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# Barrier-based Longitudinal Connectivity Index for Managing Urban Rivers

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**Abstract:** A large variety of barriers can affect longitudinal connectivity, which leads to shipping blocking and even flood hazard. However, few existing methods can quantify physically the river channel connectivity from the barrier's details perspective in a watershed. This paper establishes a new model of the River Channel Connectivity Index (RCCI) to quantify the unobstructed degree of river flow in river channels within geographic information system (GIS ) platforms based on the modified concept of time accessibility. A comprehensive classification system of barriers is setup before these barriers are identified by the remote sensing technology. The model is applied to Dashi Watershed in suburban Beijing, China. Results show that submersible bridges and sediment siltation are the main barriers in the watershed. RCCI values in the mountainous areas are generally higher than that of the plains. The assessment results verified by two historical flood events show that the RCCI can reveal where the river channel connectivity is impaired, how serious it is, and what the reason is for managers. Through scenarios' results, the best restoration measure for each tributary is obtained from the perspective of reducing flood hazards. The new RCCI method not only has methodological significance, but also helps policymakers to enhance river flooding reduction and determine restoration priorities of the river channel.

**Keywords:** river channel; longitudinal connectivity; barriers; time accessibility; planning; flood hazard

## 1. Introduction

Natural watersheds are increasingly being affected by economic and social activities, which can introduce various types of barriers (e.g., dams and culverts) to river channels, reducing hydrologic connectivity, and leading to transport blockage, ecological habitat damage, and heightening flood hazard risks [1–3]. Good hydrologic connectivity is a key element for maintaining ecological integrity and it can be used by city managers to reduce flood risks, manage water resources, and restore fluvial ecological systems in practice.

Hydrologic connectivity aims at river ecological protection and mainly refers to water-mediated transferring of matter, energy, and organisms within or between elements of the hydrologic cycle [4,5]. A variety of approaches and metrics have been developed depending on the aim of the research and the target species in hydrological connectivity studies [6].

Hydrological connectivity can be interpreted in terms of static/structural and dynamic/functional connectivity [4,7]. Structural connectivity refers to the spatial patterns in the landscape. It is measureable and easy to understand. A series of metrics on structural connectivity is based on high-resolution digital elevation model (DEM) data. Several topography-based indices have been developed and applied in different contexts [8–14]. Landscape ecologists are familiar with using graph theory to describe and analyze river networks. Then, a series of assays of landscape connectivity indices are used to measure the structural connectivity [15,16].

In the three dimensions manifested by hydrological connectivity, longitudinal connectivity is defined as connections between upstream and downstream sections of a river network, as opposed to vertical of lateral connections [17,18]. Natural and anthropogenic barriers (e.g., buildings and dams) have impeded longitudinal connectivity severely, especially in urban and suburban watersheds [9,10]. For example, Segurado et al. [19] introduced dams into the analysis of structural connectivity of the Tagus river network in Portugal based on a landscape connectivity metric. When assessing the effect of barriers on aquatic biological communities, the Dendritic Connectivity Index (DCI) is widely used and modified to quantify longitudinal connectivity [1,3,20–23]. In previous studies, anthropogenic barriers include dams, culvert, and roads, and natural barriers include waterfalls and beaver dams [22,24–26]. Combined with field investigation, barriers are defined as anthropogenic or natural deposits that block river flow in the river channels in this paper. Although researches on hydrologic connectivity considered barriers in the calculation of a certain index, they are based on a specific object, such as water, biological species, sediment, or soil-moisture [17,27], and study the effect of barriers on connectivity of these specific objects. The sizes and attributes of barriers are highly variable [3]. Previous researchers may consider the difference of small culverts and large dams. However, culverts are different in size and dams are different in scales. It seems that there is a blank that puts the details' information of a barrier in the calculation of longitudinal connectivity in the previous studies. Furthermore, the critical item of the river channel is ignored. As the container of runoff or discharge, a river channel directs the movement of river flow, organisms, and materials [28,29]. River channel connectivity as the basis of hydrological connectivity decreased by barriers should be paid more attention.

In this paper, a comprehensive classification system of barriers is developed for a suburban watershed. The blocking degrees of river flow through these barriers are weighted by a method combining subjective and objective weighting strategies. Based on the blocking degrees, a new concept, "river channel connectivity" (RCC), is proposed, which is defined as the unobstructed degree of the river flow in natural or artificial river channels. Moreover, a new assessment model, river channel connectivity index (RCCI), is established to quantify such an unobstructed degree. Then, the RCCI model is applied to Dashi Watershed in the suburb of Beijing, China. The results are validated by using two historical flood events from the potential applications of the RCCI model. Furthermore, scenarios analyses are introduced for scientific and quantitative fluvial environment planning from the perspective of reducing flood hazard.

## 2. Study Area and Field Data Collection

### 2.1. Study Area

Dashi Watershed is located in the Fangshan District of Beijing, China. It belongs to the Haihe River Basin. The 126 km long Dashi River drains an area of 1267 km$^2$ with 16 catchments. It is divided into mountains and plains by 100 m contours (Figure 1). It is characterized by a semiarid and semi-humid monsoon climate with an average annual evaporation of 1500 mm and an average annual rainfall of 700 mm. Moreover, the watershed has an average annual runoff of 95.7 million m$^3$, and its rainfalls concentrate in July and August, accounting for 80% of the annual total precipitation. Rainfall usually occurs in high intensity and short duration events, which often leads to severe regional flood events in summer [30].

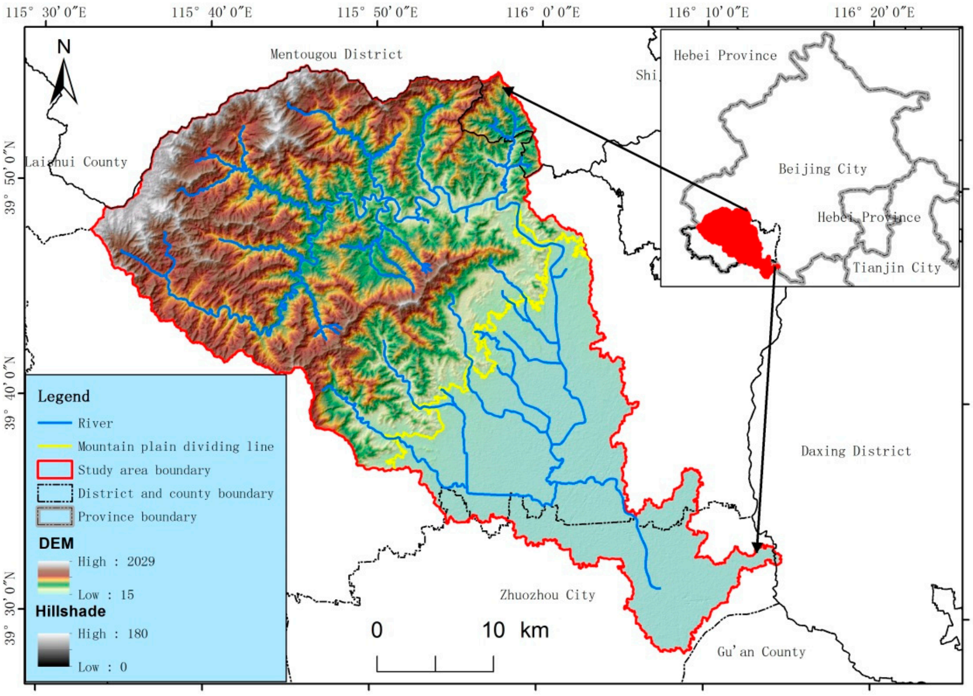



**Figure 1.** Location of study area and Dashi Watershed.

### *2.2. Data Sources and Preprocessing*

The 30-m shuttle radar topography mission (SRTM) DEM data are used to generate the watershed and catchment boundaries. The river channel and barriers are identified by visual interpretation using the SPOT6 remote sensing image data of 4 August 2015 and multi-period images from Google Earth. Before being used in the model, the above data underwent preprocessing, such as georeferencing, radiation calibration, and image fusion. Local references are used to generate the statistical data, and spatiotemporal information of relevant rainstorm disasters [31–33]. These documents are also used as the important basis for the classification and weight assignment of barriers.

## **3. Methodology**

The various barriers are classified and weighted before they are identified from the river channel by the interpretation of the high-resolution image. The RCCI model is first presented in this study by modifying the accessibility method. Additionally, the passability of river flow is the key factor in the model. The RCCI model is applied to calculate the connectivity of different tributaries and river segments, and the results are validated by two historical flood events of 2000 and 2012 in the watershed. Finally, based on the scenarios' analyses, guides for fluvial environment planning are obtained from the perspective of reducing flood hazard (Figure 2).

### *3.1. Classification and Weight Assignment of Barriers*

All barriers could be classified into four types listed in Table 1 according to the local expertise and the related references [33] in Dashi Watershed. Different barrier types have different blocking weights on the river flow. The blocking weight represents the natural river flow passability, which is the key parameter of the proposed RCCI model. The weight is based on the barrier's holding capacity of the river flow, which depends on the shape and the type of the barrier [1]. Table 1 presents the subjective blocking weights (in the column of $p_{ni}$) of all kind of barriers using the Delphi method [34]. The Delphi method was an anonymous process where ideas were assigned to the participants in the form of a questionnaire [35,36]. There were two questions in the questionnaire. One was whether the classification of the barriers was reasonable; the other was to grade the blocking weights of various barriers. The questionnaires were sent out to 20 experts by E-mail. Then, responses were collected and analyzed. Investigators achieved "group" consensus on the classification, the rank of barriers, and most of the blocking weights, in the second round. Finally, the average values of these different weights were calculated as the final blocking weights if a barrier had several different weights from different experts. Therefore, the anonymous nature of the Delphi process ensures that a single dominant group member does not inordinately influence the group's outcome [36].

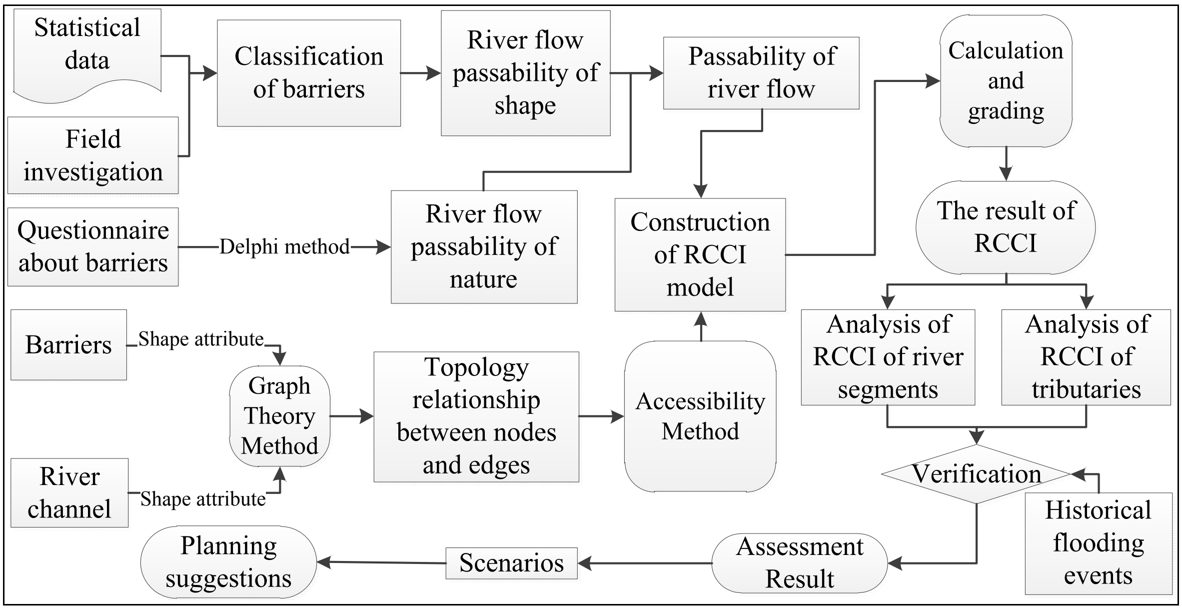



**Figure 2.** The technical flowchart of the river channel connectivity index (RCCI ) model.

**Table 1.** Classification, grade, and blocking weight assignment of barriers.

| Types | Names | Description | $p_{ni}$ |
|---|---|---|---|
| Reservoirs | Medium-sized | Storage capacity is more than 10 million $m^3$. | 0.30 |
| | Small-(I)-sized | Storage capacity is of 1–10 million $m^3$. | 0.40 |
| | Small-(II)-sized | Storage capacity is of 0.1–1 million $m^3$. | 0.50 |
| | Pond | The pond is a small water storage built in mountainous or hilly areas, and its storage capacity of local runoff is less than 100,000 $m^3$. | 0.60 |
| Dams | Sluices | The grading standards are the same as the reservoir. The storage capacities of the two sluices are equivalent to the medium-sized reservoir in Dashi Watershed. | 0.30 |
| | Rubber Dam | Also known as a rubber sluice, crest can overflow. The storage capacities of the two rubber dams are equivalent to the small-(II)-sized reservoir in Dashi Watershed. | 0.50 |
| Submersible Bridges | | Submersible bridges are simple ordinary bridges, which are constructed across the river channel. When water rises slightly, river flow will go through above the bridge. | 0.60 |
| Deposits in a river channel | Illegal Buildings | Illegal buildings are built in the river channel partly or wholly, such as village houses or cemeteries, etc. | 0.60 |
| | Sediment siltation | The sediment siltation in a river channel is produced naturally or man-made, such as sand mining activity. | 0.70 |

### 3.2. Identification of River Channels and Barriers

Figure 3 shows the technical flowchart on how to identify the four kinds of barriers (marked in blue) and the river channels. The water bodies are identified firstly by the threshold value (near infrared bands (B4)) and exponential methods (normalized difference water index, NDWI) according to the spectral characteristics before the river channel and reservoirs distinguished according to their shapes. Secondly, all the reservoirs and dams are identified based on the shape characteristics from the image extracted by the river channel and information in the references [31,32]. The submersible bridges and sediment siltation barriers are identified by visual interpretation using multi-period images from Google Earth since the submersible bridges are easily confused with other bridges in the image texture, and the sediment siltation has an irregular shape. Finally, the identification results are verified by the field investigation for ensuring the accuracy of the river channel and barriers (Table 2). Additionally, some other RCCI-related parameters, such as the number and widths of spillways, widths of gates, and heights of submersible bridges and rubber dams, are generated from the local documents and references [31,32] in the case that some key information about river depth and the actual height of barriers cannot be interpreted from remote sensing images (Figure 3).

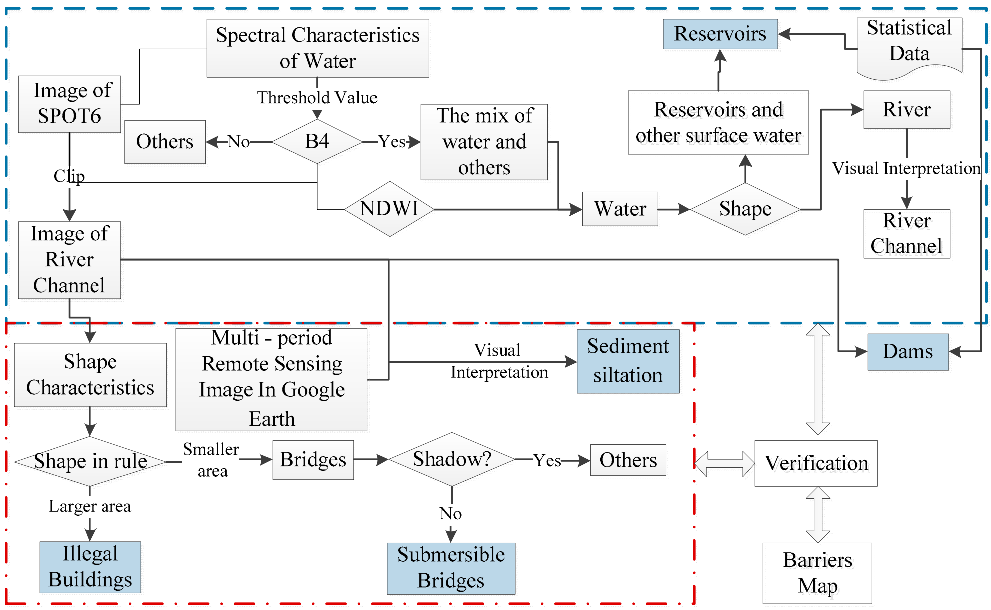
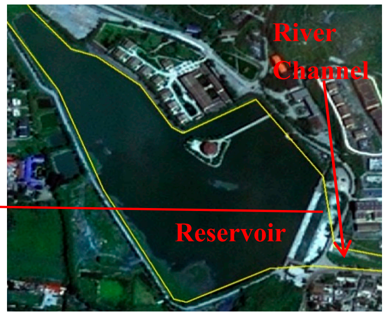
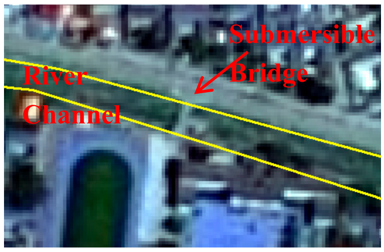



**Figure 3.** The technical flowchart for the identification of river channels and barriers.

### 3.3. Definition and Calculation of RCCI

As the quantitative indicator of river channel connectivity (RCC), RCCI is measured by using an accessibility method defined by the modified traditional accessibility method. Previous researchers defined accessibility as the intensity of the possibility of interaction [37,38]. Here, we define accessibility as the degree of difficulty for a certain volume of river flow to overcome various physical barriers from one particular location to the other one in the river channel. The quantitative assessment indicators of accessibility generally include time accessibility and distance accessibility [39]. The former is adopted since it can be altered by barriers, and the difficulty in the definition refers to the time parameter in this study. In the case of no barriers in a natural river channel, as shown in Figure 4a, the time accessibility required for river flow is the minimum from the upstream point, $A$, to the downstream point, $B$, therefore, the connectivity is the maximum. The channel is divided into $n + 1$ sections if there are $n$ barriers [1], which decreases the river volume in unit time due to the reduced connectivity in the fragmented river channel. Therefore, we assume that the RCCI value equals to the ratio of the time accessibility of river flow in the river channel without any barriers to with some barriers in the condition of the same volume ($V$) of river flow running from one point to another point in a channel by starting from the Equation (1). The range of the RCCI value is [0, 1].

**Table 2.** The barriers in the field landscape and remote sensing imagery.

| Name | Photo | Image |
| --- | --- | --- |
| Reservoir |  |  |
| Rubber Dam |  |  |
| Submersible Bridge |  |  |
| Illegal Buildings |  |  |
| Sediment siltation |  |  |

$$\text{RCCI} = \frac{t}{T} \tag{1}$$

where $t$ is the time without any barriers in a river channel, and RCCI equals to 1 in this situation; $T$ is the time with barriers in the same river channel.

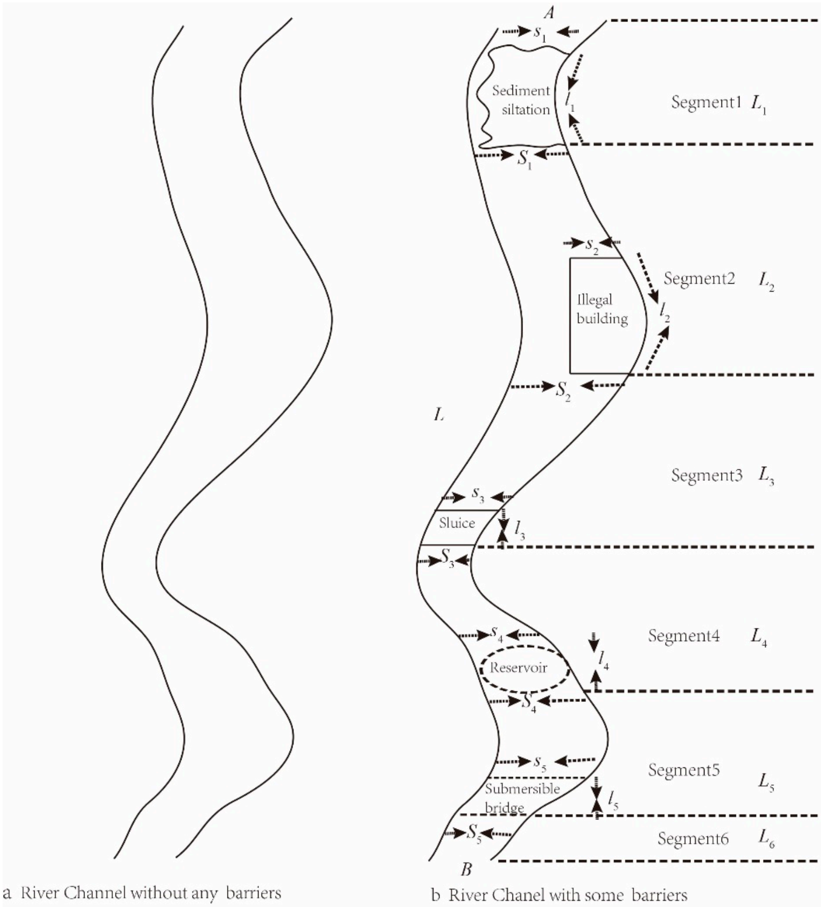



**Figure 4.** Conceptualized diagram of different barriers and parameters in the RCCI model. (**a**) is a natural river channel with no barriers; and (**b**) is the same river channel with some barriers.

The Equation (2) in physics is as follows:

$$t = \frac{L}{v} \tag{2}$$

where $t$ refers to the time of the river flow from the upstream to the downstream point (s); $L$ is the length of a river channel (m); $v$ is the flow speed (m/s).

Additionally, Equations (3) and (4) can be obtained:

$$t' = \frac{V}{Q} \tag{3}$$

$$Q = v \times S \tag{4}$$

where $t'$ is the time of the river flow going through a cross-section of a channel (s); $V$ is the volume of the river flow (m$^3$); $Q$ refers to the runoff rate (m$^3$/s); and $S$ is the cross-sectional area of a channel (m$^2$).

Therefore, Equation (5) can be referred to from the Equations (2)–(4):

$$t = \frac{LSt'}{V} \tag{5}$$

When there are $n$ barriers with length, $l_i$ ($i$ = 1, 2, 3 … $n$), in the channel, as is the case in Figure 4b, the components of $T$ include the time of the river flow with barriers and without barriers. $T$ is calculated by using Equation (6):

$$T = \frac{(L - \sum_1^n l_i) \times St'}{V} + \sum_1^n \left(\frac{l_i S t_i''}{V}\right) \tag{6}$$

where $t_i''$ is the time of the river flow going through the river channel segment, which is impaired by barrier $i$ (s).

When there is a barrier $i$ in the channel, the cross-sectional area for the river flow changes to $S - S_i$. $S_i$ refers to the cross-sectional area of barrier $i$, and it is determined by the maximum width and maximum height in the water of the barrier ($m^2$). In addition, the river depth is set according to the normal flow level. Then, we can refer to Equations (7)–(9) from the established Equations (2)–(6):

$$t_i'' = \frac{S}{S - S_i} t' \tag{7}$$

$$T = \frac{(L - \sum_1^n l_i) \times St'}{V} + \sum_1^n \left(\frac{l_i S \frac{S}{S - S_i} t'}{V}\right) \tag{8}$$

$$T = \frac{(L - \sum_1^n l_i) \times St'}{V} + \sum_1^n \left(\frac{l_i S \frac{1}{p_{si}} t'}{V}\right) \tag{9}$$

The ratio of $(S - S_i)$ to $S$ is defined as the river flow passability of the shape ($p_{si}$) in the channel with barrier $i$.

Those factors affecting the passability of river flow are related not only to the objective geometry of a barrier, but also to its type, which is treated as the subjective one as introduced in Section 3.1 (Table 1). Both the shape and the nature of a barrier determine the passability of the river flow through a specific barrier ($p_i$). The same weights are assigned for the two parameters to calculate $p_i$:

$$p_i = 0.5 \times p_{si} + 0.5 \times p_{ni} \tag{10}$$

The improved $T$ is:

$$T = (1 - \sum_1^n x_i) \frac{LSt'}{V} + \sum_1^n \frac{x_i LSt'}{V} \times \frac{1}{p_i} \tag{11}$$

where $x_i$ equals the ratio of $l_i$ to $L$.

The calculation of RCCI is done by Equation (12):

$$\mathrm{RCCI} = \frac{1}{1 + \sum_1^n \left(\frac{x_i}{p_i} - x_i\right)} \tag{12}$$

RCCI can not only calculate a tributary connectivity (the connectivity of $A$ to $B$ in Figure 4b), but also characterize a segment connectivity of a specific tributary (the connectivity of segment $i$ in Figure 4b; in which $x_i$ equals the ratio of $l_i$ to $L_i$). The RCCI value of each segment depends only on the segment length, barrier length, and the river flow passability of the barrier. However, the RCCI value of each tributary depends on the ratio of each barrier length to the total tributary length, as well as the passability of the river flow of the corresponding barrier.

## 4. Results

### *4.1. Spatial Distribution of Barriers in the Watershed*

Table 3 and Figure 5 show the information of the barrier number and their spatial locations for planners. Results show that the number of the submersible bridges accounts for 50% of all barriers as the majority barrier in Dashi Watershed. Deposits in a river channel are the second largest type of barrier, which accounts for 44%. In the mountainous area, there are 158 barriers; the number of submersible bridges accounts for 59% as the majority, and the number of deposits in a river channel accounts for 33%, of which sediment siltation accounts for only 11%. In the plain area, there are 122 barriers; the majority is sediment siltation, representing 47%, followed by 37% of submersible bridges and 11% of illegal buildings. The sediment siltation is the major component of barriers in the plain area due to the slow flow speed and human activities (e.g., dams and levee construction preventing longitudinal and lateral connectivity). Cross-river bridges are basically viaducts in the plain due to the greater number of cities, thus the number of submersible bridges is less than that in the mountain area.

**Table 3.** Number and ratio of various types of barriers in Dashi Watershed.

| Types | | The Whole Region | | Mountainous Area | | Plain Area | |
|---|---|---|---|---|---|---|---|
| | | Number | Ratio | Number | Ratio | Number | Ratio |
| Reservoirs | | 15 | 5% | 11 | 7% | 4 | 3% |
| Dams | | 4 | 1% | 2 | 1% | 2 | 2% |
| Submersible Bridges | | 138 | 50% | 93 | 59% | 45 | 37% |
| Deposits in a river channel | Sediment siltation | 75 | 27% | 18 | 11% | 57 | 47% |
| | Illegal Buildings | 48 | 17% | 34 | 22% | 14 | 11% |
| Total | | 280 | 100% | 158 | 100% | 122 | 100% |

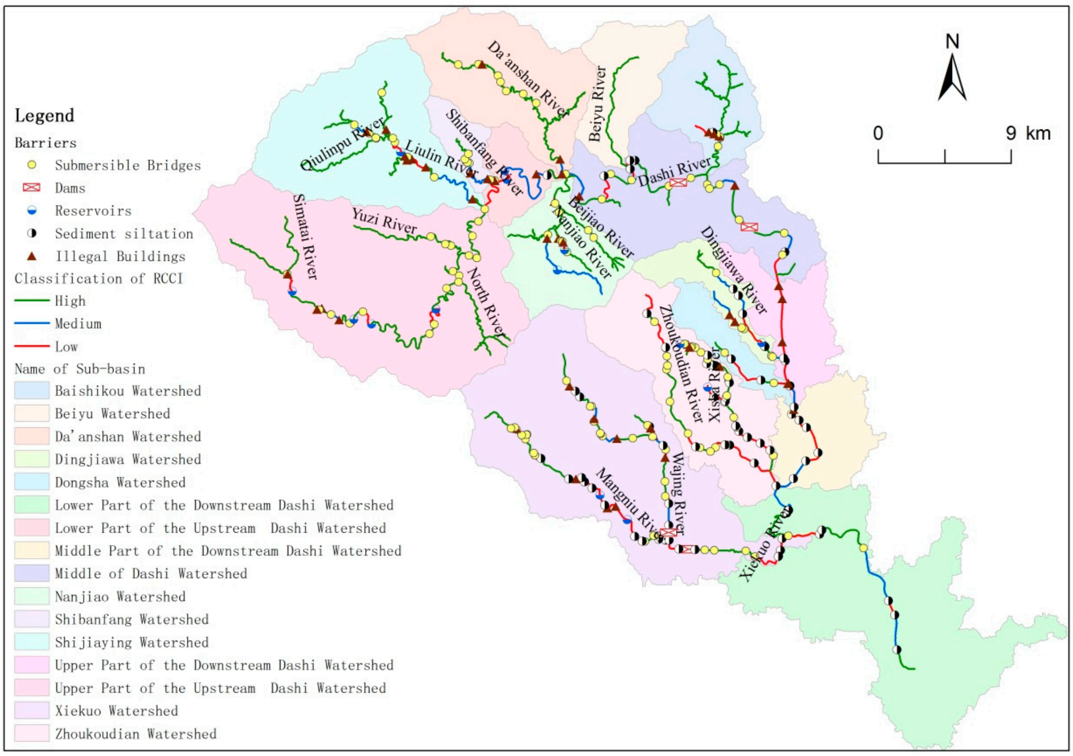



**Figure 5.** RCCI assessment results for segments.

## 4.2. Assessment Results of RCCI in the Watershed

### 4.2.1. RCCI Assessment Results for River Segments

The internal RCC differences of one tributary are demonstrated by the analysis of river segments' RCCI assessment results. Planners can see how a single barrier affects the connectivity of a river channel. There are 341 river segments divided by 280 barriers in Dashi Watershed, and the range of RCCI values is from 0.23 to 1.00, with an average value of 0.89 and a standard deviation of 0.15. The values are divided into three classes by two break points based on the RCCI calculation. The two points are calculated based on the ratio of time accessibility with a barrier to without (T/t). One break point is setup at the ratio of 1.02 referring to more than 2% extra time, while the other break point is setup at the 1.1 referring to more than 10% extra time. Accordingly, the RCCI is defined as 0.98–1.00 for high connectivity, 0.98–0.91 for medium connectivity, and 0–0.91 for low connectivity. The proportions of segment number at various levels of connectivity in each catchment are presented in Table 4 and Figure 5.

The assessment results shown by Figure 5 and Table 4 are as follows: (1) The seven catchments in the plain are all low connected, but there are some high connected segments with no barriers or few barriers of small size, such as submersible bridges and dams. The nine catchments are high connected in the mountain area except the lower part of the upstream Dashi Watershed. However, there are a few low connected segments because of reservoirs or illegal buildings; (2) the RCCI result of segments can reflect the various connectivity characteristics caused by a single barrier in different parts of a tributary. For example, there are 13 segments divided by 12 barriers in Mapaoquan River. In the 12 barriers, there are seven sediment siltations, four submersible bridges, and one reservoir. The lengths of sediment siltation range from 226 m to 880 m. The length ratio ($x_i$) of sediment siltation to segment ranges from 0.27 to 1.00, with an average of 0.75. Correspondingly, the RCCI is low with values from 0.65 to 0.85, with an average value of 0.72. However, the average length of the four submersible bridges is 7.25 m, the average $x_i$ is 0.06, and the average RCCI is 0.97. It could be concluded that $x_i$ (the ratio of the barrier length to the segment) has a negative effect on segment RCCI values. Therefore, RCCI is affected by the barrier type. Three high connected segments are presented in two sites of its downstream area and one site near Xisha River. Thus, we concluded that connectivity is clearly affected by the type and shape of the barriers in the river channel.

**Table 4.** Percentage of river segments with different levels of connectivity in each catchment.

| Name of Sub-Basin | Segments | The Percentage of Each Level Segments in Number | | | The Length of Segment/m | The Percentage of Each Level Segments in Length | | | Classification | Basic Morphological Types |
|---|---|---|---|---|---|---|---|---|---|---|
| | | High/% | Medium/% | Low/% | | High/% | Medium/% | Low/% | | |
| Upper Part of the Downstream Dashi Watershed | 7 | 0 | 14 | 86 | 8617 | 0 | 18 | 82 | Low | Plain |
| Middle Part of the Downstream Dashi Watershed | 7 | 0 | 28 | 72 | 6571 | 23 | 0 | 77 | Low | Plain |
| Zhoukoudian Watershed | 58 | 40 | 8 | 52 | 35,907 | 46 | 1 | 53 | Low | Plain |
| Dongsha Watershed | 6 | 50 | 0 | 50 | 6328 | 30 | 0 | 70 | Low | Plain |
| Lower Part of the Downstream Dashi Watershed | 9 | 33 | 22 | 45 | 24,808 | 41 | 43 | 16 | Low | Plain |
| Xiekuo Watershed | 73 | 41 | 15 | 44 | 51,763 | 53 | 10 | 37 | Low | Plain |
| Dingjiawa Watershed | 18 | 33 | 28 | 39 | 14,983 | 32 | 41 | 27 | Low | Plain |
| Lower Part of the Upstream Dashi Watershed | 5 | 20 | 40 | 40 | 13,914 | 14 | 50 | 36 | Low | Mountain |
| Middle of Dashi Watershed | 28 | 57 | 11 | 32 | 35,714 | 66 | 16 | 18 | High | Mountain |
| Shijiaying Watershed | 24 | 63 | 16 | 21 | 33,969 | 72 | 19 | 9 | High | Mountain |
| Nanjiao Watershed | 23 | 65 | 18 | 17 | 31,133 | 74 | 22 | 4 | High | Mountain |
| Baishikou Watershed | 23 | 70 | 13 | 17 | 22,461 | 91 | 1 | 8 | High | Mountain |
| Shibanfang Watershed | 12 | 50 | 33 | 17 | 6749 | 48 | 47 | 5 | High | Mountain |
| Upper Part of the Upstream Dashi Watershed | 35 | 83 | 6 | 11 | 69,987 | 90 | 2 | 8 | High | Mountain |
| Da'anshan Watershed | 12 | 84 | 8 | 8 | 23,630 | 94 | 5 | 1 | High | Mountain |
| Beiyu Watershed | 1 | 100 | 0 | 0 | 10,001 | 100 | 0 | 0 | High | Mountain |

Note: River channel connectivity level defined for each sub-basin is based on majority segments of a certain level; that is, the proportion of certain segments exceeded the average of 33%.

4.2.2. RCCI Result for Tributaries

The range of the tributary RCCI value is from 0.74 to 1.00 in Dashi Watershed based on the calculation of the RCCI model. The RCCI values are classified according to the standard in Section 4.2.1. The results show that the number of low connectivity tributaries is 41%, which are mainly in the catchments located in the middle and south of the watershed. The number of medium connectivity tributaries is 11%, and the high connectivity tributaries accounts for 48%, which are mainly within catchments located in the northwest of the watershed (Figure 6).

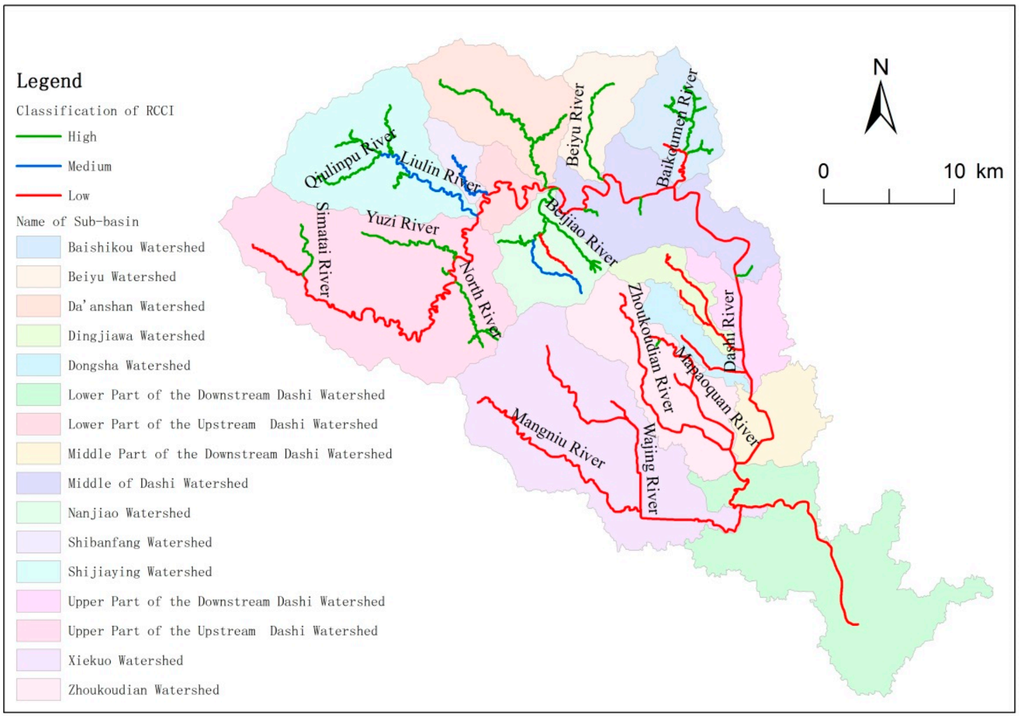



**Figure 6.** RCCI assessment result for each tributary.

The RCCI assessment results of each tributary are mainly related to the number and shape of the distributed barriers. The RCCI of Mangniu River is 0.74 as the smallest value due to the large number and various types of barriers. However, Beiyu River shows a high connectivity with no barriers. The RCCI of Liulin River in the mountainous area is much greater than that of Mapaoquan River. The number of barriers in the Mapaoquan River is equal to that of the Liulin River, however, 50% of the barriers in the Liulin River are submersible bridges of a small size while 58% of barriers in the Mapaoquan River are sediment siltation, which are more obstructive to the river channel connectivity. The RCCI of Wajing River and Dongsha River are both about 0.88. The shape attributes of the distributed barriers in the two rivers make the difference. In Wajing River and Dongsha River, the ratio of barrier lengths exceeding 100 m accounts for 28% and 60%, respectively. Furthermore, there is a 775 m sediment siltation as the longest barrier in Dongsha River even though it has fewer barriers than Wajing River.

*4.3. Verification of RCCI Assessment Results*

Flood hazards might happen due to barriers existing in the river channel. Results of the RCCI model are validated by two historical flood events of 2000 and 2012 in the watershed. The RCCI values are firstly mapped to match spatially to the town locations, with the 2000 flood events reported from the "Report of Flood Control Planning in Fangshan District" [33]. The flood events occurred in Da'anshan Village, Nanjiao Village, Shilou County, Fozizhuang Village, Hebei County, Chengguan Street, Liulihe District, and other towns on 4 July 2000, where the RCCI values of the segments are mostly small in the plain area (Figure 7). In addition, the RCCI average values of each town are counted by the spatial analysis tool in the Arcgis10.0 platform before they are classified according to the standard in Section 4.2.1. The Pearson correlation analysis between the average value and the binary variable whether the town is flooded is conducted by SPSS 19.0 (International Business Machines Corp: New York, NY, USA). The rules are set as follows: High connected is set as 0, medium connectivity is set as 1, and low connected is set as 2. As for the binary variable, it is set as 1 if the town is flooded, and else set as 0. Results show that there is a medium correlation between the flooded town and the RCCI classification (correlation coefficient, $r_p = 0.405$, $p < 0.05$, $n = 18$). Therefore, it indicates there is a relationship between the low connectivity and the flooded towns.

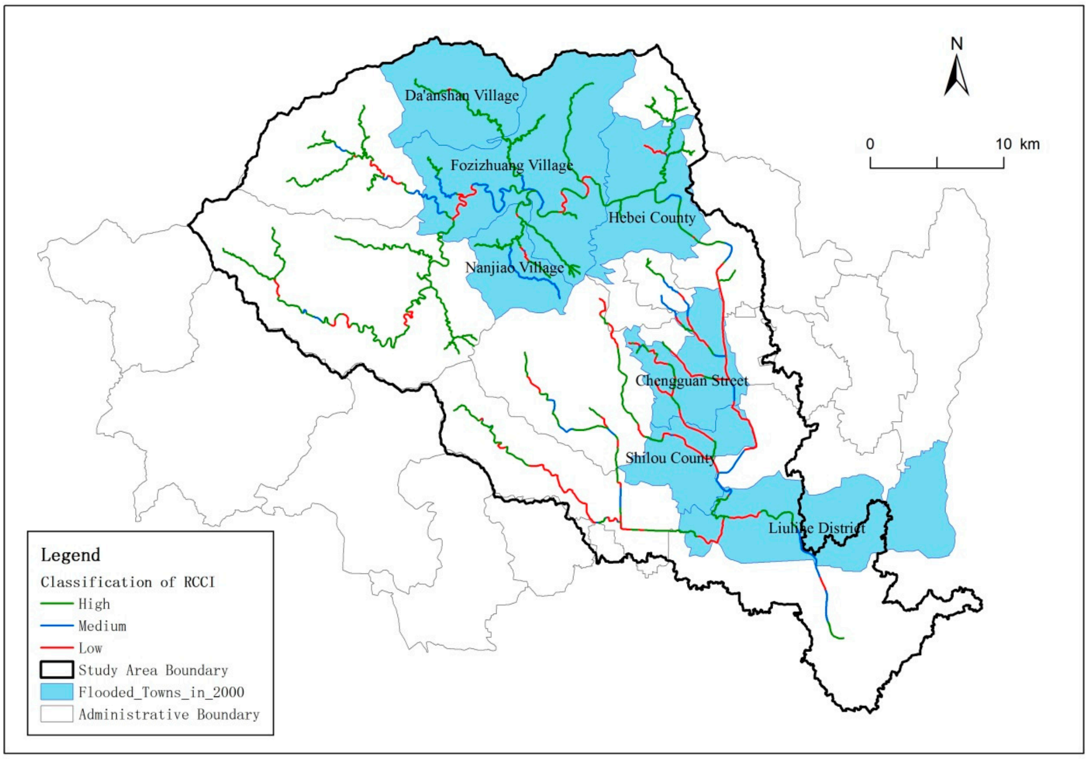



**Figure 7.** RCCI model validation by the flooded town data of 4 July 2000.

The greatest flood hazard in the past 50 years happened due to the heavy rain in Fangshan District on 21 July 2012. Flooded tributaries included the Zhoukoudian River, Xiekuo River, Dongsha River, Mapaoquan River, and Mangniu River, where the RCCI values are small. The Pearson correlation between the RCCI classification of each tributary and the binary variable of whether the tributary is flooded is also carried out by SPSS 19.0. The rules are set the same with the above. Results show that there is a medium correlation between the flooded tributary and the RCCI classification (correlation coefficient, $r_p = 0.539$, $p < 0.01$, $n = 23$). Therefore, it also indicates there is a relationship between the low connectivity and the flooded tributaries.

It can be concluded that there is a certain correlation between RCCI and the town/river flooded disaster. The smaller the RCCI value, the more obstructed the river channel, the larger possibility of overtopping, and the more vulnerable the town/river is to flood disasters. This also precisely verifies the rationality of the proposed method in reflecting the river channel connectivity to some extent.

### *4.4. Scenario Results*

The flood events just act as a verification of the results of the proposed model. To some extent, flood disaster might happen when the barriers exist in the river channel because the river flow may pass from the main channel into the floodplain [9]. Through Sections 4.2 and 4.3, low connected tributaries are in 41%, which may result in a flood risk. To guide fluvial environment planning from the perspective of reducing flood hazard, six scenarios, A-F, are designed to evaluate how the channel connectivity would change under different barrier removal scenarios. Scenario A assumes that all tributaries have no barriers in Dashi Watershed (RCCI of 1.00; baseline); in scenario B-F, submersible bridges, sediment siltation, illegal buildings, reservoirs, and dams are removed to recalculate the RCCI of tributaries, respectively. Using the detailed method in Section 3.3, the RCCI values of scenarios A-F are shown in Table 5. Compared with actual RCCI, an appropriate and quantitative planning scheme for each tributary is obtained. For example, when sediment siltation in Mapaoquan River, Xisha River, Zhoukoudian River, Xiekuo River, and Dongsha River are removed, the RCCI of them would be improved to 0.960, 0.930, 1.000, 0.998, and 0.980, respectively. Therefore, it can be concluded from the scenario-based analysis that removing sediment siltation provides the greatest decrease to flood risk in these rivers, and the most effective planning scheme for these rivers is dredging the river channel. When illegal buildings in Wajing River, Shuangquan River, Baishikou River, Nanjiao River Liulin River, Shibanfang River, and Da'anshan River are removed, the RCCI of them would be improved to 0.960, 1.000, 0.970, 0.949, 0.970, 0.996, and 1.000, respectively. Thus, to improve river connectivity and reduce potential flood risks, the most effective river restoration and planning strategy for these tributaries is to remove illegal buildings.

**Table 5.** RCCI values at different scenarios.

| Name | Scenario A | Scenario B | Scenario C | Scenario D | Scenario E | Scenario F | Actual RCCI |
|---|---|---|---|---|---|---|---|
| Beiyu River | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| North River | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| Baikoumen River | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| Shangshuiyu River | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| Yanglin Rvier | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| Qiulinpu River | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| $Shijiaying_1$ River | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| Jinjitai River | 1.000 | 0.997 | 1.000 | 0.999 | 1.000 | 1.000 | 0.996 |
| Yuzi River | 1.000 | 1.000 | 0.990 | 0.990 | 0.990 | 0.990 | 0.990 |
| Zhongjiao River | 1.000 | 0.988 | 0.990 | 0.998 | 0.990 | 0.990 | 0.987 |
| Beijiao River | 1.000 | 1.000 | 0.990 | 0.990 | 0.990 | 0.990 | 0.990 |
| Simatai River | 1.000 | 0.990 | 0.990 | 1.000 | 0.990 | 0.990 | 0.990 |
| Da'anshan River | 1.000 | 0.990 | 0.980 | 1.000 | 0.980 | 0.980 | 0.980 |
| $Shijiaying_2$ River | 1.000 | 0.989 | 0.980 | 0.998 | 0.980 | 0.980 | 0.980 |
| Shibanfang River | 1.000 | 0.972 | 0.970 | 0.996 | 0.970 | 0.970 | 0.970 |
| Mao'ershan River | 1.000 | 0.930 | 0.930 | 0.950 | 0.980 | 0.930 | 0.930 |
| Liulin River | 1.000 | 0.921 | 0.920 | 0.970 | 0.945 | 0.920 | 0.920 |
| Nanjiao River | 1.000 | 0.904 | 0.902 | 0.949 | 0.945 | 0.902 | 0.902 |
| Baishikou River | 1.000 | 0.903 | 0.930 | 0.970 | 0.900 | 0.900 | 0.900 |
| Dashi River | 1.000 | 0.900 | 0.930 | 0.920 | 0.940 | 0.894 | 0.890 |
| Dongsha River | 1.000 | 0.881 | 0.980 | 0.890 | 0.880 | 0.880 | 0.880 |
| Shuangquan River | 1.000 | 0.881 | 0.880 | 1.000 | 0.880 | 0.880 | 0.880 |
| Wajing River | 1.000 | 0.878 | 0.910 | 0.960 | 0.876 | 0.880 | 0.876 |
| Xiekuo River | 1.000 | 0.871 | 0.998 | 0.870 | 0.870 | 0.870 | 0.869 |
| Zhoukoudian River | 1.000 | 0.860 | 1.000 | 0.860 | 0.860 | 0.860 | 0.858 |
| Dingjiawa River | 1.000 | 0.854 | 0.900 | 0.852 | 0.940 | 0.852 | 0.852 |
| Xisha River | 1.000 | 0.793 | 0.930 | 0.810 | 0.810 | 0.789 | 0.789 |
| Mapaoquan River | 1.000 | 0.779 | 0.960 | 0.778 | 0.800 | 0.778 | 0.778 |
| Mangniu River | 1.000 | 0.744 | 0.810 | 0.760 | 0.870 | 0.743 | 0.743 |

## 5. Discussion

### *5.1. The Application of RCCI in Other Rivers*

The key to this work is that the proposed RCCI model is based on the time accessibility method concept, which is applied to the river channel for the first time. The time accessibility is fundamentally reasonable to be applied for assessing the river channel connectivity by considering the barrier issue. The concept of RCC and the definition of RCCI are simple to understand and they could be used in other rivers.

On the other hand, as the study case of this paper, the Dashi Watershed is a representative suburban watershed of northern China. This paper has classified and weighted these barriers in Table 1. It could be used in such small-scale suburban watersheds directly. Moreover, Table 2 in the manuscript is the interpretation sign, which can be used as the standards to extract barriers from remote sensing data in a certain river basin.

### 5.2. Verification of RCCI Assessment Results by Flood Data

The best method for the RCCI validation might be using the monitoring data of the river flow time in a watershed [40,41]. However, the flow speed data could not be obtained as the river flow in the semiarid areas, like Dashi Watershed, due to its frequent drying up. Therefore, the RCCI validation could be conducted from the potential application of RCCI, such as the relationship to flood disasters. The danger of flooding through levee collapse or overtopping occurred in Zhoukoudian River, Xiekuo River, and Mangniu River in the heavy rain on 21 July 2012 [33]. Barriers, such as sediment siltation in the river channel, decreased the cross-sectional area of a channel. River flow would overtop to the floodplain if there is a large amount of discharge, which might result in a flood hazard. Therefore, results of the RCCI are validated by two historical flood events. As seen from Figure 7, the RCCI in the flooded town indicates a low connected level, and it might be reasonable that the RCCI could explain the flood hazard to some extent. Nevertheless, most segments of the flooded town within a mountainous area are highly connected, and the RCCI is not effective on these places. The RCCI value represents the river channel connectivity directly and it is only one of multiple impacts linked with flood hazards. Some key factors, such as precipitation, hydrological regime, and geomorphology, might potentially cause flood hazards [42–44]. It can be concluded that the proposed RCCI has certain limitations in the application of flood hazard prediction. RCCI should be improved by adding other factors according to actual demands in specific applications.

### 5.3. Reliability Analysis Based on the Time Accessibility Method

The proposed RCCI model is established based on the time accessibility method. Although the flow speed variable is introduced in Equation (2), the river flow speed is affected by various variables, such as elevation, slope, and roughness of a river channel. There are two hypotheses in the proposed model: (1) The time of the river flow going through the cross-section of a river channel increases when the cross-sectional area decreases due to an existing barrier if a barrier is the key issue for the river flow to go across; (2) river flow speed is assumed to be the same with or without a barrier in a channel. The RCCI value equals to the ratio of the time of a river channel without any barriers to the same river channel with some barriers, hence the river flow speed variable would be eliminated from the equation due to the above two hypotheses. Therefore, the only time difference between a river channel with barriers and without barriers is the increased time due to the presence of barriers. The flow speed might change after the river flow passes through the existing barriers. A constant, $K$, can be set theoretically as the ratio of the flow speed before and after passing through a barrier no matter how the field flow speed changes, though the $K$ value varies largely within the different rivers and different kinds of barriers. As the RCCI value is a ratio value, the $K$ value is assumed to be 1 for the convenience of calculation in this paper. Therefore, RCCI of different rivers in the study area is compared and analyzed under the equal standard. A future work will focus on how to get the actual $K$ value for each barrier by using the field survey method for the improvement of the current RCCI model.

The methodology proposed in this paper is an original metric of river channel connectivity. It measures a structural connectivity of the river channel from the longitudinal dimension. The river channel is set as the object; and river flow is introduced into the construction of the RCCI model. However, flow speed is eliminated in the calculation. The proposed model is a pure structural connectivity metric based on the structures of the river channel and barriers. In contrast, when considering barriers, previous hydrological longitudinal connectivity researchers prefer to set the river flow and aquatic biological communities as the study object [1,21,26]. The Dendritic Connectivity

Index (DCI) is a popular assessment index when setting aquatic biological communities as the study object. When setting river flow as the study object, Grill et al. modified the DCI model by combing the HydroROUT model [21]. The hydrological model needs a discharge database, which limits the application in the semiarid areas, like Dashi Watershed. The data for the RCCI model is easily obtained and the assessment method based on time accessibility method is understandable. The proposed method in this paper is suitable in the semiarid areas and may be modified to be used in other areas.

### *5.4. The Weakness of the RCCI Model*

It seems that the use of the Delphi method makes it difficult to apply the RCCI model to other rivers because of the expert knowledge on barrier impacts. In Section 5.1, we have discussed that the Dashi Watershed is a representative suburban watershed of northern China; Table 1 could be used in other rivers directly. However, factors affecting the unobstructed degree of a river channel are not limited to the four categories in this paper. The channel morphology, such as lithology, elevation, and slope, are all key factors to the channel connectivity [10]. The above factors are not included in the RCCI calculation as this paper is focused on analysis of the various physical barriers on RCC. Nonetheless, sediment siltation, submersible bridges, and other artificial blocking factors are common barriers in the suburb of northern China. Considering hydrologic features, such as hydrologic topography, gradient, and rainfall, could be taken as further study on RCCI.

## 6. Conclusions

Reduced river channel connectivity can result in wide impacts on ecology and hydrology along a river or within a watershed. The proposed RCCI model provides a simple and convenient method for river channel connectivity assessment without any hydrological database only from the perspective of barriers. Furthermore, it keeps wide potential applications for the future impact assessments linking with hydrology and ecology, which gives rise to more new assessment indices modified from the core idea of RCCI. In this paper, RCCI presents a new vision to address fluvial planning problems from the perspective of reducing flood hazards, and it can guide river regulation and determine restoration priorities of a river channel for the government. This paper applies the RCCI model to Dashi Watershed in suburban Beijing, China. Results show that submersible bridges and sediment siltation are the main barriers in the watershed, while the sediment siltation is more common in the plain area. The segment RCCI indicates the spatial variety of river connectivity along each river channel and reveals the corresponding barrier structure. The range of tributary RCCI is from 0.74 to 1.00 in Dashi Watershed, which decreases from the Beiyu River to the Mangniu River. Assessment results from both tributaries and segments indicate that the RCC in the northwest mountainous areas are generally better than that of the south middle plains. The validation of the RCCI model shows that the RCCI can reflect the connectivity of the river channel. Based on scenario-based evaluation, effective restoration measures for each tributary to improve its connectivity is obtained, which provides useful information to support the decision making of planners in general and flood managers. For example, the most effective planning scheme for Mapaoquan River, Xisha River, Zhoukoudian River, Xiekuo River, and Dongsha River is dredging the river channel. For Wajing River, Shuangquan River, Baishikou River, Nanjiao River Liulin River, Shibanfang River, and Da'anshan River, removing illegal buildings will improve their connectivity effectively, and reduce flood risks.

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