

Article

Analysis of Basin Morphologic Characteristics and Their Influence on the Water Yield of Mountain Watersheds Upstream of the Xiongan New Area, North China

Hui Yang  and Jiansheng Cao *

Key Laboratory for Agricultural Water Resources, Hebei Key Laboratory for Agricultural Water-Saving, Center for Agricultural Resources Research, Institute of Genetics and Developmental Biology, Chinese Academy of Sciences, Shijiazhuang 050001, China; yangh.14b@igsnr.ac.cn

* Correspondence: caojs@sjziam.ac.cn

Abstract: In this study, based on the DEM, we extracted the drainage networks and watersheds of the Daqing River with ArcGIS, investigated the basin characteristics and the differences in their spatial distributions and analyzed the relations of the drainage density with some surface conditions and how the drainage density influenced the water yield. The results suggested a power function between the mainstream length and drainage area, showing that with the increase in basin area, the basins became longer. The result of the power function between the relief and drainage area with negative exponent values means the relief changed more slowly with increasing basin area. The values of the circularity ratio and elongation ratio indicate that the basin shape of the mountain watersheds in the Daqing River was narrow and predisposed to flooding during periods of heavy rainfall. The orders of the streams in the mountain watersheds ranged from five to seven. The average bifurcation ratio of those nine mountainous watersheds reveals the order of the $u + 1$ rivers in each basin of the Daqing River was on average 4 times larger than that of order u rivers. The drainage density (D_d) was high in the north and low in the south of the Daqing River. Rainfall was negatively correlated with drainage density, but the correlation between them was not significant at the 0.05 level. Drainages developed in places with poor vegetation cover. The drainages in the southwest, north and west developed considerably, while drainages in the east and southeast did not develop much. Yet, the available data showed the impact of the watershed area, elongation ratio and drainage density on the water yield was not significant. In contrast, there was a significant positive correlation between channel slope and the water yield modulus. The hypsometric integrals and the relation between drainage density and hypsometric integral suggest that the landform evolution of the mountain basins along the Daqing River were in the old stage with no further increase trend of drainage density in the future.

Keywords: Xiongan New Area; stream network; drainage density; water yield; mountain river



Citation: Yang, H.; Cao, J. Analysis of Basin Morphologic Characteristics and Their Influence on the Water Yield of Mountain Watersheds Upstream of the Xiongan New Area, North China. *Water* **2021**, *13*, 2903. <https://doi.org/10.3390/w13202903>

Academic Editors: Yaning Chen, Bin He, Zhi Li, Gonghuan Fang, Weili Duan and Athanasios Loukas

Received: 12 August 2021

Accepted: 9 October 2021

Published: 15 October 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Mountain rivers are important corridors that link upland and lowland environments and mediate the supply, transport, and storage of organic and inorganic materials [1,2]. Mountain rivers play an important role in flood control and perform other functions, such as conserving water resources, regulating the microclimate, and maintaining water ecology and biodiversity. However, they often face problems such as short-term flood responses, water shortages in the dry season, and river channel artificialization [3].

Mountain rivers are often confined by immobile topographic features, such as bedrock and large boulders with channel gradients commonly exceeding 1% [2,4,5]. This leads to these types of rivers having steep hydraulic rating curves that initiate rapid transport of small sand and gravel fractions within the large structural matrix formed by large, century-scale floods nested within an even larger geological context [2,6]. Stream network

characteristics are the basic parameters of hydrological and water environment research, as well as one of the important contents of terrain analysis and hydrological analysis. A stream network is a conduit that links the upstream catchment processes and its impacts on the downstream streams and floodplains [7]. The stream network structure is established through its branches, confluence and bifurcation. Basin parameters, such as river type, drainage density (D_d), stream number and length, affect the process of rainfall and runoff [8]. While D_d is defined as the ratio of total channel length in a catchment to the total catchment area [9], it is a scale-independent parameter that is influenced by the accurate representation of topography, which is primarily represented in the form of digital elevation models (DEMs). A plethora of studies have sought to understand how the resolution of topographic data governs basin parameters [7,10–12] and the algorithm for extraction of river networks, including the flow direction algorithm and convergence threshold determination [8,13]. In fact, river network structures and their embedded hydrological dynamics play an important role in ecohydrological processes [14]. Therefore, after obtaining stream networks from DEMs, further studies need to reveal the relationship between the features of extracted drainage networks and other natural factors based on the widely available and easily accessible DEM, the significance of the characteristics of stream networks in typical rivers and how the underlying geomorphic processes governing the initiation, growth and development of channel networks, not just how the features of the DEMs affect stream networks, for example, the resolution.

The mountain rivers in China are seasonal and have the following characteristics [15]: they have steep slopes with short runoff generation and confluence times [16]; they are subject to serious soil and water erosion, which increases the pressure on river flood controls [17]; and they are associated with strong river channel scouring, simple river channel forms and vegetation, and severe riverbed erosion [18]; and they experience cold, long winters, low rainfall with uneven seasonal distribution, and severe non-point source pollution that is difficult to control during flood and snowmelt periods [3].

The plan to construct the Xiongan New Area, which was reported by China's Central Committee and State Council, is regarded as "a strategy crucial for the millennium to come" by the Chinese government (<http://politics.people.com.cn/GB/n1/2017/0401/c1001-29185929.html>, in Chinese; access date: 8 October 2021). The Xiongan New Area prioritizes eco-environmental protection and green living environments. One noticeable characteristic of Xiongan is that it is located next to Baiyangdian Lake, the largest natural freshwater wetland on the semiarid North China Plain (NCP), which is known as the "Pearl of North China" and the "Kidney of North China" [19–21]. The lake is located in the middle and lower reaches of the Daqing River basin, which is a typical mountain basin in northern China and has an important impact on the central North China Plain in terms of climate regulation and environmental characteristics [22]. Due to the steep terrain, thin soil cover, poor vegetation and fan-shaped tributary distribution of the area and the characteristics of high intensity, short duration, uneven distribution and sudden occurrence of the storm events that occur in the Daqing River basin, floods with high and concentrated peaks with short lead times are often triggered [23], which easily cause significant flooding and serious soil erosion. The New Area is located in a region of slow flooding and stagnation on the Daqing River, and its current flood recurrence period is only one in ten years; the area has suffered many flood disasters [24]. Sudden flash floods cause a large amount of coarse sand gravel to pile up in the downstream channel, destroying villages, burying farmland and causing siltation of river channels, which all bring considerable economic losses to the local people.

Previous studies about the Daqing River focus on the water environment (Xu and Wang, 2000) and the runoff and sediment characteristics [25–28]. Therefore, the objective of this paper is to study the characteristics of drainage networks and watershed geometry of the mountain watersheds of the Daqing River; the relations of drainage density with topography, vegetation coverage and surface material composition; and discuss the implications of indices of drainage network and watershed geometry for water yield and watershed evolution. Our results may provide some basic watershed characteristic data for other

scholars in this basin study and a reference for further study of the water cycle process and effective utilization of water resources in the Daqing River basin and a scientific basis for the formulation of flood control policies and water conservation in the Xiongan New Area.

2. Study Area

The Daqing River is a primary tributary of the Haihe River in northern China and is located at $113^{\circ}34'3''$ – $117^{\circ}46'7''$ E, $38^{\circ}4'42''$ – $40^{\circ}3'2''$ N. The area of the watershed is $43,060 \text{ km}^2$, with a length of 275 km, an average width of 156 km and an average slope of 5.22%. The average annual runoff is $4.3 \times 10^8 \text{ m}^3$. According to the Water Resource Zoning Map of the Haihe River basin, provided by the Haihe River Water Conservancy Commission (HRWCC), the Daqing River basin mainly consists of two geomorphic units: the upper reaches of the west are mountainous areas that account for 43% of the basin area, and the middle and lower reaches of the east are plains areas (Figure 1). The river basin is fan-shaped and divided into northern and southern branches. The southern branches of the mountain basin are mainly composed of six tributaries, including the Ci River (CIR), Sha River (SR), Tang River (TR), Jie River (JR), Cao River (CR) and Bao River (BR). After entering the plain, the Ci River and Sha River converge into the Zhulong River. The northern branches are mainly composed of four tributaries, namely, the Zhongyi River (ZYZ), Beiyi River (BYR), Juma River (JMR) and Dashi River (DSR). After entering the plain, the Juma River divides into two branches, namely, the Beijuma River and Nanjuma River. These ten tributaries flow into Baiyangdian Lake. The terrain of the basin is higher in the northwest and lower in the southeast, with an elevation difference of nearly 2800 m (Figure 1).

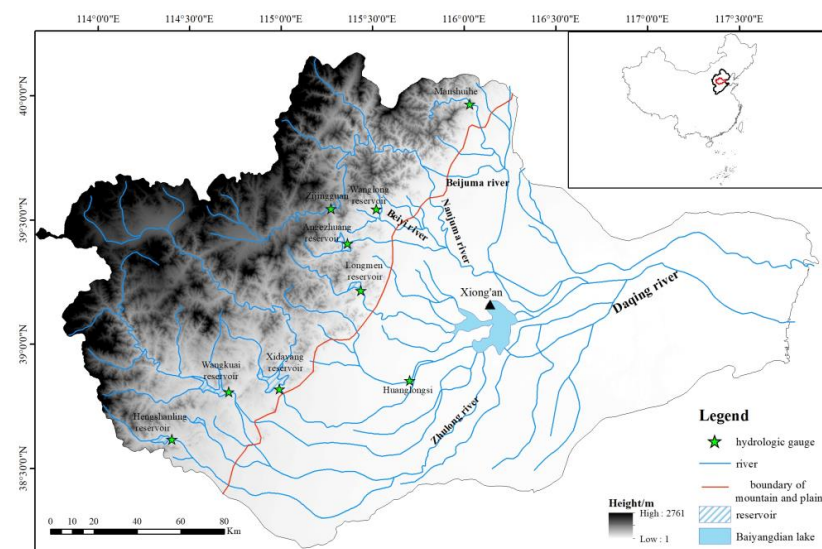


Figure 1. Schematic diagram of Daqing River basin.

The Daqing River has a warm temperate monsoon climate with distinct seasons and an uneven distribution of precipitation during the year that is mainly concentrated from July–September. The average annual rainfall ranges from 500–700 mm and often comes in the form of heavy rain in July and August. The exposed lithology on the surface includes granite gneiss, limestone and loose quaternary deposits. The landform is dominated by mountains and basins. Coarse bone soils are the main soil in the mountains and loess covers the hill platform around the basin [29].

3. Data description and Methods

3.1. Data

The topographic maps of the study area projected to produce a raster DEM with a resolution of $30 \text{ m} \times 30 \text{ m}$ were downloaded from the Geospatial Data Cloud (<http://www.gscloud.cn/>, access date: 8 October 2021). The normalized differential vegetation index

(NDVI) products for the year 2018 with a 1 km spatial resolution were also downloaded from the Geospatial Data Cloud (<http://www.gscloud.cn/>, 8 October 2021). Soil data with a resolution of 1 km were extracted from the 1:1,000,000 Soil Database of China downloaded from the Nanjing Institute of Soil Science, Chinese Academy of Sciences (<http://www.issas.cas.cn/>, 8 October 2021). The rainfall and runoff data of nine hydrology gauges, including the Hengshanling reservoir station in the Ci River, Wangkuai reservoir station in the Sha River, Xidayang reservoir station in the Tang River, Longmen reservoir station in the Cao River, Huanglongsi station in the Jie River, Angezhuang reservoir station in the Zhongyi River, Wanglong reservoir station in the Beiyi River, Zijingguan station in the Juma River and Manshuihe station in the Dashi River (Figure 1), were from the hydrological yearbook of the Haihe River basin of China, collected by HRWCC.

3.2. Method

3.2.1. The Extraction of River Networks

Based on the DEM, the hydrological analysis tool set in the spatial analysis module of ArcGIS10.5 software was used to extract the river network through a series of processing steps, including filling depression, calculating flow direction and flow confluences and accumulations. The accumulation area threshold was 0.1 km², which is the minimum accumulation area for a bedrock channel with hydraulic erosion in the main channel [30]. Additionally, the threshold is the lower limit of the gullies whose length is larger than 400 m and width is more than 100 m in the loess hilly region [31].

3.2.2. The Variables for Expressing Basin Form

The morphological feature parameters included watershed geometry (area, main stream length, perimeter, circularity ratio and elongation ratio) and drainage morphology (relief, total stream length and drainage density). The detailed calculation methods for those parameters are shown in Table 1 [8].

Table 1. Detailed meaning and calculation method of morphological feature parameters in the Daqing River.

Parameters	Symbol and Definition	Unit	Reference
Drainage area	A	km ²	
Main stream length	L	km	
Drainage perimeter	P	km	
Circularity ratio	$R_c = 4\pi A/P^2$	/	[32]
Elongation ratio	$R_e = 2(A/\pi)^{1/2}/L$	/	[33]
Relief	H	m/km	
Total stream length	$\sum L$	km	
Drainage density	$D_d = \sum L/A$	km/km ²	[9]

According to the satellite images and field investigations, only the land surface of the upper mountain watersheds is rigged with dense drainages. Therefore, the drainage density in the upper mountain watersheds is meaningful for characterizing the broken degree of the land surface and is investigated in this study. For utilization of the information of the soil data, which has a spatial resolution of 1 km, the drainage density was calculated through ArcGIS 10.5 with a 1 km × 1 km grid unit. The coarse grid distribution of drainage density was converted to its continuous spatial distribution through the Ordinary Kriging method for calculating the areas of different levels of drainage density.

3.2.3. Topographical Attributes

Topographical attributes include the slope gradient and aspect. The catchment slope (slope, degrees) and aspects were calculated using ArcGIS and the algorithm proposed by Burrough and McDonnell [34].

3.2.4. Hypsometric Integral

The hypsometric integral curve shows the basin topography on the coordinate with the ratio of horizontal area between the contour and the upper perimeter (a_i , km²) to the total drainage basin area (A , km²) as the abscissa values ($x_i = a_i/A$) and the ratio of height of the contour above basin outlet (h_i , m) to the total height of the basin (H_t , m) as the ordinate values ($y_i = h_i/H_t$), expressed by the function $y = f(x)$. The integral of this function is named a hypsometric integral and has a value between 0 and 1 [35]. The hypsometric integral (HI) was calculated as follows,

$$HI = \int_0^1 f(x)dx \quad (1)$$

where x is the ratio of the horizontal area between the contour and the upper perimeter (km²) to the total drainage basin area (km²).

3.2.5. Analysis of Drainage Density

As a unique property of the landscape, D_d is related the underlying geomorphic processes acting in a catchment based on its topography [36]. Usually expressed as the ratio of total channel length to total catchment area [9], D_d is controlled by the local lithology [37], topography [38], vegetation [39,40] and regional climatic patterns [41,42]. Therefore, we analyzed the relationships between drainage density and precipitation, surface material composition, vegetation coverage and topography. The software of Statistical Product and Service Solutions (SPSS) and Microsoft Excel were used to analyze the correlations and trends.

4. Results and Discussion

Because of the small mountainous area of the Bao River, we extracted the river network and watershed boundaries of the other nine tributaries in mountainous areas from a DEM, including the Ci River, Sha River, Tang River, Jie River, Cao River, Zhongyi River, Beiyi River, Juma River and Dashi River (Figure 2).

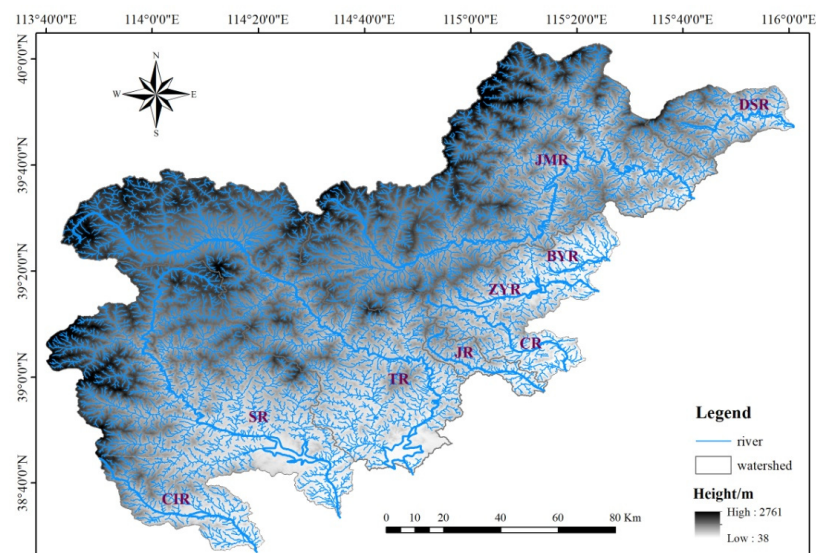


Figure 2. Watersheds of the mountainous areas in the Daqing River generated from a DEM (rivers are shown by abbreviated names: CIR—Ci River, SR—Sha River, TR—Tang River, JR—Jie River, CR—Cao River, ZYR—Zhongyi River, BYR—Beiyi River, JMR—Juma River and DSR—Dashi River).

4.1. Watershed Geometry

Many watershed geometry features are related to the drainage area [43]. We analyzed the correlation between the main stream length (L , km) and area (A , km²) (Figure 3),

relief (H , m/km) and A (Figure 4). Both relationships were power exponents, and the variation of trends were significant ($L = aA^b$, $b = 0.64\text{--}1.87$, $R^2 = 0.95\text{--}0.99$, $p < 0.01$; $H = cA^d$, $d = -1.36\text{--}0.33$, $R^2 = 0.82\text{--}0.99$, $p < 0.01$); namely, with the increase of area, the main stream length increases and relief decreases significantly, respectively. If L was proportional to $A^{0.5}$, the geometric morphology upstream was similar to that downstream [44]. As shown in Figure 3, L and A were positively correlated, but the minimum b value was 0.64, which was greater than 0.5. Therefore, we believe that the basin forms of the mountain watersheds in the Daqing River change along the channel. With the increase in basin area, the basins became longer. H and A were negatively correlated, and the relief changed more slowly with increasing basin area. From Figures 3 and 4, except for the Dashi River, the b value and d value of the other eight rivers were close, which means that their basins had similar forms.

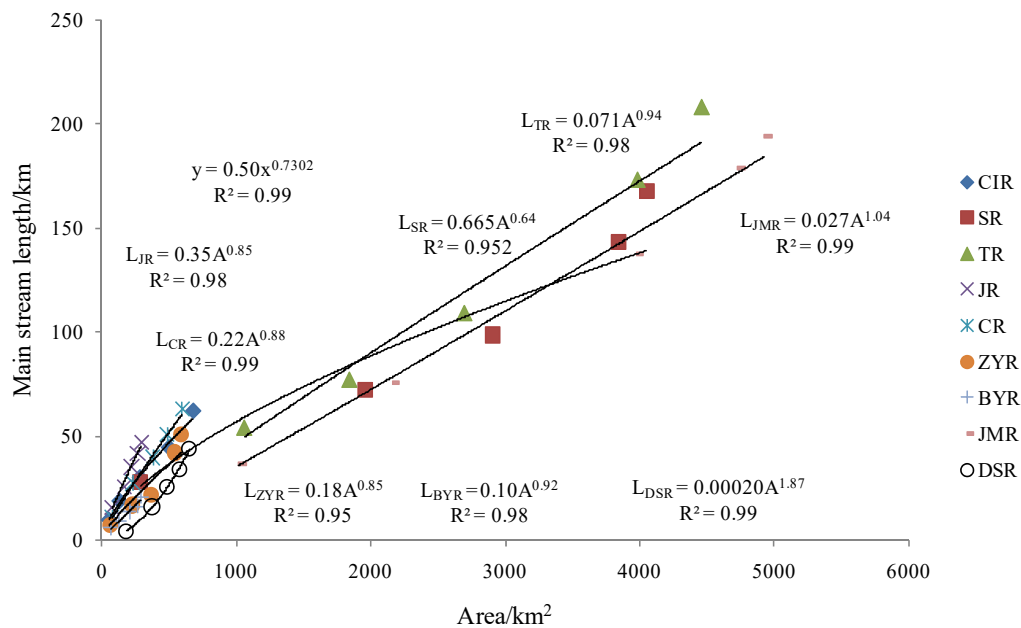


Figure 3. Correlation of the main stream length and area of mountain watersheds in the Daqing River. (referring to Figure 2 for the abbreviated names of rivers).

There are many indices expressing the basin shape [44], but only two parameters are widely used. They are the circularity ratio and elongation ratio (Table 1). The circularity ratio (R_c) and elongation ratio (R_e) were additional parameters that were used to describe the watershed geometry morphology. If the drainage basin shape is round, the value of R_c and R_e should be equal to 1 and 1.275, respectively; if the shape is square, R_c and R_e should be 0.785 and 1.128. With the increase in stream length, R_c continues to decrease and R_e approaches zero, and the shape becomes narrower and longer [32,33]. The R_c of mountain watersheds in the Daqing River ranged from 0.14 to 0.36, and the values of R_e were 0.36–0.94. We can conclude that the basin shape of the mountain watersheds in the Daqing River was narrow. According to Liu [45], the flood confluence time is short for a narrow basin. Therefore, the small basin circularity ratio of the Daqing River is favorable to the formation of high flood peaks, which easily delivered a large amount of runoff from the basins during the rainy day to the Xiongan New Area.

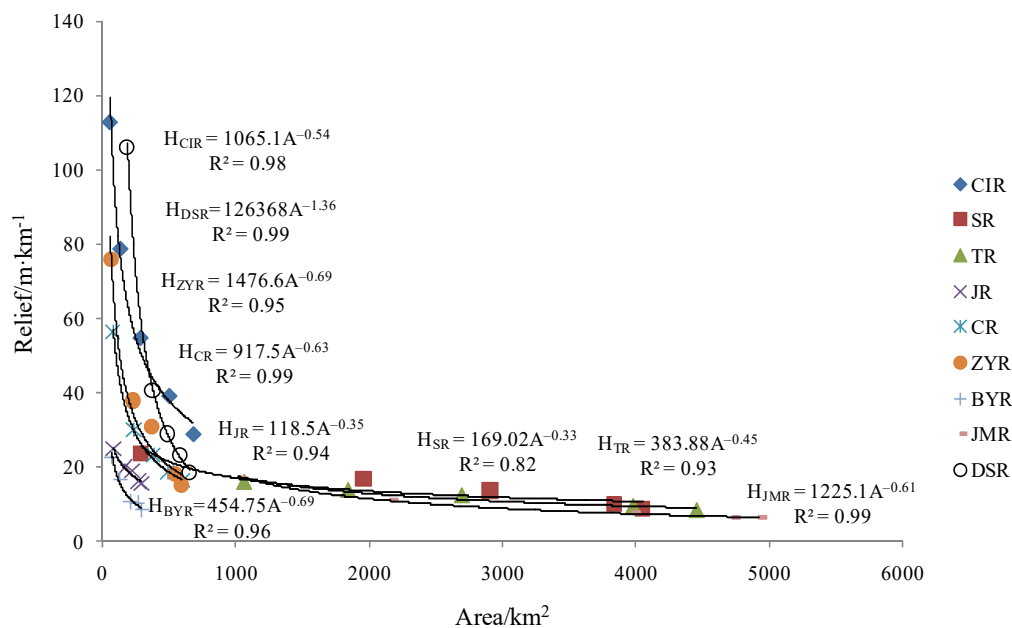


Figure 4. Correlation of relief and area of mountain watershed in Daqing River. (referring to Figure 2 for the abbreviated names of rivers).

4.2. River Network Morphology

As mentioned above, the upper and lower reaches of the Daqing River have distinctive landforms. In the lower reaches of the Daqing River, there are no tributaries on both banks. Thus, the river network morphological characteristics of the upper reaches of the Daqing River, including river bifurcation ratio and drainage density were analyzed here.

4.2.1. Stream Order

The ordering scheme proposed by Strahler [43] was used here. The bifurcation ratio $R_b = N_u/N_{u+1}$, where N_u and N_{u+1} denote the number of stream segments of order u and $u+1$, respectively. Watersheds with different natural geographical conditions tend to have different drainage bifurcation ratios [46]. For the watersheds in flat or hilly and gully regions, the R_b is close to 2; for the watersheds in mountainous regions, it is 3–5. The R_b in the mountain area is larger than that in the plain area. The R_b grows with the development of a drainage system [44].

Strahler [43] pointed that, except for the areas with hard geological substrata, the differences of R_b between regions were small. Morisawa [47] proved that the R_b in fifteen small watersheds on the Appalachian Plateau was close to a constant. Therefore, the average drainage bifurcation ratio is the most reasonable parameter to reflect the drainage structure.

We ordered the extracted drainage network using the Strahler criterion [43]; namely, the primary finger-tip stream is the order I, and the new stream formed by the convergence of the two order I streams is the order II, and in this way, the streams in the whole basin will be ordered until the end. The channel that flows through the whole basin with the amount of water and sediment is called the highest order stream. Therefore, the stream orders of the mountain watersheds in the Daqing River ranged from five to seven. Specifically, the upper reaches of the Jie River and Beiyishui River were 5th-order streams, Ci River, Cao River and Dashi River were 6th-order streams, and the other four rivers were 7th-order streams. The average bifurcation ratio of nine rivers was calculated according to the stream order results. For mountain watersheds, the bifurcation ratio ranged from 3–4. The bifurcation ratio of areas with loose rocks, sparse vegetation, and heavy rainfall was high [46]. The average bifurcation ratio of those nine mountain watersheds was 3.8–4.8. In other words, the order of the $u + 1$ rivers in each basin of the Daqing River was on average 4 times larger than that of order u rivers.

4.2.2. Drainage Density

The drainage density of mountain watersheds in the Daqing River ranged from 2–2.3 km/km², and the spatial difference was small. According to the method mentioned above, we obtained a spatially continuous distribution of drainage density (Figure 5). D_d can be divided into four areas, including 0–1 km/km², 1–2 km/km², 2–3 km/km² and above 3 km/km². For mountain watersheds in the Daqing River, D_d was mainly distributed from 1–2 km/km² and 2–3 km/km²; specifically, the distribution areas of the southern watersheds fluctuated little, and the average distribution area of 1–2 km/km² and 2–3 km/km² was 71%. The 1–2 km/km² distribution area of the Juma River and Dashi River in northern watersheds increased significantly, and the average distribution area from 2–3 km/km² was 68%.

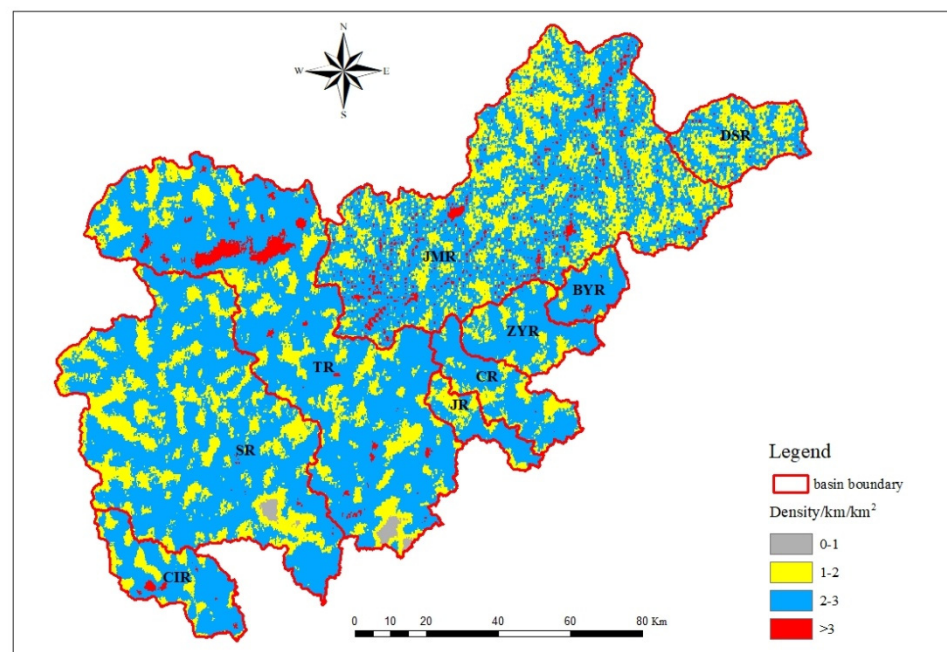


Figure 5. Spatial distribution of drainage density in mountain watersheds of the Daqing River (referring to Figure 2 for the abbreviated names of rivers).

4.3. Relationship between D_d and Rainfall and Vegetation Cover

Collins and Bras [40] summarized the feedback of vegetation and runoff under varying mean annual precipitation levels in a schematic representation showing an initial increase in drainage density in arid areas, followed by a decrease in semiarid regions and an increase in humid environments.

We drew rainfall and D_d with SPSS as follows: $D_d = -0.001x_{\text{rainfall}} + 2.501$ ($R = 0.542$, $N = 9$, $p = 0.132$). Rainfall is negatively correlated with drainage density, which agrees with the results of Collins and Bras [40] in semiarid regions, but the correlation between them did not show no significance at the 0.05 level. Although rainfall is the driving force behind gully development, for the small areas of mountain watersheds in the Daqing River, the average spatial variation in rainfall is not obvious.

Based on the change in NDVI in the upper reaches of each watershed in 2018, the correlation between the NDVI and drainage density was analyzed, and the correlation equation was obtained by SPSS as $D_d = -0.198x_{\text{NDVI}} + 1.227$ ($R = 0.738$, $N = 9$, $p = 0.02$). This indicated that gullies developed in places with poor vegetation cover but not in places with good vegetation cover. Of course, it is difficult to determine the causal relationship between these factors because there may be a positive feedback mechanism; that is, the development of gullies in places with poor vegetation is conducive to the development of

gullies, while the development of gullies, strong erosion and soil erosion inhibit the growth of vegetation [8].

4.4. Relationship between D_d and Soil Type

Basin lithology affects the extent of landscape dissection. Some variation in D_d by lithology type was also observed; the average D_d for shale and schist was well above the observed mean D_d , whereas the values for limestone and acidic volcanic rocks were well below the mean D_d [48]. The national soil database was used to obtain the classification of surface substances in the Daqing River (according to the classification standard of FAO90). The extracted river networks in the study area were superimposed on the soil type, and the distribution of gullies on each soil type was analyzed. The drainage density of each soil type was calculated (Figure 6). There are seven types of surface materials in mountain watersheds of the Daqing River, namely, cambisols (CM), luvisols (LV), regosols (RG), fluvisols (FL), leptosols (LP), anthrosols (Atc) and gleysols (Glm). The proportional distribution area of each soil type and the percentages of sand, silt and clay are shown in Figure 6. The main soil types in the mountain watersheds of the Daqing River were CM, LV and RG, with a distribution area of 91%. These three soil types all had a high content of sand gradation, approximately 50%, followed by silt. Clay made up the lowest proportion of the soil content, at approximately 20%.

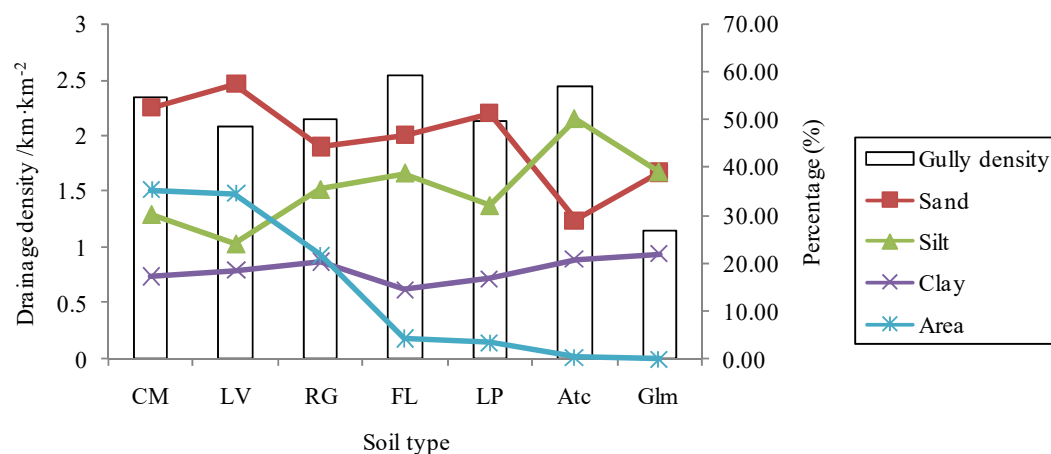


Figure 6. Drainage density of different soil types in mountain watersheds of the Daqing River (soil types are shown by abbreviated names: CM—cambisols, LV—luvisols, RG—regosols, FL—fluvisols, LP—leptosols, Atc—anthrosols and Glm—gleysols).

D_d was the lowest in Glm (1.15 km/km²) and the highest in FL (2.54 km/km²). For the other soil types, D_d was between 2 and 2.5 km/km². If soil particles are coarse and the permeability of the soil is high, the soil corrosion factor K value is low [49]. Melton [50] also found that D_d decreased with soil infiltration capacity. Figure 6 shows that the coarse gradation content of FL was the highest, at 85.5%. Thus, we can explain why the D_d of FL was the largest. The ability to resist soil erosion influences D_d . In addition, although the sand content of Atc was low, the D_d as relatively high, at 2.44 km/km². It can be concluded that soil erosion is affected not only by soil properties but also by anthropic factors.

4.5. The Drainage Density and Terrain

4.5.1. The Drainage Density on Different Slopes

The drainage density on different slopes is of particular interest as it helps to understand the relationship between erosion rates and patterns of channelization, which are critical for testing eco-geomorphic landscape evolution models [38,51].

Except for the maximum slope of the Juma River, which was 47°, the slopes of all other river basins were below 42°. We divided the slope into seven grades: 0–6°, 6–12°,

12–18°, 18–24°, 24–30°, 30–36° and over 36°. We calculated the distributions of gullies on different slope grades (Figure 7). The D_d in each study area decreased with increasing slope; there were no gullies with slopes higher than 36° in the Ci River, Jie River, Cao River, Zhongyi River or Beiyi River. In addition, the slopes of the Juma River and Dashi River mainly ranged from 6–18°, and the slopes in the other research areas were mainly distributed in the range from 0–12°, accounting for 62–81% of the whole mountain area. All gullies were concentrated between 0° and 12°, and the density value was above 2 km/km². When the slope was greater than 24°, the value of D_d decreased to 0.8 km/km² and below. The maximum D_d of all rivers was between 0 and 6°, but the value of maximum D_d was different. D_d was highest in the Dashi River (4.1 km/km²), followed by the Juma River (3.6 km/km²), and the rest of the rivers were all approximately 3.0 km/km². The D_d values were high in the north and low in the south.

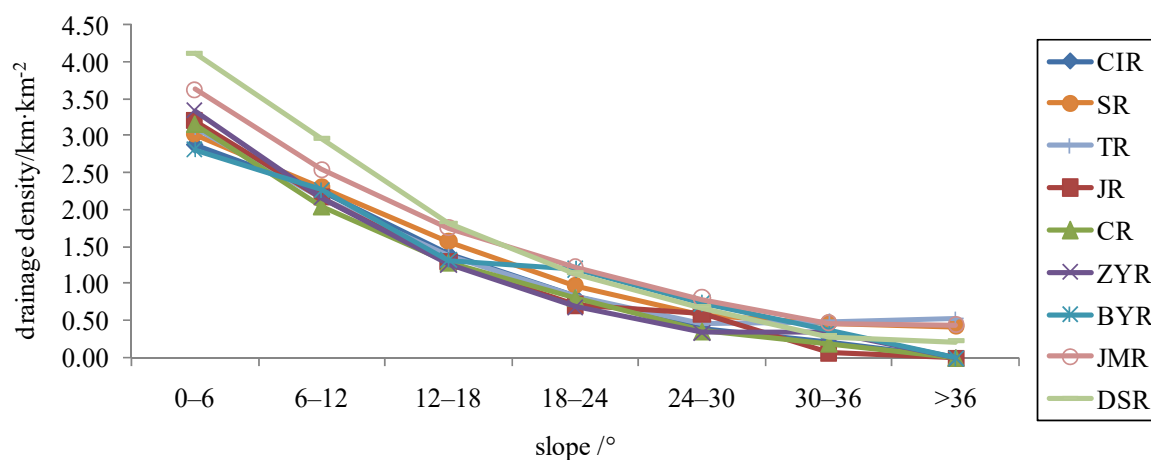


Figure 7. Distribution of drainage densities in different slopes of mountain watersheds in the Daqing River (referring to Figure 2 for the abbreviated names of rivers).

4.5.2. The Drainage Density in Different Aspect of Slopes

Aspect is an important terrain factor. Some studies have shown that the differences of rainstorms, rainfall erosivity, soil moisture and vegetation growth conditions make the soil erosion pattern and intensity in different aspects have obvious asymmetry [52]. For revealing the impacts of aspects on drainage development in the Daqing River, we divided the slope aspect into north (N), northeast (NE), east (E), southeast (SE), south (S), southwest (SW), west (W) and northwest (NW). There were differences in D_d on each aspect. The maximum D_d was 2.45 km/km², and the minimum was 1.63 km/km² (Figure 8). SPSS was used to compare and test the average D_d of each aspect, and they had values of 2.16 km/km² (N), 2.08 km/km² (NE), 2.03 km/km² (E), 2.02 km/km² (SE), 2.10 km/km² (S), 2.20 km/km² (SW), 2.16 km/km² (W) and 2.07 km/km² (NW). In the formation process of the gullies, there was a directivity of upstream erosion, subdivision of gullies and development of branches. Relatively speaking, the gullies in the southwest, north and west developed considerably, while gullies in the east and southeast did not develop much. The measurement coefficient of the linear correlation between drainage density and aspect was 0.44, $p = 0.042 < 0.05$, which passed the significance test. This indicated that aspect influenced drainage density, but the two did not have a simply linear relationship. This is because the difference in aspect results in differences in other influencing factors, such as rainfall and solar radiation, and the change in vegetation growth caused by different solar radiation leads to different development and evolution of erosion gullies [52].

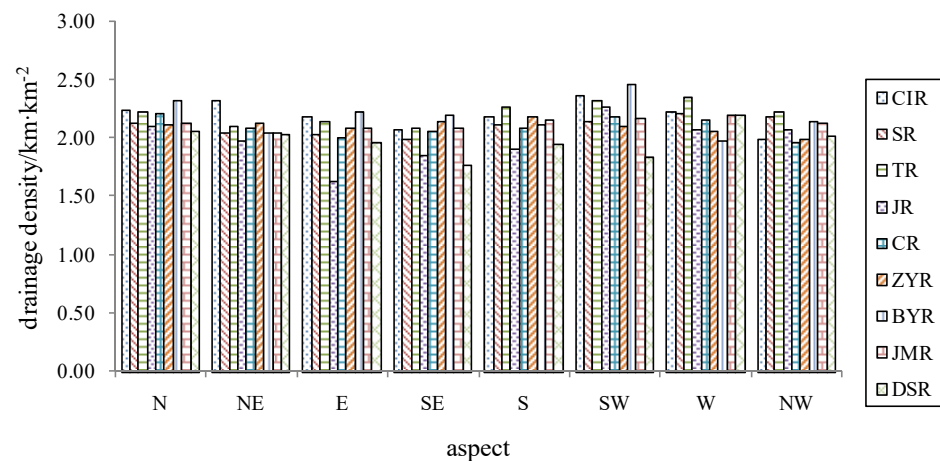


Figure 8. Distribution of drainage densities in different aspects of mountain watersheds in the Daqing River (referring to Figure 2 for the abbreviated names of rivers).

4.6. Indicative Significance of D_d

As shown in Figure 9, the HI values in the mountain basins of the Daqing River were all below 0.4. The correlation between HI and D_d was significant ($R = 0.87, p = 0.015$), but these factors were not simply linearly related. With the increase in HI, D_d first decreased and then increased. With 0.3 as the boundary, the closer HI was to 0.3, the smaller D_d was, and conversely, the larger D_d is. It was concluded that the landform of the mountain basin of the Daqing River is in an advanced stage of erosion development and that D_d will no longer increase [35].

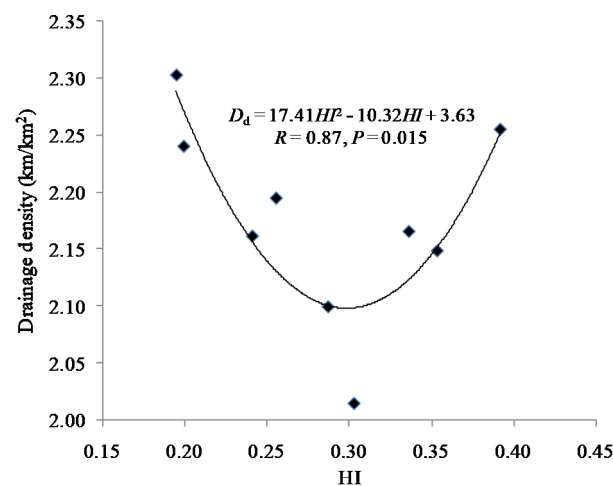


Figure 9. Correlation between the D_d and HI values of mountain watersheds in the Daqing River.

4.7. Effect of Channel Morphology on Water Yield

The measured runoff data of the Ci River, Sha River, Tang River, Cao River, Zhongyi River, Juma River and Dashi River were analyzed. Based on SPSS, the relationship between A and the water yield modulus ($S_r, 10^4 \text{ t/km}^2 \bullet \text{a}$) was $S_r = 5962.3/A + 7.3$ ($R = 0.421, N = 7, p = 0.346$). The relationship between R_e and S_r was $S_r = -528.6R_e^3 + 457.5R_e - 140.7$ ($R = 0.714, N = 7, p = 0.202$). According to the above two equations, although the correlation coefficient between S_r and A and R_e was not low, neither of them passed the significance level of 0.05.

The relationship between the slope of the channel ($S, \%$) and S_r was $S_r = e^{3.6-24.13/S}$ ($R = 0.78, N = 7, p = 0.039$). There was a significant positive correlation between these factors, that is, the greater the slope was, the greater the water yield.

Drainage density is not only an important index of watershed erosion but also an important factor affecting catchment confluence and sediment transport in gullies. The relationship between D_d and S_r was $S_r = 21.5 D_d - 33.27$ ($R = 0.214$, $N = 7$, $p = 0.645$). The water yield modulus was proportional to the drainage density; that is, the water yield modulus increased as the drainage density increased. Melton [50] also observed that D_d increased with increasing percentage of bare ground and runoff, but in this region, the two were not significantly correlated.

In addition, the impacts of other factors, such as rainfall, relief, slope gradient, etc., may produce large deviations in the constructed relations between specific water yield and indices of basin geometry, so the small number of available data samples do not prove the influence of basin geometry on water yield.

5. Conclusions

Based on the DEM, which had a resolution of 30 m, we extracted the river network of nine mountain watersheds in the Daqing River. The shape of the mountain watersheds in the Daqing River was narrow. The stream orders ranged from five to seven. The average bifurcation ratio was 3.8–4.8. The drainage density was in the range from 2–2.3 km/km², and there was low spatial variation.

Although rainfall is the driving force of gully development, for the small areas of mountain watersheds in the Daqing River, the average spatial variation of rainfall is not obvious. Rainfall was negatively correlated with drainage density, but the correlation between them was not significant at the 0.05 level. The correlation between NVDI and D_d indicated that gullies developed in places with poor vegetation cover but not in places with good vegetation cover. D_d decreased with increasing slope; it was highest in the Dashi River (4.1 km/km²), followed by the Juma River (3.6 km/km²), and the rest of the rivers had values of approximately 3.0 km/km². D_d values were high in the north and low in the south. The gullies in the southwest, north and west developed considerably, while gullies in the east and southeast did not develop much.

With 0.3 as the boundary, the closer HI was to 0.3, the smaller drainage density was, and conversely, the larger drainage density was. The landform of mountain basins in the Daqing River was in an advanced stage of erosion development, and the drainage density is no longer increasing. In addition, there was a significant positive correlation between the channel slope and water yield modulus, and the other watershed parameters were not significantly correlated with the yield modulus.

Author Contributions: Writing—original draft preparation, H.Y.; writing—review and editing, J.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was financially supported by National Key Research and Development Plan Project of China (grant numbers 2018YFC0406501-02), National Natural Science Foundation of China (grant numbers 41877170, 42001009) and the Natural Science Foundation of Hebei Province (grant numbers D2021503001).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data, models, and code generated or used during the study appear in the submitted article.

Acknowledgments: We thank the three anonymous reviewers and academic editor for their critical comments and constructive suggestions on the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Hynes, H.B. *The Ecology of Running Waters*; University of Toronto Press: Toronto, ON, Canada, 1970.
2. Wohl, E.E. *Mountain Rivers. Water Resources Monograph 14*; American Geophysical Union: Washington, DC, USA, 2000.

3. Chen, Q.; Guo, B.; Zhao, C.; Zhang, J. A comprehensive ecological management approach for northern mountain rivers in China. *Chemosphere* **2019**, *234*, 25–33. [[CrossRef](#)]
4. Grant, G.E.; Swanson, F.J.; Wolman, M.G. Pattern and origin of stepped-bed morphology in high-gradient streams, Western Cascades, Oregon. *Geol. Soc. Am. Bull.* **1990**, *102*, 340–352. [[CrossRef](#)]
5. Wohl, E.; Kuzma, J.N.; Brown, N.E. Reach-scale channel geometry of a mountain river. *Earth Surf. Proc. Land.* **2004**, *29*, 969–981. [[CrossRef](#)]
6. Fryirs, K.; Brierley, G. Antecedent controls on river character and behaviour in partly confined valley settings: Upper hunter catchment, NSW, Australia. *Geomorphology* **2010**, *117*, 106–120. [[CrossRef](#)]
7. Yadav, B.; Hatfield, K. Stream network conflation with topographic DEMs. *Environ. Model. Softw.* **2018**, *102*, 241–249. [[CrossRef](#)]
8. Yang, H.; Shi, C. Basin form characteristics, causes and implications of the ten kongduis in the upper reaches of the Yellow River. *Quat. Int.* **2017**, *453*, 15–23. [[CrossRef](#)]
9. Horton, R.E. Drainage-basin characteristics. *Trans. Am. Geophys. Union* **1932**, *13*, 350–361. [[CrossRef](#)]
10. Passalacqua, P.; Do Trung, T.; Fofoula-Georgiou, E.; Sapiro, G.; Dietrich, W.E. A geometric framework for channel network extraction from lidar: Nonlinear diffusion and geodesic paths. *J. Geophys. Res. Earth Surf.* **2010**, *115*, F01002. [[CrossRef](#)]
11. Pelletier, J.D. A robust, two-parameter method for the extraction of drainage networks from high-resolution digital elevation models (DEMs): Evaluation using synthetic and real-world DEMs. *Water Resour. Res.* **2013**, *49*, 75–89. [[CrossRef](#)]
12. Clubb, F.J.; Mudd, S.M.; Milodowski, D.T.; Hurst, M.D.; Slater, L.J. Objective extraction of channel heads from high-resolution topographic data. *Water Resour. Res.* **2014**, *50*, 4283–4304. [[CrossRef](#)]
13. Byun, J.; Seong, Y.B. An algorithm to extract more accurate stream longitudinal profiles from unfilled DEMs. *Geomorphology* **2015**, *242*, 38–48. [[CrossRef](#)]
14. Rinaldo, A.; Gatto, M.; Rodriguez-Iturbe, I. River networks as ecological corridors: A coherent ecohydrological perspective. *Adv. Water Resour.* **2017**, *112*, 27–58. [[CrossRef](#)] [[PubMed](#)]
15. Zhu, G.P.; Wang, X.R.; Wang, M.; Qi, S.; Gao, J.R. Advances on near natural comprehensive control of urban river. *Sci. Soil Water Conserv.* **2006**, *4*, 92–97.
16. Mikus, P.; Wyzga, B.; Walusiak, E.; Radecki-Pawlik, A.; Liro, M.; Hajdukiewicz, H.; Zawiejska, J. Island development in amountain river subjected to passive restoration: The Raba River, Polish Carpathians. *Sci. Total Environ.* **2019**, *660*, 406–420. [[CrossRef](#)] [[PubMed](#)]
17. Kuemmel, M.; Reichert, P.; Siber, R.; Schuwirth, N. Ecological assessment of river networks: From reach to catchment scale. *Sci. Total Environ.* **2019**, *650*, 1613–1627. [[CrossRef](#)] [[PubMed](#)]
18. Prodanovic, P.; Simonovic, S.P. An operational model for support of integrated watershed management. *Water Resour. Manag.* **2010**, *24*, 1161–1194. [[CrossRef](#)]
19. Song, C.; Ke, L.; Pan, H.; Zhan, S.; Liu, K.; Ma, R. Long-term surface water changes and driving cause in Xiong'an, China: From dense Landsat time series images and synthetic analysis. *Sci. Bull.* **2018**, *63*, 708–716. [[CrossRef](#)]
20. Cui, B.; Li, X.; Zhang, K. Classification of hydrological conditions to assess water allocation schemes for Lake Baiyangdian in North China. *J. Hydrol.* **2010**, *385*, 247–256. [[CrossRef](#)]
21. Yang, Z.; Mao, X. Wetland system network analysis for environmental flow allocations in the Baiyangdian Basin, China. *Ecol. Model.* **2011**, *222*, 3785–3794. [[CrossRef](#)]
22. Wang, X.L.; Zhang, Y. Current state of water environment of Daqing River basin and countermeasures. *Water Resour. Prot.* **2000**, *2*, 33–35. (In Chinese with English abstract)
23. Tian, J.; Liu, J.; Wang, J.; Li, C.; Yu, F.; Chu, Z. A spatio-temporal evaluation of the WRF physical parameterisations for numerical rainfall simulation in semi-humid and semi-arid catchments of Northern China. *Atmos. Res.* **2017**, *191*, 141–155. [[CrossRef](#)]
24. Xia, J.; Zhang, Y.Y. Water resource and pollution safeguard for Xiongan New Area construction and its sustainable development. *Bull. Chin. Acad. Sci.* **2017**, *11*, 1199–1205.
25. Lu, L.; Yu, Y.D.; Liu, J.H.; Qin, D.Y. Analysis of hydrologic characteristics in Haihe River Basin. *Haihe River Water Conserv.* **2011**, *6*, 1–4. (In Chinese)
26. Liu, W.J.; Zhao, Z.J. Analysis of the influence of the change of hydrological characteristics of Daqing he river basin on Baiyangdian wetland. *Groundwater* **2012**, *34*, 101–102. (In Chinese)
27. Yan, Y.X.; Wang, S.J.; Yan, M.; He, L.; Cheng, D.S. Spatial patterns of scale effect of specific sediment yield in Haihe River Basin. *Prog. Geogr.* **2014**, *33*, 57–64. (In Chinese with English abstract)
28. Yuan, Z.J.; Sun, Q. Runoff-sediment relationship for various spatial scales in the Daqing he rocky mountainous area. *Resour. Sci.* **2016**, *38*, 750–757. (In Chinese with English abstract)
29. SL665-2014. *Technical Standards for Comprehensive Treatment of Water and Soil Erosion in the Earth Rock Mountain Areas of Northern China*; China Water Power Press: Beijing, China, 2014.
30. Whipple, K.X.; Tucker, G.E. Dynamics of the stream-power river incision model: Implications for height limits of mountain ranges, landscape response time scales, and research needs. *J. Geophys. Res.* **1999**, *104*, 17661–17674. [[CrossRef](#)]
31. Chen, Y.Z.; Jing, K.; Cai, Q.G. *Modern Erosion and Control in the Loess Plateau*; Science Press: Beijing, China, 1988. (In Chinese)
32. Miller, V.C. *A Quantitative Geomorphic Study of Drainage Basin Characteristics in Clinch Mountain Area, Virginia and Tennessee*; Project NR 389-042, Tech. Rept. 3; Columbia University Department of Geology, O.N.R. Geography Branch: New York, NY, USA, 1953.

33. Schumm, S.A. Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey. *Geol. Soc. Am. Bull.* **1956**, *67*, 597–646. [[CrossRef](#)]
34. Burrough, P.A.; McDonnell, R.A. *Principles of Geographical Information Systems*; Oxford University Press: Oxford, UK, 1998.
35. Strahler, A.N. Hypsometric (area-altitude) analysis of erosional topography. *Geol. Soc. Am. Bull.* **1952**, *63*, 1117–1142. [[CrossRef](#)]
36. Moglen, G.E.; Eltahir, E.A.B.; Bras, R.L. On the sensitivity of drainage density to climate change. *Water Resour. Res.* **1998**, *34*, 855–862. [[CrossRef](#)]
37. Talling, P.J.; Sowter, M.J. Drainage density on progressively tilted surfaces with different gradients, wheeler ridge, california. *Earth Surf. Process. Landf.* **1999**, *24*, 809–824. [[CrossRef](#)]
38. Tucker, G.E.; Bras, R.L. Hillslope processes, drainage density, and lands cape morphology. *Water Resour. Res.* **1998**, *36*, 1953–1964. [[CrossRef](#)]
39. Luoto, M. New insights into factors controlling drainage density in subarctic landscapes. *Arctic. Antarct. Alpine Res.* **2007**, *39*, 117–126. [[CrossRef](#)]
40. Collins, D.B.G.; Bras, R.L. Climatic and ecological controls of equilibrium drainage density, relief, and channel concavity in dry lands. *Water Resour. Res.* **2010**, *46*, W04508. [[CrossRef](#)]
41. Smith, V.B.; David, C.H.; Cardenas, M.B.; Yang, Z.-L. Climate, river network, and vegetation cover relationships across a climate gradient and their potential for predicting effects of decadal-scale climate change. *J. Hydrol.* **2013**, *488*, 101–109. [[CrossRef](#)]
42. Chaick, O.A.; Roering, J.J.; Heimsath, A.M.; Levick, S.R.; Asner, G.P.; Khomo, L. Shaping post-orogenic landscapes by climate and chemical weathering. *Geology* **2013**, *41*, 1171–1174. [[CrossRef](#)]
43. Strahler, A.N. Statistical Analysis in Geomorphic Research. *J. Geol.* **1954**, *62*, 1–25. [[CrossRef](#)]
44. Chien, N.; Zhang, R.; Zhou, Z.D. *Fluvial Processes Study*; Science Press: Beijing, China, 1987.
45. Liu, R.L. *The Characteristics of Water Network and Landforms of the Beisha River in Taishan Mountain*; Shandong Normal University: Jinan, China, 2011; (In Chinese with English abstract).
46. Hoton, R.E. Erosional development of stream sand their drainage basins; hydrophysical approach to quantitative morphology. *GSA Bull.* **1945**, *56*, 275–370. [[CrossRef](#)]
47. Morisawa, M.E. Quantitative geomorphology of some watersheds in the Appalachian Plateau. *Geol. Soc. Am. Bull.* **1962**, *73*, 1025–1046. [[CrossRef](#)]
48. Sangireddy, H.; Carothers, R.A.; Stark, C.P.; Passalacqua, P. Controls of climate, topography, vegetation, and lithology on drainage density extracted from high resolution topography data. *J. Hydrol.* **2016**, *537*, 271–282. [[CrossRef](#)]
49. Wu, Q.F.; Zhang, H.J. *Soil Erosion*; Science Press: Beijing, China, 2012.
50. Meton, M.A. *An Analysis of the Relations Among Elements of Climate, Surface Properties, and Geomorphology*; Technical Report 11; Office of Naval Research, Department of Geology, Columbia University: New York, NY, USA, 1957.
51. Ochi, T. Drainage density and relative relief in humid steep mountains with frequent slope failure. *Earth Surf. Process. Landf.* **1997**, *22*, 107–120. [[CrossRef](#)]
52. Chen, H.; Fang, H.Y.; Cai, Q.G.; Lei, T.W.; Liang, G.L. Comparison of different aspects of erosion evolution in the loess hilly area: A case study of Wangjiagou Rinaldo catchment of western Shanxi province. *Resour. Sci.* **2006**, *28*, 176–184. (In Chinese with English abstract)