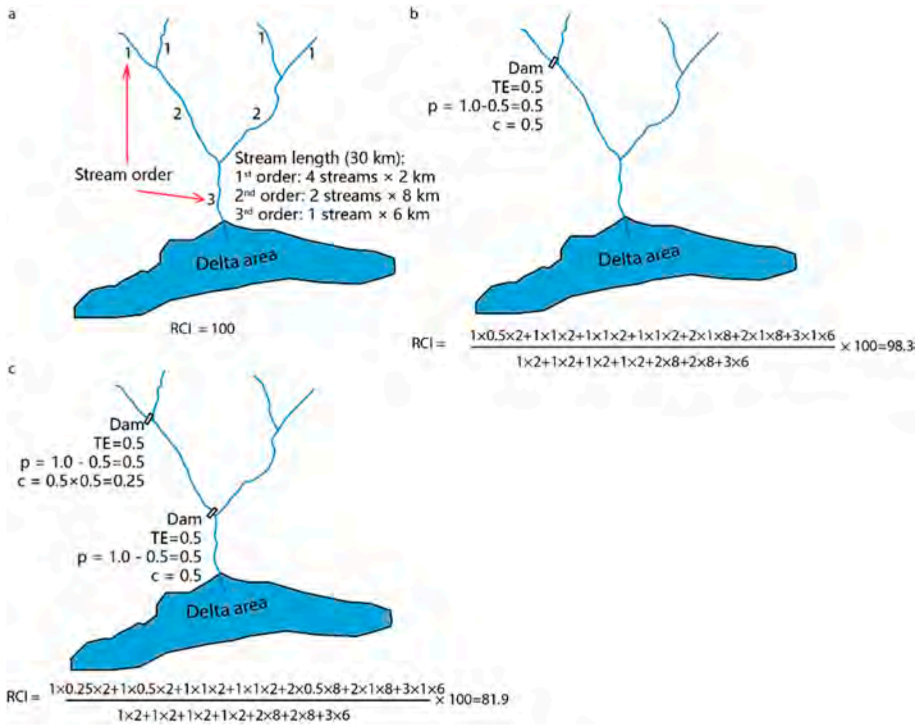

Figure 3. Illustration of the river connectivity index (RCI) model based on river length, river size (indicated by stream order), and passability for each dam in the downstream direction. (**a**). RCI calculation with no dam on the streams. (**b**). RCI calculation with only one dam on the streams. (**c**). RCI calculation with multiple dams on the streams.

3.2. Basin Disconnectivity Index (BDI)

Unlike the RCI measuring how the river is disconnected by dams, the BDI measures how the entire river basin has been disconnected by dams based on a river system classification map. The classification map, as coarse-filter targets, classifies different river sections and the corresponding catchments into different representative river systems based on basin characteristics. There is an agreement that protecting common communities should conserve representative river ecosystems, the ecological and hydrological processes that support them, and the river systems in which they are evolved. Thus, this study used river-system classification as a key input for BDI to evaluate river basin disconnectivity. The classification framework, proposed by Snelder et al. [47], using climate, topography, geology, and network structure as classification variables, was used here. The premise of this approach is that, by conserving representative river systems and the corresponding hydrological processes that maintain the environments, river systems' integrity are conserved. This study defined the river basin disconnectivity index (BDI) based on previous work [15] to measure how disconnected the Yangtze River has become under dam development (Figure 4):

$$BDI = \frac{\sum_{i=1}^{n}\left(ns_i^2 - ns_i\right) \times wp_i}{NS^2 - NS} \times 100\% \tag{4}$$

where ns_i is a total number of distinct river systems related to network section i; NS is total number of river systems found in the Yangtze basin; wp_i is the weighted percentage of river length in section i relative to the total river network length, which is defined as:

$$wp_i = \frac{\sum_{j=1}^{J}\left(w_j \times l_j\right)}{\sum_{k=1}^{K}\left(w_k \times l_k\right)} \tag{5}$$

where w_i and l_i are the stream order and stream length for each stream in section i; J is the number of streams in section i; K is the total number of streams in the entire river basin.

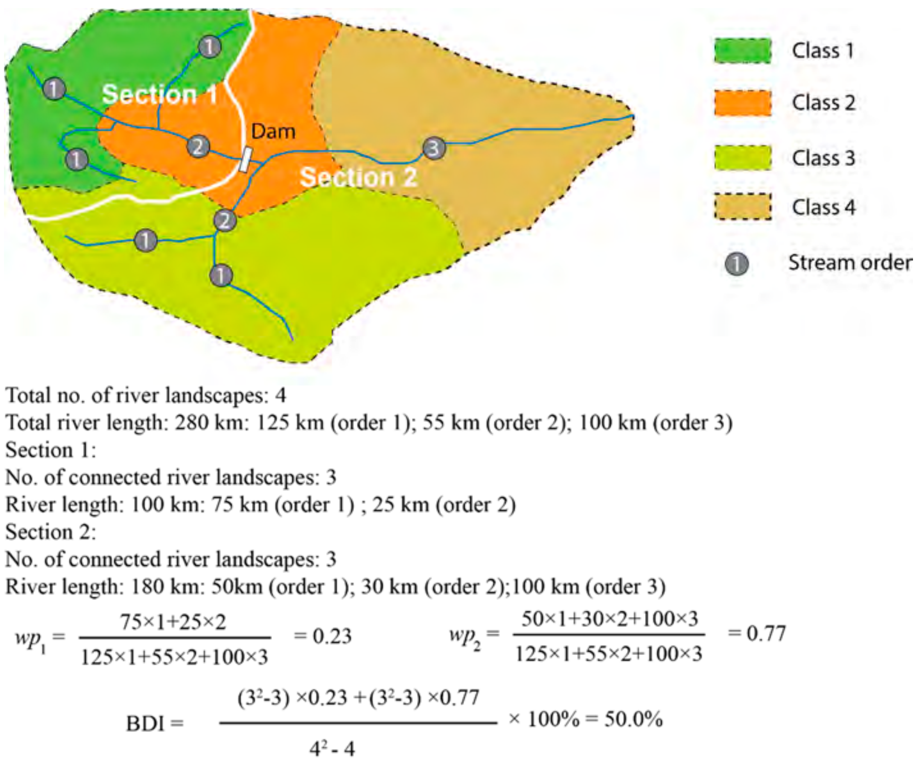

Figure 4. Illustration of the basin disconnectivity index (BDI) model based on channel length and river-system classification map.

The index is defined as a function of the number of distinct river systems that remain connected upstream or downstream of a dam combined with the length of river network upstream or downstream of a dam. The assumption that every representative river system provides equal functional connectivity to any of the remaining river systems allows us to lump those parts of the Yangtze's river network that offer connectivity by the number of river systems, and attribute this by weighted network length. The functional connectivity of a river system can; therefore, be quantified by summing the total number of connected river systems upstream of each dam and incorporating the total weighted length of the river network upstream of each dam, relative to the total number of river systems and total weighted network length.

3.3. The Degree of Regulation for Each River Section (DOR)

Generally, the impact of small dams on flow regulation can only be fully evaluated if the operation schemes of the associated reservoirs are obtained; yet they are seldom available at large scales. To quantify the impact on the regulation of downstream flows, this study defined the degree of regulation for each river section (DOR) as:

$$DOR = \frac{\sum_{i=1}^{n} C_i}{Q} \times 100\% \tag{6}$$

where C_i is the reservoir storage capacity in m^3, n is the number of upstream reservoirs, Q is the river section's annual runoff in m^3. The DOR model was first used by Dynesius and Nilsson [48] as well as the follower Nilsson et al. [7] to measure the magnitude of flow regulation. We here modified the model so that it can assess multiple river sections/streams, A high DOR denotes a higher volume of water that can be impounded during a given year and released at later times (Figure 5).

River section	River runoff ($10^4 m^3$)	Upstream dams	Total regulated volume ($10^4 m^3$)	DOR
1	10	1	5	50.0%
2	15	2	12	80.0%
3	10	--	0	0.0%
4	10	--	0	0.0%
5	15	3	10	66.7%
6	45	1, 2	17	37.8%
7	45	--	0	0.0%
8	150	1, 2	17	11.3%
9	190	1, 2, 3	27	14.2%

Figure 5. Simplified river network to demonstrate computation of the degree of regulation (DOR) for each river section.

4. Results

4.1. Preliminary Comparative Assessments

Some basic metrics, such as the ratio of reservoir capacity to basin area and the ratio of reservoir capacity to river runoff, can serve as a first-level approximation of the potential impact on a river system. For example, the ratio of reservoir storage capacity to basin area is a gross measurement of the magnitude of potential change in river flows and the consequent water flow disruption caused by dam construction [49,50]. Regions with high capacity-to-area ratio show a great potential change in river flow. At the tributary-basin scale, the highest ratio of 718,800 m^3 km^{-2} occurs in the Xiu tributary basin. This tributary basin may have experienced the greatest river regulation. The comparison of the amount of reservoir capacity to the mean annual runoff also revealed similar results. In terms of individual sub-basins in the upper Yangtze reaches, the ratio of capacity to runoff ranged from 0.08 year in the Jinsha tributary-basin to 0.49 year in the Tuo tributary-basin (Table 1). The opposite extremes are the Xiu, Han, and Fu tributaries. In these tributary basins, the constructed reservoirs store 106%, 90%, and 90% of their corresponding annual runoffs, indicating that these tributary basins are likely to experience the greatest flow alternation as the impoundment of river channels regulates discharge downstream, potentially affecting flooding patterns, flow regimes, and sediment delivery [51,52]. It is likely that with the increase in the average time that water is retained in reservoirs (increase in the capacity-runoff ratio), the impacts will become more evident. For example, an average ratio of 1.06 years indicates the reservoirs in the Xiu tributary have a large capacity to absorb flows and thus the downstream channel would experience a diminished flow regime; conversely, an average ratio of 0.08 year indicates that the reservoirs in the Jinsha tributary would have little impact on the flow regime downstream of the reservoirs. Evidence of this idea has been reported in the Yangtze River basin by many researchers [53].

Table 1. Tributaries, their general characteristics, reservoir capacity data, and information on capacity: area and runoff ratios.

	Sub-basin	**Drainage Area (10^4 km^2)**	**Runoff (km^3 yr^{-1})**	**Reservoir Capacity (km^3)**	**Capacity: Area (10^3 m^3 km^{-2})**	**Capacity: Runoff Ratio (yr)**
Upper reach	Jinsha River	47	135.1	11.3	24.0	0.08
	Min River	13	87.5	3.9	30.0	0.04
	Tuo River	3	14.9	7.3	243.3	0.49
	Jialing River	15	72.7	17.1	114.0	0.24
	Wu River	9	42.9	11.6	128.9	0.27
Middle reach	Han River	15	55.3	49.8	332.0	0.90
	Dongting Lake Region					
	Lei River	2.7	13.1	3.7	137.0	0.28
	Yuan River	9.4	64.3	15.5	164.9	0.24
	Zi River	3	21.7	5.9	196.7	0.27
	Xiang River	9.8	72.2	17.4	177.6	0.24
	Poyang Lake Region					
	Xiu River	1.6	10.8	11.5	718.8	1.06
	Gan River	7.4	68.7	18.5	250.0	0.27
	Fu River	1.5	14.7	4.3	286.7	0.29
	Xin River	1.6	17.8	2.8	175.0	0.16

4.2. Quantifying the Cumulative Impact of Dams on River Disconnectivity

This study initially calculated the cumulative impact of 1358 large- and medium-sized dams on river disconnectivity in the Yangtze River basin (Table 2). The results illustrated the importance of considering river connectivity, expressed by the location of dams in relation to other already existing dams. The RCI value for the whole Yangtze River has decreased from 100 to 43.97, indicating the Yangtze River has experienced strong alterations in river connectivity over the past decades, placing the basin among other heavily dammed rivers in the world.

Table 2. Summary of model parameterization and RCI values for each tributary.

	Tributary	Stream Length (km)	No. of Nodes	No. of Dams	RCI
Upper reach	Jinsha River	51,453	5613	82	42.60
	Min River	15,225	1661	23	22.83
	Tuo River	3769	361	30	12.37
	Jialing River	20,550	1851	91	15.83
	Wu River	10,140	1089	71	11.66
Middle reach	Han River	21,212	1948	189	34.80
			Dongting Lake Region		
	Yuan River	11,567	1062	110	17.55
	Li River	3255	279	36	65.33
	Zi River	3555	359	44	33.66
	Xiang River	11,418	1137	134	49.57
			Poyang Lake Region		
	Gan River	8685	861	99	50.99
	Xiu River	1835	178	15	54.10
	Fu River	1892	199	21	86.55
	Xin River	2007	188	34	59.90
Total	Overall Yangtze	211,527	21,530	1358	43.97

As anticipated, a single dam near the mouth of a tributary basin is sufficient for the reduction in river connectivity [27], but the impact to river connectivity varies greatly with location due to differences in basin topology and the locations of dams. For example, the lowest RCI happened in the Wu tributary basin, which is mainly attributable to ten large cascade dams constructed on its main stem (Figure 6). Conversely, the Fu tributary, with the highest value of RCI, still has no dam on its main stem. Collectively, rivers in the middle Yangtze reaches obtained relatively higher RCI than their counterparts in the upper reaches. Indeed, the ecosystem of the upper branches of the Yangtze has been severely impacted. It should also be highlighted that the rivers with low RCI values are all the rivers with rich water power resources: The Min, Jinsha, Tuo, Wu tributaries and the mainstem of the upper Yangtze reach and the Yuan and Zi tributaries in the middle reach. The rivers, such as the Fu and Xin tributaries, with low hydropower resources have narrowly escaped disconnectivity.

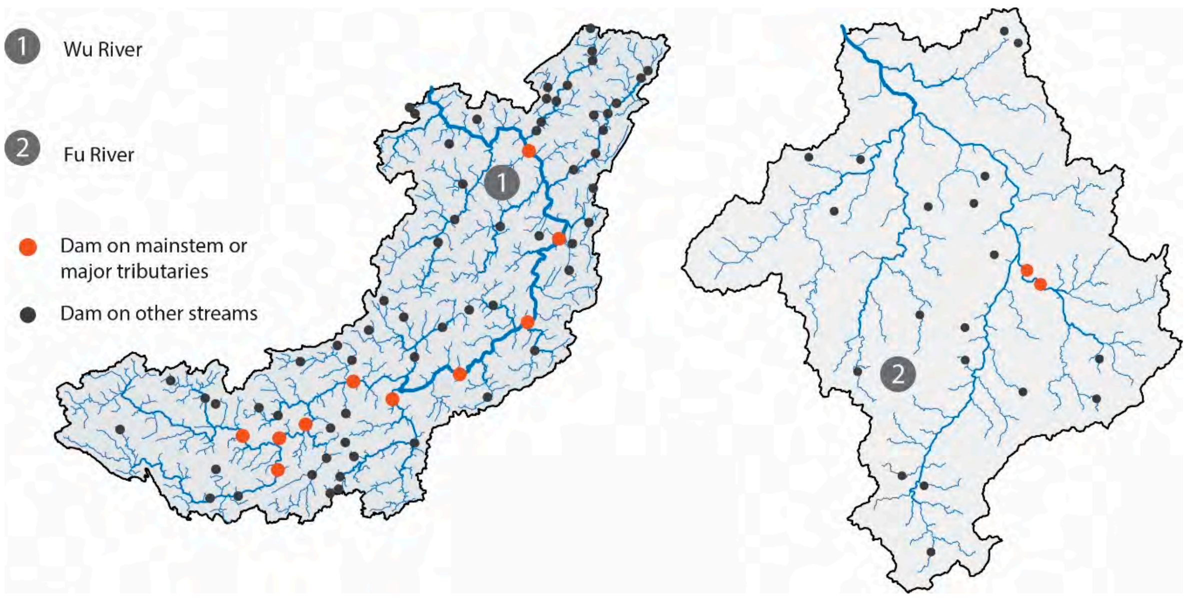

Figure 6. A comparison between the Wu tributary with RCI value of 11.66 and the Fu tributary with RCI value of 86.55: Ten large dams are constructed on the Wu tributary and its major tributaries, while only two dams are constructed on the major tributary of the Fu tributary.

These results show that the site of a dam determines its relative impact on river disconnectivity. The RCI can demonstrate the magnitude of the cumulative impacts on river connectivity. As evidenced in the tributaries of the Yangtze River, dams located at the headwaters or small streams can minimize loss of river connectivity (e.g., Fu and Lei tributaries), while dams placed at the main stem or major tributaries can lead to a noticeable impact on river disconnectivity.

4.3. Quantifying the Impact on River Basin Disconnectivity Using BDI

With careful consideration of the river basin characteristics, this study identified 12 distinct river systems (Figure 7a) based on the classification framework proposed by Snelder et al. [47]. Using the classification map, the Yangtze River with 12 distinct river systems, and with full intactness, would capture 100% connectivity. Nevertheless, the result in Figure 7b shows that the Yangtze River already shows a high degree of river basin disconnectivity. In the upper Yangtze reach, with seven distinct river systems being locked behind the mega TGD, only six river systems remain connected in the main stem area. This demonstrates the TGD's harmful effect on river disconnectivity. What is even worse, a substantial part of tributary basins, especially the Jinsha, Wu, Min, Jialing, and the Yuan tributaries only maintain connectivity among one to three distinct river systems. The result shows that connectivity between different river systems in the middle and lower basin is the highest because of no dams constructed on the main stem. Even so, only a small portion of the Yangtze river system still maintains connectivity between seven out of twelve river systems.

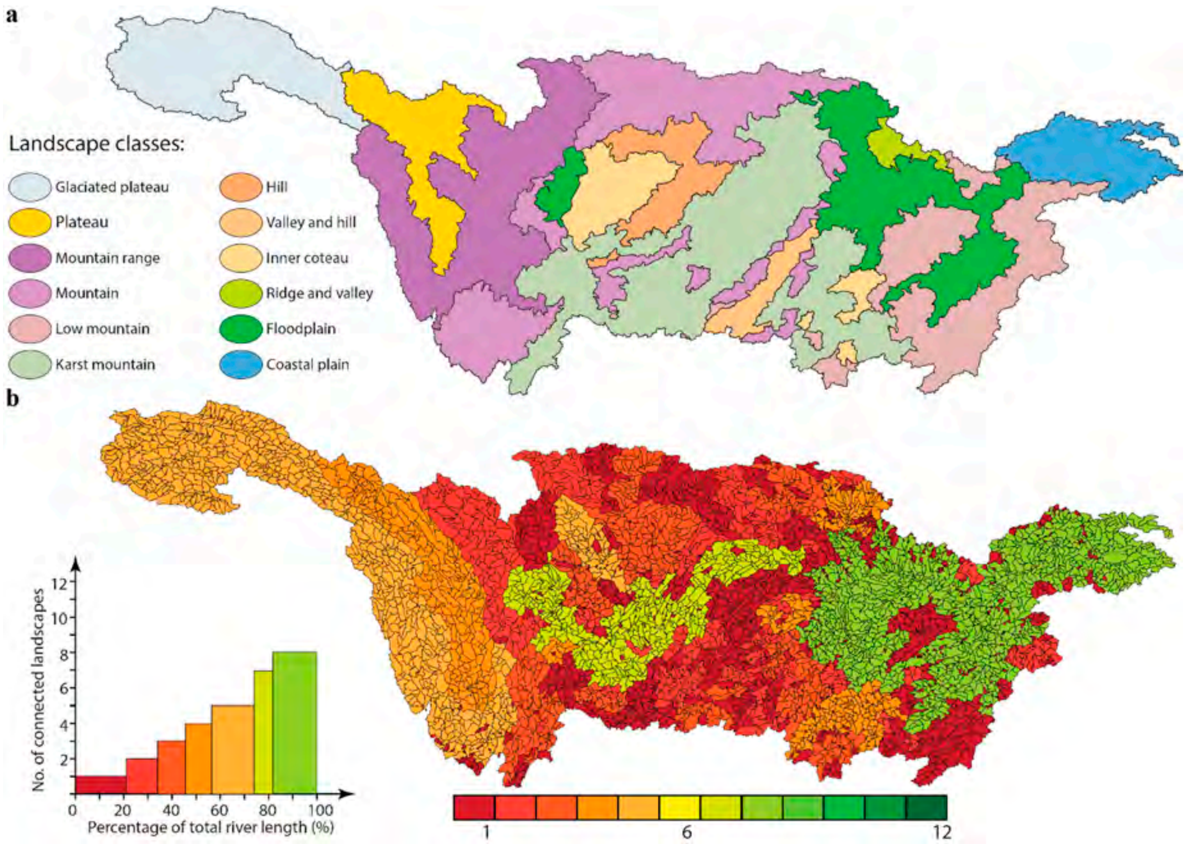

Figure 7. Results for river basin disconnectivity analysis for the entire Yangtze River basin based on river-system classification map. (**a**). River-system classification map based on basin characteristics. (**b**). Current status of river basin disconnectivity for the whole Yangtze basin.

From the results, it can be seen that a proposed dam on the Yangtze main stem or major tributaries would significantly disconnect the river basin. The results also show that the middle-lower main stem area and some tributary basins in the Poyang Lake region are relatively less impacted, left without dams. The analysis on river basin disconnectivity provides insights into how different river systems are distributed across the Yangtze River basin and how they relate to each other in terms of spatial configuration. This allows the identification of links between different river systems and supporting processes where connectivity is a key variable, such as sediment and nutrient transport.

4.4. Calculating Flow Regulation by Small Dams Using DOR

The result shows that approximately 170,000 km^2, or 9.4% of the Yangtze River basin, is intercepted by small dams. Statistical analysis shows the cumulative frequency of the number of small dams: Dams with catchments less than 5 km^2 occur at the highest frequency, and with increasing catchment area, their frequency decreases sharply. The direct effect of small dams is the reduction in downstream flow [39]. The statistical result and map of the impacted river sections are given in Table 3 and Figure 8, which displayed that the relative effect increases gently, with stream order peaking at the fourth order. Large stream sections show sharply decreased in DOR again because substantial flows cannot be easily regulated by small dams. When adopting a DOR threshold of 5%, it shows that 54,977 km or 26% of the streams are impacted by upstream small dams. Of these, 45,878 km are first-, second-, and third-order streams, representing 25% of all streams in the three size classes. Approximately 771 km or 11% of large streams with stream orders greater than five are affected. Among the streams, the fourth-order streams are the most severely affected, 32% of which are affected.

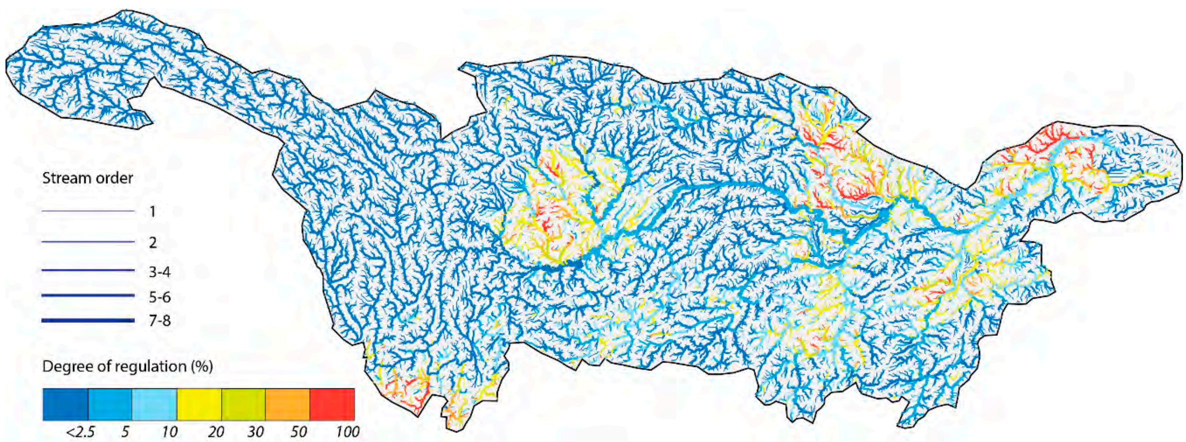

Figure 8. Affected river sections downstream of small dams. Different colours show an increasing degree of regulation, whereas the line width is proportional to stream order.

Several tributaries stand out as being highly affected by the construction of numerous small dams, such as the Tuo, Xin, Zi, and Xiang rivers (Table 3). For example, approximately 78% of the Tuo River is affected by small dams. The other three rivers are affected less, but still, have more than 40% of stream sections affected by small dams. The four rivers are all in the dam-dense areas, such as the Sichuan Lowland in the upper Yangtze reach, the Poyang Lake region and the Dongting Lake region in the middle Yangtze reach (Figure 8).

The analysis indicates that, although large dams can undoubtedly impose a dramatic impact on hydrological processes via the huge quantities of flows that they can impound, small dams can also significantly alter regional river flows through their sheer number and density. River basin development and management frameworks using methods like the DOR assessment can instruct decisions considering the longitudinal configuration of new dams as well as the dams in operation. The corresponding management policies could also be improved by prioritizing the spatial configuration of new small dams, on the basis of which sites would have the minimum predicted cumulative impacts downstream.

Table 3. Total tributary length, number of dams, and extent of affected tributaries (in kilometers and percentages) downstream of small dams for different tributaries in the Yangtze River basin, tabulated by river size and by DOR.

Tributary	Total Length (km)	No. of Dams	Extent of Affected River with a DOR >= 5%						Extent of Affected Rivers (All River Sizes Combined)				
			By Stream Order						By DOR				
			1	2	3	4	5	6	≥5%	≥10%	≥30%	≥50%	Unit
Jinsha River	51,696	1817	1975	1366	823	292	0	0	4457	3227	1468	733	km
			7.9	11.5	10.7	11.8	0.0	0.0	8.6	6.2	2.8	1.4	%
Min River	15,225	889	429	386	124	0	0	0	939	659	133	14	km
			5.8	10.7	5.4	0.0	0.0	0.0	6.2	4.3	0.9	0.1	%
Tuo River	3769	1793	1322	729	426	459	0	0	2937	2563	1098	526	km
			79.0	66.3	85.2	100.0	0.0	0.0	77.9	68.0	29.1	14.0	%
Jialing River	20,550	3531	3162	1638	1021	422	37	104	6385	4823	1208	466	km
			33.4	30.4	37.8	27.4	4.9	14.7	31.1	23.5	5.9	2.3	%
Wu River	10,148	1086	1026	833	372	246	339	0	2817	1090	123	49	km
			20.5	33.0	25.1	41.3	63.1	0.0	27.8	10.7	1.2	0.5	%
Hanjiang River	21,212	3461	3067	2246	713	517	156	480	7179	5662	2908	1831	km
			50.0	38.0	29.1	39.6	18.0	100.0	33.8	26.7	13.7	8.6	%
Dongting Lake Region													
Lei River	3255	500	184	168	11	153	0	0	517	285	83	15	km
			12.4	21.3	2.4	29.7	0.0	0.0	15.9	8.8	2.5	0.5	%
Yuan River	11,567	1662	1836	573	200	51	0	0	1661	638	95	46	km
			32.4	20.8	15.6	4.0	0.0	0.0	14.4	5.5	0.8	0.4	%
Zi River	3555	1241	700	245	220	572	0	0	1736	648	122	3	km
			40.2	29.0	55.6	100.0	0.0	0.0	48.8	18.2	3.4	0.1	%
Xiang River	11,418	3854	2302	1159	727	373	567	0	5130	2678	486	181	km
			41.7	40.8	48.4	39.0	100.0	0.0	44.9	23.5	4.3	1.6	%
Poyang Lake Region													
Xiu River	1835	644	304	55	28	35	26	0	449	243	44	29	km
			34.2	9.0	38.4	15.1	100.0	0.0	24.5	13.2	2.4	1.6	%
Gan River	8685	2918	950	542	289	179	66	0	2026	981	215	151	km
			23.4	24.9	21.0	30.8	13.9	0.0	23.3	11.3	2.5	1.7	%
Fu River	1892	1125	293	154	86	8	42	0	583	407	88	20	km
			29.7	36.8	26.1	7.0	100.0	0.0	29.4	20.5	4.4	1.0	%
Xin River	2007	1862	533	142	76	235	0	0	987	551	20	2	km
			49.4	31.0	32.5	100.0	0.0	0.0	49.2	27.5	1.0	0.1	%

[a] For the results "by stream order," the percent value refers to all river sections of the respective size class in the tributary basin; for the results "by DOR," the percent value refers to all rivers of all sizes in the tributary basin.

5. Discussion

5.1. Uncertainty Analysis

The primary challenge in RCI calculation is identifying whether the probability for sediment passability through a dam (TE) is independent among nearby dams. Independence may not be appropriate in situations where passability is dependent on water discharge (which varies at large spatial scales). For example, because the Gezhouba Dam is close to the TGD (38 km), the water discharge at the Gezhouba Dam is significantly affected by that released from the TGD. In this case, the probability of passing the Gezhouba Dam may not be independent. Although the RCI requires estimates of passability at individual dams and better estimates of passability will serve to reduce uncertainty, designing an approach to estimate passability of dams is still challenging at present. Additionally, the approach should be validated against observed connectivity patterns.

Another challenge is that each river system was considered to be of equal relevance throughout the entire Yangtze basin when analyzing river basin disconnectivity using the BDI. In fact, more crucial information could be obtained if the individual river systems and their associations with specific processes; basin layout can be better geographically quantified. Besides, it should be noted that the BDI value is also dependent on the river-system classification map. One may get slightly different results with a different classification map. Thus, an appropriate classification map is the fundamental determinant for the assessment based on BDI.

The results of the DOR study also should be carefully interpreted to avoid any misleading implications. First, the effects and aftermaths of flow regulation could vary dramatically for various river sizes. In the Yangtze basin, sixth-, seventh-, and eighth-order streams are probably most important for far-ranging socioeconomic and environmental aspects. Yet, first-, second-, third-, and fourth-order streams can also offer local or regional hydrological services, for example, ecological habitats, water resources for irrigation, or representing upper reaches for domestic water supply. When these streams are affected by small dams, the impacts are actually hidden at a basin-wide scale. Second, the DOR ratio is of high importance. For stream sections with high DOR values, evident modifications in inter- and intra-annual flow regimes can be predicted. However, smaller values could also indicate critical short-term or small-amplitude alterations. Third, it will mainly rely on individual dam operation rule and additional impacts. For example, some small dams are in operation as run-of-the-river power plants; thus, they may not regulate river flows as expected. Finally, this study also recognized that environmental impacts may vary and that some rivers may be more threatened than their counterparts by a certain degree of regulation because the effects are the consequences of joint forces, such as dam construction, deforestation, water diversion, land cover change, and climate change. Undoubtedly, further studies are required with respect to the associated environmental consequences.

In addition, the DOR approach intrinsically is affected by different uncertainties. In addition to technical issues, such as flow estimation using regression techniques, some could not be addressed due to insufficient data, such as high-resolution DEM data, the rule of dam operation, etc. Besides, for small dams, the annual amount of water withdrawals and water transfers for various purposes (irrigation and domestic uses), plus the regulated volumes for energy generation, could be much larger than the total reservoir capacity. The impact of small dams could be underestimated based on the DOR. The DOR approach only accounted for effects caused by upstream dams on downstream sections; however, for other upstream tributaries, disconnectivity may be aggravated by the construction of new downstream small or large dams. These impacts are not addressed in this study. Therefore, considering these impacts, it can be believed that the predictions of the range of impacted river sections are relatively conservative.

Despite the limitations related to the implementation of the assessments, results have to be judged against the large-scale needs of water resource managers and policymakers. Many critical characteristics along with the Yangtze River network, such as highly disconnected conditions and disruptions in river connectivity, are well represented in this study. Major changes between the tributaries or within geographical reaches (upper, middle, and lower reaches) can be easily mapped. The assessments provide valuable information on expected impacts, supporting large-scale decision making.

However, it should also be highlighted that the assessments are quite complex and subject to the aforementioned uncertainty. In this study, only anthrophonic impacts were considered. In fact, significant changes in river flow regimes caused by climate change have also been observed [54–56]. By 2050, the impacts of climate change could have a generally bigger impact on river runoffs than it is predicted that dams have had until now [56]. Thus, in real applications, the assessments in this study solely may underestimate actual environmental impacts on rivers. Further assessments incorporating climate change should be carefully involved.

5.2. Comparison of the Metrics

This study first quantified the impacts of 1358 dams on river disconnectivity in the Yangtze River basin using two different metrics. The RCI facilitated the consideration of longitudinal connectivity in the Yangtze River network. An advantage of the index is that it allows the evaluation of the impacts of individual projects at the scale of the entire river network by encompassing cumulative impacts of many large- and medium-sized dams. However, if we compare the index with BDI (Figure 9), we may get some meaningful findings. For example, when the TGD was initially closed in 2003, the value of RCI decreased by 20%, relative to a slightly higher drop of 23.5% in BDI. Although both indices show the significant impact of the TGD on river connectivity, Figure 9 shows that RCI is more sensitive than

BDI. For example, in a specific river section, if the river already maintains connectivity among only one river system due to previous dam construction, BDI would not decrease any more, even though more dams are constructed on the river, but the decreasing RCI can still reflect the variation in river connectivity. In Figure 9, although more dams were constructed after 2010, RCI decreased accordingly, but no apparent change in BDI occurred.

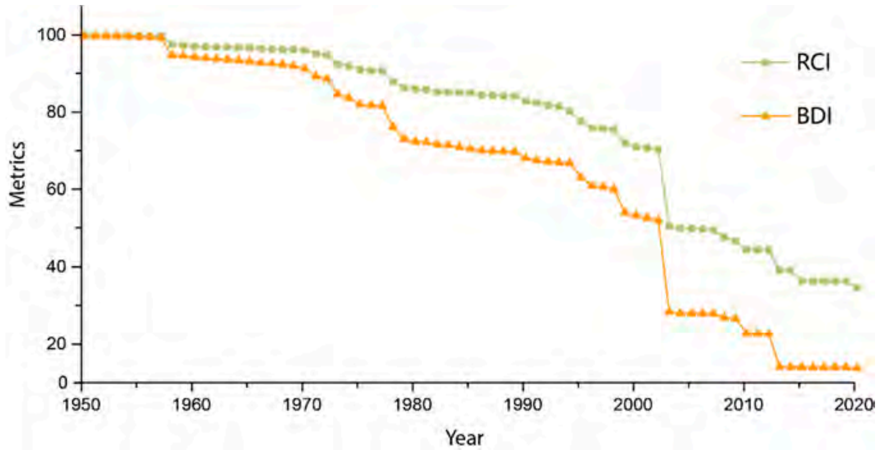

Figure 9. Variation of river connectivity and fragmentation for the Yangtze River represented by RCI and BDI from 1950 to 2020.

5.3. The Role of Small Dams

To investigate the role of small and large dams in flow regulation based on DOR, a comparative analysis was carried out (Figure 10). Figure 10a,b reveal that small dams primarily affect streams at the regional scale (with stream order < 5), while large dams principally affect large streams. In terms of the impacts on the fourth-order streams, small dams show almost equal impacts with large ones. For example, 26% of first-order streams are affected by small dams, while only approximately 4% of first-order streams are affected by large dams. In addition, small dams have worsened the impacts on large streams. For example, excluding the impacts of small dams, there are no seventh- and eighth-order streams with DOR > 30% (Figures 10b and 11a). When both small and large dams are considered, 20% of seventh-order streams and 100% of eighth-order streams are affected by DOR > 30% (Figures 10c and 11b). These study results revealed that the impacts of small dams are comparable to large dams for fourth-order streams, or even significantly exceed large dams for first-, second-, and third-order streams.

Some more alarming conclusions could be drawn by comparing previous study results. A previous study about global large rivers [7] indicated that, of 292 investigated large rivers, 108 rivers (37% of the rivers) have no dams constructed on the rivers (DOR = 0); 41 rivers (14% of the rivers) can also be considered as free-flowing rivers (DOR ≤ 2%); the remaining 143 rivers (49% of the rivers) are regulated by dams (Figure 12). Similar results can also be obtained at continental scales (such as North America and Asia), although the condition for Asian rivers is relatively more severe. The World Resources Institute found that at least one large dam modifies 46% of the world's 106 primary watersheds [57]. However, by mapping the DOR values for the Yangtze tributaries to the DOR structures (Figure 12), it can be seen that the portion of undammed or free-flowing tributaries in the Yangtze basin is much lower than global average: Most tributaries are in high or moderate regulation ranges, except the Jinsha and Min tributaries. The total regulated flow in the Yangtze River basin (290 km^3) is even much higher than the river flows regulated by large dams (226 km^3) in the entire European Union. The modification of river flows in the Yangtze River basin has particular implications. The greatest flow regulation was the Han and Xiu tributaries, with more than 90% of river flows regulated. The tributaries with flow regulation greater than 5% cover approximately 84% of the river network, account for approximately

90% of the Yangtze River flow, and affect nearly 400 million people, or 96% of the population living in the Yangtze River basin. The affected population is even more than the population of the United States.

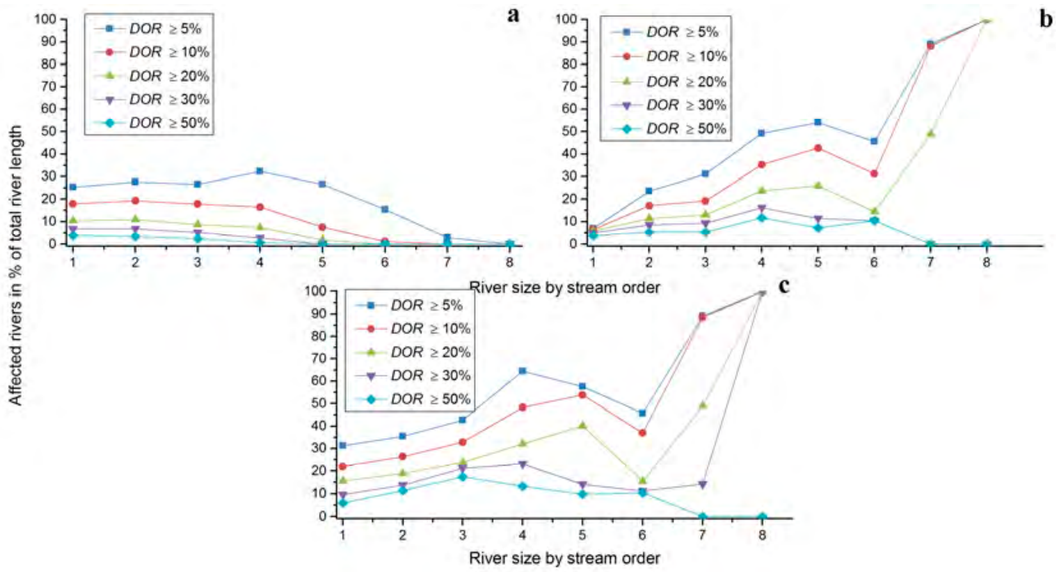

Figure 10. Comparison of the impacts caused by large dams and small dams based on DOR ratios: (**a**) DOR ratios for small dams in the Yangtze basin; (**b**) DOR ratios for large dams in the Yangtze basin; and (**c**) DOR ratios for all dams in the Yangtze basin.

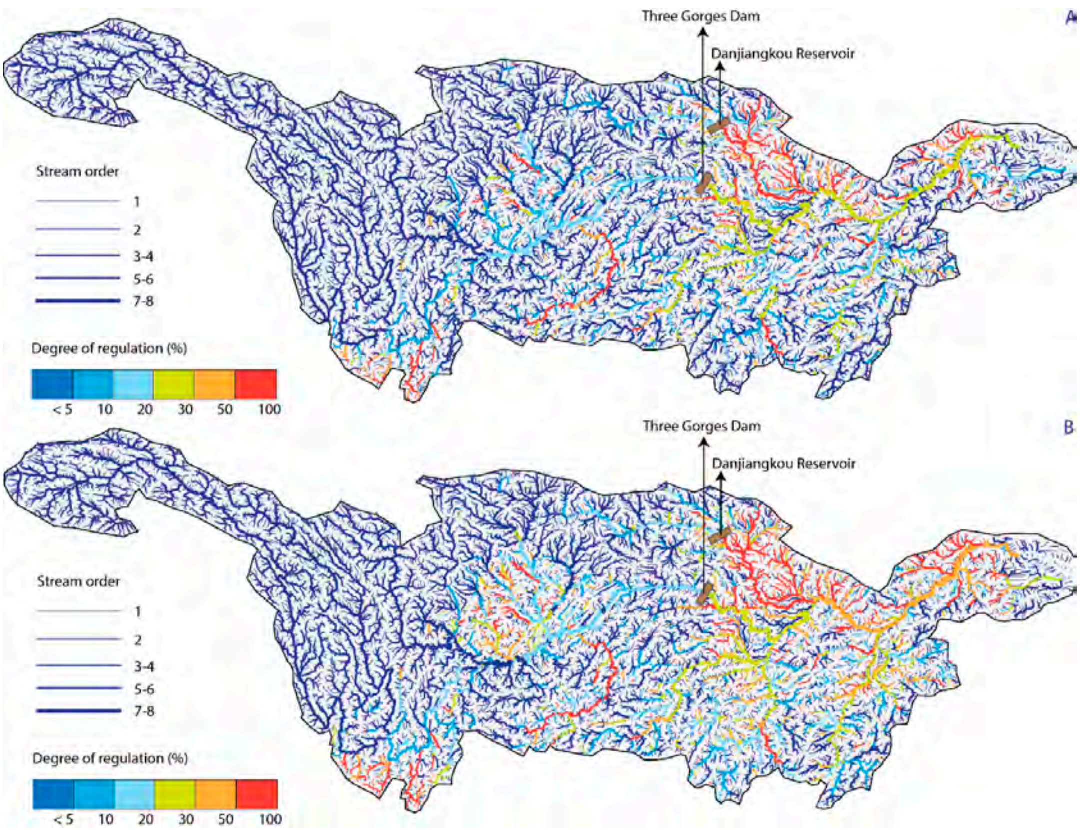

Figure 11. Affected river sections in the Yangtze River basin: (**a**) Affected river sections by only large dams; and (**b**) affected river sections by both large and small dams. Different colors show an increasing degree of regulation, whereas the line width is proportional to stream order.

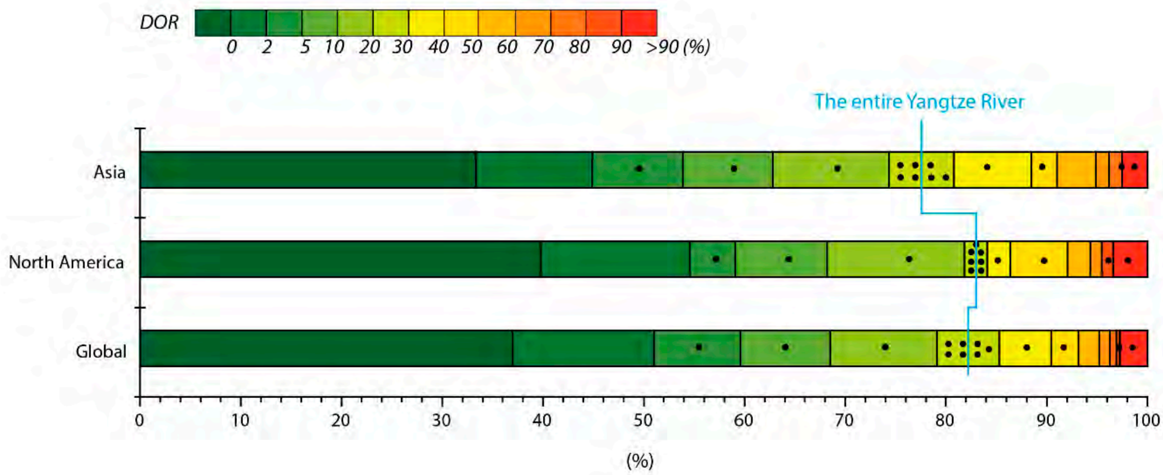

Figure 12. Flow regulation for the 14 Yangtze tributaries against DOR structures at global and continental scales.

5.4. Past and Future Trends

In the Yangtze basin, the recent trend has been toward more and bigger dams because of increasing national demand for energy. For example, China intends to increase its hydropower capacity from 566 × 10^9 kW.h yr^{-1} in 2010 to 1200 × 10^9 kW.h yr^{-1} in 2020. According to the distribution of hydropower resources, China has planned 13 hydropower bases, six of which are located in the Yangtze basin [58], namely the Jinsha River, Yalong River (one major tributary of the Jinsha River), Dadu River (one major tributary of the Min River), Wu River, the main stem of the upper Yangtze River, and the Yuan River, have already disconnected due to dam construction.

The lower Jinsha River is a very important river section in terms of water supply to the TGD. This stretch of the river is also ecologically important as it contains the greatest diversity of fish species found in the upper Yangtze basin [59]. The China Three Gorges Project Corporation, a state-authorized investment institution responsible for the construction of the TGD, began building a new dam on the Jinsha River in 2005. Now completed (but not yet operating), the Xiluodu Dam (12.6 million kW; 278 m tall) ranks second in size to the TGD. Apart from the Xiluodu Dam, three more cascade dams (Wudongde, Baihetan, Xiangjiaba) have been proposed for the main stem of the lower Jinsha River. However, it will be part of a 12-dam cascade along the Jinsha River because construction is not proceeding in a coordinated fashion; the ultimate number of dams could exceed this number. The new growth in dams could further disconnect the Yangtze River.

Figure 13 presents the year-by-year disconnectivity history of the Yangtze River in comparison with the world's five largest rivers on the basis of the variation in DCI/RCI. It illustrates that the indices decrease over time as dams are built on the rivers. Graf [49] reported that, in North America, the greatest rate of increase was from the late 1950s to the late 1970s. The resultant value of DCI then takes a nosedive from the 1950s to 1970s, such as the Columbia and Mississippi rivers. The oft-heard colloquial wisdom that "the nation's dam building era is over" was born out by the relatively minor increases in storage after 1980 in North America. This general history explains why the downstream environmental costs of dams have only recently captured the attention of scientists. The maximum potential for the downstream hydrologic disruptions through related reservoir storage has been in place for less than three decades, and the effects have only recently become obvious [49]. In Asia; however, dam construction still keeps a strong momentum, especially after the 1990s. Most of the large Asian rivers (such as the Mekong, Indus, Ganges, and Yangtze) are being dammed at a dazzling pace. Figure 13 shows that a sharp decrease in DCI/RCI for the Mekong and Yangtze occurred since 1975. Moreover, the decreasing trend will remain for the next 10 years based on the prediction. Although Asian rivers experienced river disconnectivity later than their counterparts in North America, all the rivers, including the Yangtze River, ended up with high river disconnectivity.

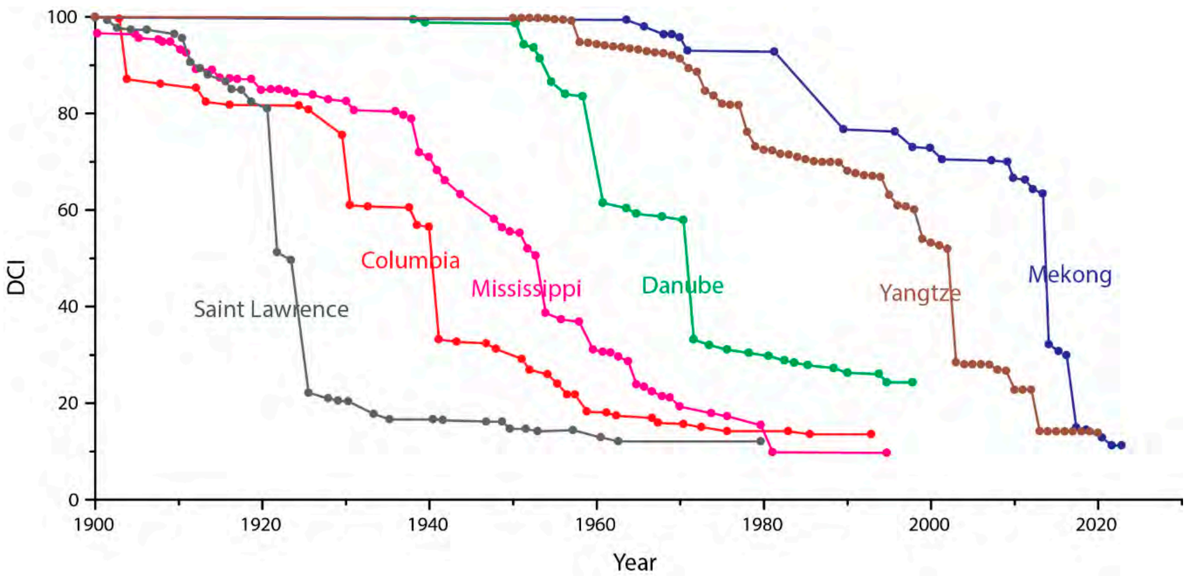

Figure 13. Basin disconnectivity history for selected large rivers in the world. Data for the Yangtze River was provided by this study; data for other rivers were provided by Grill et al. (2014).

Considering the possible future trend for river disconnectivity in the Yangtze basin, further investigations are required to identify possible environmental risks and formulate possible policy responses for proactive management intervention, for example, sediment starvation and the resultant downstream channel corrosion, stationary flow, and resultant changes in temperature, as well as other water properties, rise in evaporation losses, water regime change, and the resultant damages to vegetation as well as natural structures in the river banks, plus possible damages to river ecosystems and biodiversity. Each possible environmental risk should undergo a scientific evaluation to avoid possible failure in human interventions.

6. Conclusions

This study performed a basin-wide river disconnectivity assessment in the Yangtze River basin. It provides environmental insights into all major Yangtze tributaries. Another core value of this study is that the analyses will enable the replication of similar assessments in other river basins, based on which the assessments can allow water resource managers to characterize watersheds, determine priorities for optimizing water resources allocation and infrastructure plans (placement of dams), and reports on river disconnectivity as a component of river intactness.

At present, the RCI value for the whole Yangtze River has decreased from 100 to 43.97, indicating that the Yangtze has experienced strong alterations over the past decades. The measurement of BDI showed that the Yangtze River basin already shows a high degree of disconnectivity. A substantial part of tributary basins, especially the Wu, Min, Jialing, and the Yuan tributaries only maintain connectivity among one to three distinct river systems. This study also revealed that small dams can also exert significant impacts in flow regulation on regional river systems through their sheer number and density. The impacts of small dams are comparable to large dams for the fourth- and fifth-order streams, or even exceed large ones for the first-, second-, and third-order streams. They also worsen the impact of large dams on large streams.

As demands on energy and water resources increase in the Yangtze basin, the government is now engaged in a new expansion of dams in great staircases. This research can help address the environmental risks associated with further impacts caused by new dams. Integrating the approaches into environmental impacts assessments can also present a new framework to effectively integrate river connectivity and free-flowing functionality into hydropower sustainability and add a basin-wide perspective to conventional environmental impacts assessments.

In addition, it should be understood that the anthropogenic impacts are quite complex and subject to the aforementioned uncertainty, especially when climate change is considered. Climate change alone can also alter river flows, which further affect downstream water supply, hydropower generation, and habitat suitability. Thus, future studies incorporating the impacts of climate change are required to consolidate the assessments. Based on the assessments, further investigations are also necessary to identify possible environmental risks and formulate corresponding policy responses for proactive management intervention.

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