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The Three Gorges Area and the Linking of the Upper and Middle Reaches of the Yangtze River

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Abstract

The history of the Yangtze River is constituted by numerous river piracies that enabled the river to extend its drainage system. Two river captures are well recognized: the piracy of the Jinsha River (Jinshajiang) formerly tributary of the Red River at Shigu in Yunnan Province and the Three Gorges area that linked the upper and the middle Yangtze river reaches in Hubei province. The first one is well documented, while the second, because of difficulties to retrieve datable materials and the complexity of the area geomorphology, is still quite unknown. Numerous conflicting hypotheses have been formulated to explain the pattern of river piracy, no agreement exists on the location of the drainage divide and of the point of capture; chronologies extending from the Eocene to the late Quaternary are given. Geomorphic indices can be used to examine the geomorphological and tectonic processes responsible for the development of the drainage basins. In this paper, we analyzed drainage pattern, basin shape, basin asymmetry, stream junction angle to infer the drainage of the paleorivers that were pirated, and to propose a model of the pattern of river capture based on the importance of structure, tectonic and lithological controls in the area. We showed that the Three Gorges area has been very important to the history of the Yangtze river as the piracy of the upper and middle reaches enabled the river to reach its current extend.

Keywords

Yangtze River, Three Gorges, River Piracy, DEM

1. Introduction

The present-day course of the Yangtze River, long of 6300 km, the third longest river in the world, is the result of different drainage rearrangements that enabled the river to diverge its drainage from that of the Mekong River in the west, the

Red River in the South, and the Huanghe (Yellow River) in the north [1]-[11]. The current drainage network of the Yangtze River evolved from the integration of numerous drainage systems by river capture in its upper course [5] [7] [12] [13] [14] [15] [16]. Rising from the Qinghai-Tibet plateau at 6000 meters of altitude, the main tributary of the Yangtze River (Jinsha River) flows N-S parallel to the course of the Mekong (**Figure 1**). At Shigu, in Yunnan Province, the river forms a bend known in the geomorphologic literature as the first bend of the Yangtze River and shifts to a SW-NE direction. After forming a "W", the river continues its flows east to the Sichuan Basin. South of Shigu just in the prolongation of the Jinsha River rises the course of the Red River. This shift of flow direction of the Yangtze River has been interpreted by many researchers as the result of a river capture that integrated the Jinsha River which used to belong to the Red River drainage to the Yangtze River drainage system [10] [11] [17].

After the Sichuan Basin, the river flows again SW-NW and enters a mountainous region where the course of the river shifts to a W-E direction and flows through deep and steep gorges known as the Three Gorges area. There, the Yangtze crosses first the Qutang Gorge (Qutangxia), the Wu Gorge (Wuxia), then the Xiling Gorge (Xilingxia) where is located the Three Gorges Dam. After the Three gorges, the Yangtze enters its middle course composed of plains (Jianghan plain) and lakes (Dongting lake system). As for Shigu, many researchers recognize that in the Three Gorges area the present day Yangtze river was born from the piracy of two main river systems: the first river flowing from the Three Gorges area westwards to the South China sea and the second flowing eastwards constituting the present-day middle reaches of the river downstream of Yichang [5] [6] [8] [10] [14] [16] [18] [19] [20].

The overview of those former researches attests that the present-day Yangtze River system was the result of at least two river piracies, the first at Shigu in

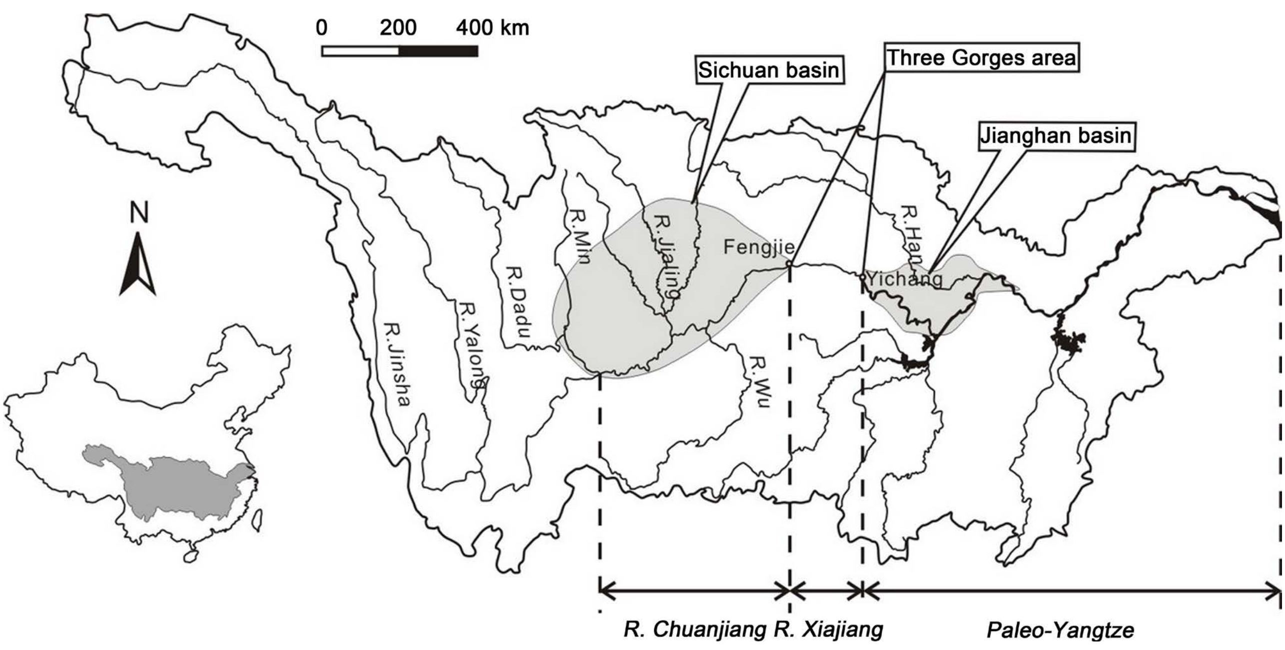

Figure 1. The Three Gorges area in the Yangtze drainage basin (revised from Clark *et al*., 2004).

Yunnan Province that integrated parts of the Red River drainage basin and the second at the Three Gorges region in Hubei province that linked the upper and middle reaches of the Yangtze River. Clark (2004) states that the piracy in the Three Gorges area was anterior to that of Shigu and the capture and integration of rivers upstream were done in a E-W direction, Jinsha River being the last to be integrated.

If it is widely accepted that a river piracy occurred in the Three Gorges area, the time, pattern, and location of that piracy are still a debate unlike Shigu bend where it has been shown that tectonic movements were preponderant [17]. Chronologies extending from Eocene to Late Quaternary are given [3] [5] [8] [14] [15] [21] [22] [23] [24] [25]. The drainage divides of the two rivers involved in the piracy were identified to be the Huangling anticline through the Xiling Gorge while others locate it at the Hengshixi anticline through the Wu Gorge. Different hypotheses explaining the course of the Yangtze through the anticlines including antecedence [4] [21], superimposition [3] [7], underground rivers flow that roof collapsed triggered but an earthquake [6] [26] are hypothesized. The debate is not to over soon as nowadays datable Quaternary materials of river terraces are scarce because flooded by the artificial lake formed after the building of the dam, cosmogenic dating is quite impossible as the area is characterized by numerous landslides and rock falls which disturbed the exposed surfaces of the gorges after their formation. Currently, numerous research projects are concentrated on the dating of heavy minerals contained in the Quaternary sediments of the downstream Jianghan plain and the results are still not obvious [23] [27]. Although, they can provide the chronology of upper stream sediments reaching the middle reaches, they give no insights on which of the gorges was the last to be opened and on how the river piracy occurred, whereas those questions are very crucial to the understand the history of the Yangtze River.

In this context, the analysis of the drainage network development [28]-[33] (drainage initiation, elaboration and extension) through scrutiny of drainage patterns [34] [35] [36], stream connections, the link between drainage pattern, structure and lithology [37]-[48], the shape of the drainage basins [49] [50] [51] [52] [53], the stream junction angles [54] can give some interesting results. As drainage evolves through time and as river piracy involves drainage rearrangement, the present day drainage network of the area should have recorded the piracy that occurred at some remote period in the past and the pattern and location of the piracy should be inferred. Thus the aim of this research was to acquire evidences as to show the pattern and location of the river piracy through the analysis of the river development of the area under structural and lithological control in sight of revealing the importance of the Three Gorges area in the evolution of the present day Yangtze River.

Study Area

The Three Gorges area is a mountainous region with a relief up to 3000 meters linking two lowlands: the Sichuan basin in the West and the Jianghan Plain to the East. It also links the Upper course and the middle reaches of the Yangtze River. The river crosses the area first in a SW-NE direction then flows W-E. The drainage basin of the Yangtze in the area is bounded in the South by the Qingjiang drainage, which reaches the Yangtze River near Yichang and in the North by the Hanjiang, which joins the river in Wuhan.

The mountainous topography is dominated by asymmetric folded structures constituted by a succession of anticlines and synclines.

In the West and center of the area, those anticlines with altitudes reaching 2000 meters are oriented SW-NE. The major anticlines are from West to East: the Qiyueshan anticline, which locates the Qutang Gorge, the Hengshixi anticline bearing the Wu Gorge and a third anticline non-named in front of the Badong big slope. 4 main synclines can be identified in the area: the first one is located west of the Qiyueshan anticline, the Yangtze River course follow this anticline from Chongqing to the Qutang Gorge that the river crosses and shift to a W-E direction, the Wushan syncline separates the Qiyueshan anticline and the Hengshixi anticline, the Guandu syncline in the west of Hengshixi anticline separated it from the third eastern anticline described above.

In the Northern part of the area, the Dabashan (Daba Mountains), where are found the highest altitudes of the area 3050 m, the folded structures are oriented E-W and follow each another parallel from south to north.

In the extreme eastern part of the area the Huangling anticline is the step that connects the mountainous area to the Jianghan plain. This granitic anticline oriented N-S bears the Xiling Gorge and also the Three Gorges Dam. This folded structure affect the drainage pattern of the area as well as the fluvial landforms as a deep and steep gorge is found wherever the Yangtze River or its tributaries in the area crosses them. This mountainous area is highly dissected by rivers flowing down the different anticlines and from the Dabashan with young "V" shape valleys.

The geology of the area is mainly composed of sedimentary rocks, which span a very long time range; from Quaternary colluviums and alluvium to Sinian carbonate rocks. The sedimentary rocks lay on some places on Archean metamorphic rocks of the Kongling Group, the oldest rocks in Yangtze Craton. According to the rock types and ages, the Three Gorges region can be classified into three geological regions.

The first region, from Fengjie to Badong, shows interbedded Triassic limestone, shale and dolomite; the second, from Badong to Zigui, is a Jurassic basin, called Zigui basin; the eastern area, from Zigui to Yichang, is a granitic area which constitute the core of the Huangling Anticline, where is located the Xiling Gorge and the Three Gorges dam. The northern part of Huangling anticline is composed of pre-Sinian metamorphic and some ultrabasic rocks (**Figure 2**).

In some of the gorges of the Hengshixi Anticline, the rivers have incised down into the Ordovician sandstone and Permian shale.

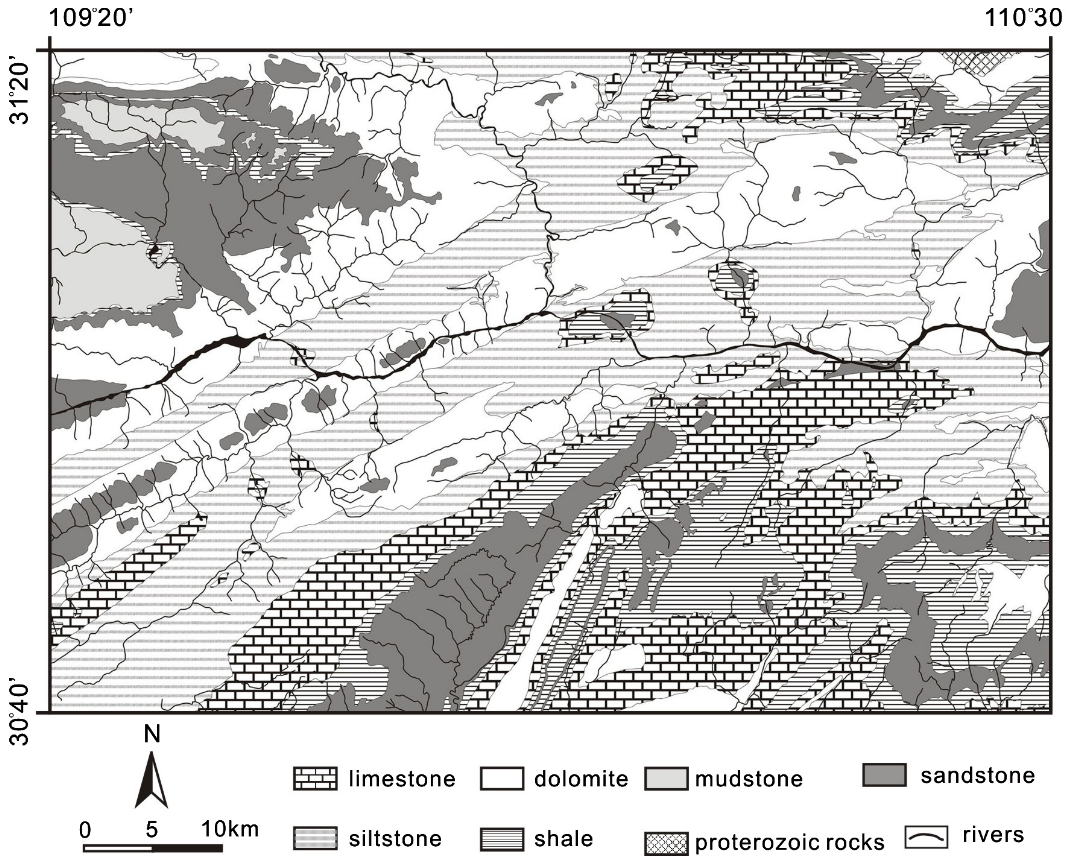

Figure 2. Lithological map of the area.

2. Materials and Methods

The analysis of drainage network necessitates the identification of streams and streams segments from maps or from Digital Elevation Models (DEM). Therefore in this research the stream network was derived from ASTER GDEM, 30 m resolution data available online free of charge. The DEM was loaded to the open source software GRASS GIS which is a powerful freeware counterpart for geomorphologists and hydrologists especially when compiled with the additional modules available and integrated with the open source statistics package: R statistics [55]-[62].

The ASTER GDEM data was first corrected by filling and deleting negatives and very low cell data by using the height of the channel of the Yangtze River at the Three Gorges dam which is about 60 meters considered as the lowest altitudes of the area. Therefore all cells values below 60 meters were deleted and the DEM raster was resampled using the spline method. The stream network was then extracted for the whole DEM and the stream were classified using the r.stream [63] modules following Strahler's stream classification method [64] [65]. The stream classified raster map was then overlaid with the corrected resampled DEM and the Region of Interest was delineated using all the streams flowing to the Yangtze River in the Three Gorges area. The DEM data of the region of interest was then cut out and saved for further processing. The analysis was then made at two scales. Drainage pattern, stream junction angle and the general morphometric parameters such as elevations (mean, maximum and minimum), slope gradient, slope profile and tangential curvature and roughness were analyzed at the scales of the whole area. To analyze the drainage morphometry such as basin shape: elongation, circularity, compactness, form factor, Horton laws of average area, of average length and of stream order, and basin asymmetry, a sample of 26 drainage basins were chosen: 14 basins in the area north of the Yangtze river course and 12 in the south. Those basin where coded from east to west, N01 to N14 for the northern basins and S01 to S12 for the southern Basins (**Figure 3**). The purpose was to detect drainage anomalies and check the optimality of the drainage network organization, as drainage network through time should evolve toward such state.

To display drainage basin evolution incremental isobase maps of successive coupled stream order was made for drainage basins. Isobases maps [66] [67] [68] relate valley order to topography. They draw erosional surfaces therefore they are related to erosional cycles.

3. Results

3.1. Presentation of the Drainage Basin of the Three Gorges Area

3.1.1. Northern Basins

The table above display that the northern part of the area is composed of streams of different orders (**Table 1**, **Table 2**). Two eighth order streams (N1 and N12 known in the area as the Xiangxi River and the Xiaojiang River), 5 rivers of seventh order (N5, N7, N8, N9, N11 respectively known as the Shennongxi River, the Daning River, the Caotangxi River, the Meixi River and the Tanxi River), 3 rivers of sixth order streams (N2, N6, N14 known in the area as respectively the

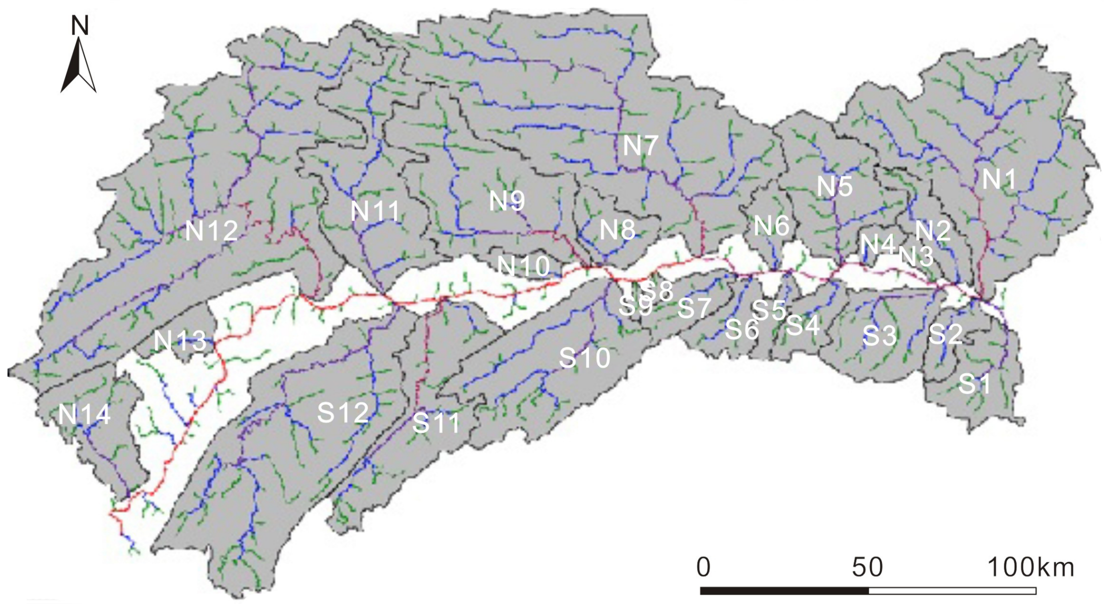

Figure 3. Sampled drainage basins of the study area. The Yangtze River is presented in red.

Table 1. General morphometrical data of the streams. The highest stream order is the Yangtze River.

Stream order	N.streams	Tot.leng. (km)	Tot.area (km^2)	Avg.leng	Avg.area	Std.leng	Std.area
1	180,762	57224.17	20507.42	0.32	0.11	0.28	0.09
2	40,749	28639.22	20499.46	0.70	0.50	0.60	0.35
3	8709	12851.59	19356.49	1.48	2.22	1.24	1.58
4	1881	6123.22	19066.53	3.28	10.14	2.75	7.18
5	413	2985.84	18341.79	7.23	44.41	5.75	27.86
6	91	1882.64	21621.27	20.69	237.60	15.09	149.00
7	20	877.48	23381.16	43.87	1169.06	36.26	874.98
8	5	388.66	21416.78	77.65	4283.36	57.20	2962.67
9	1	345.66	32667.12	345.66	32667.12	0.00	0.00

Table 2. The 14 sampled drainage basins in the north of the Yangze River.

Rivers	Local names	Max Order	Area km^2	Total number of streams	Total streams length (Km)
N1	Xiangxi River	8	3162.80	12462	7624.45
N2	Liangtai River	6	398.78	1577	955.35
N3	Xietan River	5	85.85	324	519
N4	Caoliangxi River	5	124.70	519	300.05
N5	Shennongxi River	7	1029.30	4216	2516.81
N6	Bianyuxi River	6	268.41	1150	726.16
N7	Daning River	7	4453.09	18,048	11088.86
N8	Caotangxi River	7	394.41	1770	1051.06
N9	Meixi River	7	1745.90	7346	4591.2
N10	-	5	149.94	568	351.2
N11	Tanxi River	7	1580.45	6495	3933.55
N12	Xiaojiang River	8	5209.39	22,246	13528.95
N13	-	5	235.93	950	584.23
N14	Wenxi River	6	720.58	2852	1713.08

"-" represent the unknown river names.

Liangtaihe, Bianyuxi River, and …) 4 rivers of five order streams (N3, N4, N10, N13 respectively named as, Xietan river, Caoliangxi River, …). The comparison of the drainage areas, the stream lengths, and total number of streams of those rivers shows great differences but they can be classified into three classes: large drainage basins constituted of N12, N7 and N1 (Xiaojiang River, Danning River, and Xiangxi River), middle class rivers composed of N9, N11, N5, N14.N2 and N8), small drainage basins: N6, N13, N10, N4 and N3 (**Figure 4**).

3.1.2. Southern Basins

Unlike the northern area of the Three Gorges, the southern part does not have an 8th order stream (Figure 5, Table 3). The table shows that the rivers are mainly

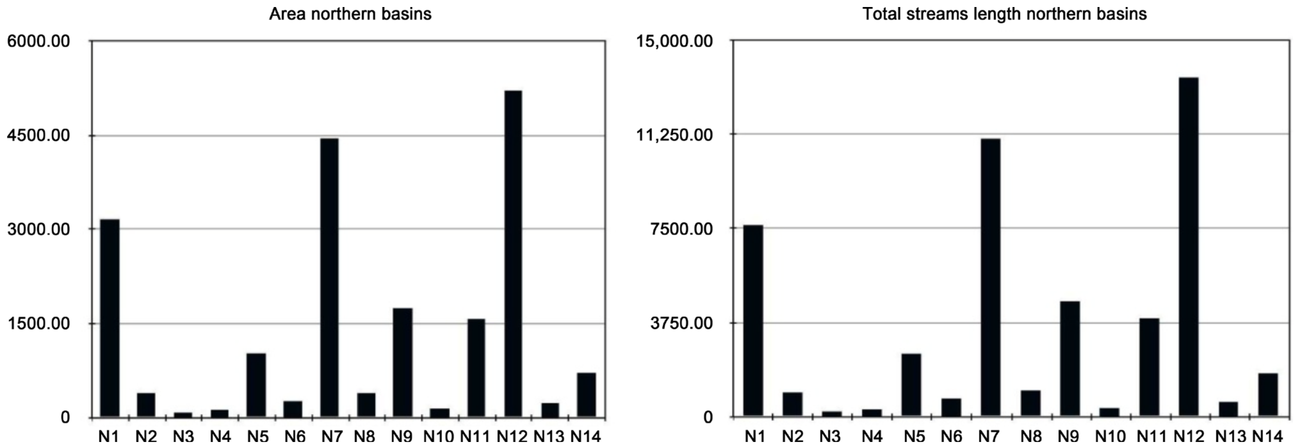

Figure 4. Plot of the drainage areas and total stream length for the 14 basins in the north of the Yangtze River.

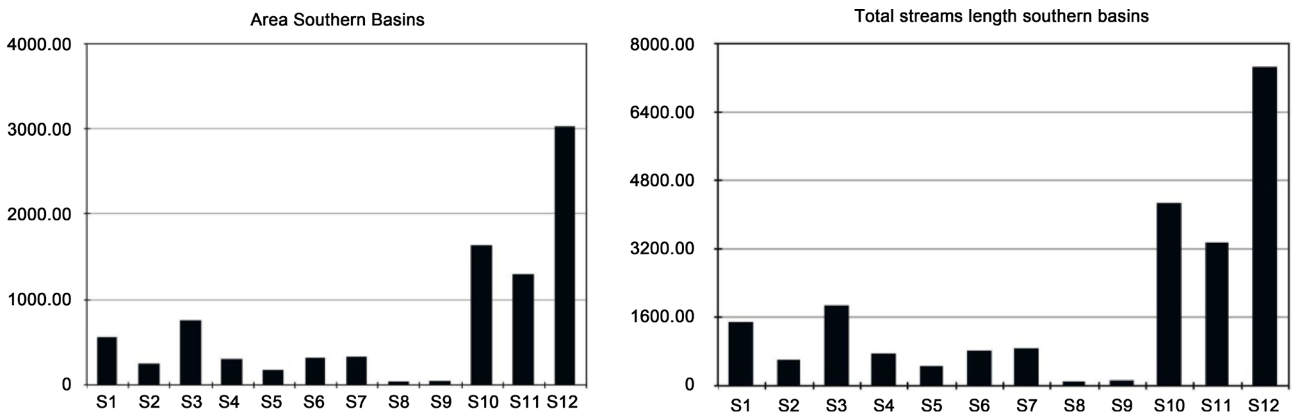

Figure 5. Plot of the drainage areas and total stream length for the 12 basins in the south of the Yangtze River.

Table 3. The 12 sampled drainage basins in the area south of the Yangtze River.

Basins	Local names	Max St. Ord.	Area	Tot. St. Num.	Tot. St. Length
S1	Jiuwanxi River	6	563.91	2380	1489.39
S2	Tongzhuang River	6	251.26	1020	613.08
S3	Qinggan River	6	758.25	3027	1877.05
S4	Wanshi River	6	303.07	1190	759.16
S5	Xiaoxi River	6	173.60	744	459.58
S6	Hongyan River	6	319.54	1402	814.35
S7	Guandu River	6	329.96	1423	879.41
S8	-	4	41.72	187	103.04
S9	-	5	46.61	200	124.12
S10	Daxi River	7	1639.57	6740	4270.25
S11	Changtan River	7	1297.36	5442	3356.11
S12	Modaoxi River	7	3034.64	12102	7465.66

"-" represent the unknown river names.

6th order streams and 7th order streams. Only one 5th order and one 4th order stream are present. In that section of the Three Gorges, 3 drainage basins (S10, S11, S12) are 7th order. S01 to S07 are all 6th order streams, and S09 is 5th order, S08 is fourth order. That shows more homogeneity than in the northern part with river of same order following each other unlike the northern area where they are scattered.

3.2. Drainage Patterns

The drainage pattern is defined as the arrangement of streams in a drainage basin. This arrangement of streams is the result of the conjugated effect of slopes, structure controls, lithological controls, or the lack of controls [35] [36] [69] [70] [71].

The geology of the Three Gorges area is composed essentially by a succession of anticlines and synclines tailored in limestone, sandstones and granites. The presence of such tectonic structures should have a great effect on the way drainage systems are organized in the Three Gorges area. Usually the patterns result from the impact of initial slope (consequent streams), random headward erosion not controlled (insequent streams), selective headward erosion controlled by lithology and structure (subsequent streams) and on secondary incision or stream capture (obsequent streams that have an opposite direction to the consequent streams or resequent streams when it has the same direction with the consequent stream at lower level). The arrangements of the different branches, tributaries, and stream segment in a drainage basin have been classified into different types: dendritic, parallel, trellis, rectangular, radial, annular, centripetal …

The map of drainage systems of the Three Gorges (**Figure 6**) area was analyzed

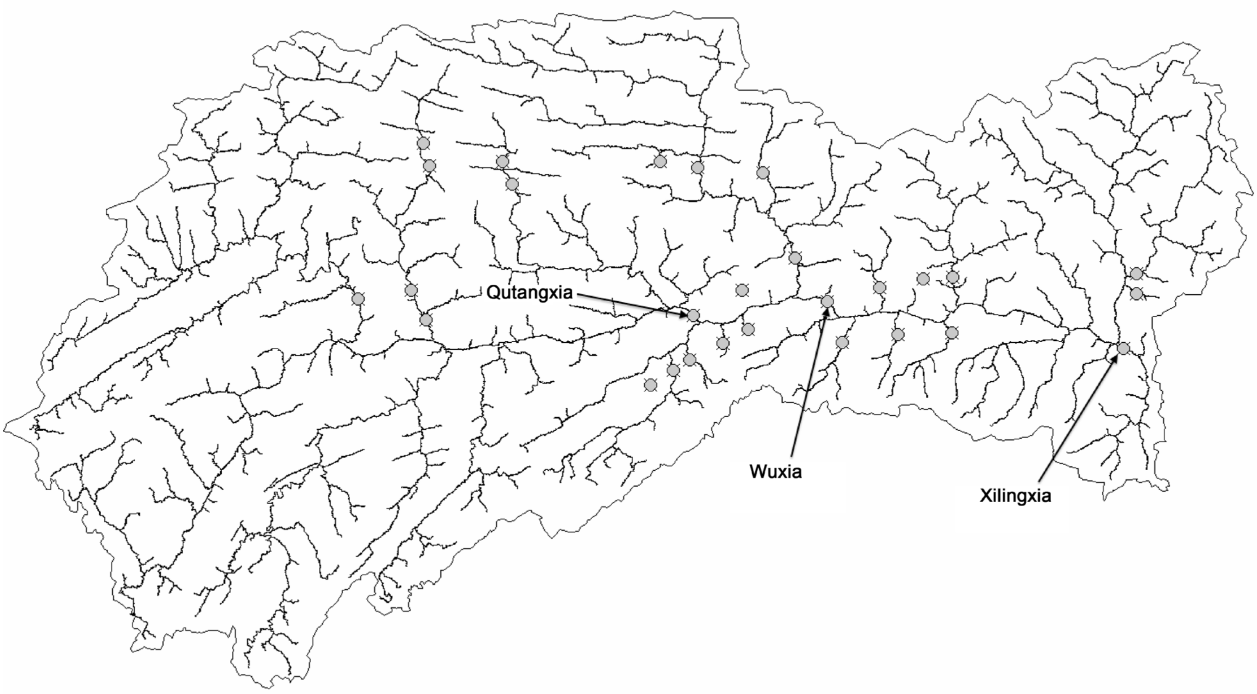

Figure 6. The map of drainage systems and the gorges of the Three Gorges; the gorges are located on the anticlines.

in regard to the presence of the different drainage patterns above. The geological, topographical and lithological conditions of the formation described below affects three types are very frequent in the area.

Dendritic type of drainage pattern is characteristic of the area of the granitic Huangling anticline region. The Xiangxi River and the Jiuwanxi Rivers are of such type. This type of drainage extends to the river from the Xiling Gorge (Xilingxia) to the Wu Gorge (Wuxia).

After the Wu gorge the Northern part of the Three Gorge area falls under the parallel drainage type with rivers running down the sides of the anticlines and flowing in the synclines in a W-E direction for the main rivers and a N-S direction for river running down the sides of the anticlines. This type characterizes the rivers from the Daning to the Wenxi Rivers.

The trellis drainage pattern is found on the river draining the southern part of the area west of the Wu Gorge. It is found on the Changtan River and Modaoxi River.

The drainage pattern evolved through time under the structural controls in the areas west of the Wu Gorge and under lithological controls between the Wu Gorge and the Xiling Gorge. The gorges are transverse and represent the attempt of the rivers to overcome the structural controls. Those Gorges are not limited only to the Yangtze River channel but other tributaries of the Yangtze in the area have their gorges.

3.3. Basin Shape

The basin shape data concerning basin elongation, circularity ratio, compactness ratio and form factor shows that the basins of the area are elongated in shape (**Table 4**). This shape can be linked also to the structural controls as the main rivers flows inside the different synclines with their tributaries flowing down the confining anticlines. The evolution of such basins is slower because the sediment load is lower than when the basins are rounded as it is known that floods formation and movement that affect erosion and transport capacities are linked to basin shape [72].

3.4. Horton Laws of Averaged Area

Horton found out that: the averaged area of drainage basins of successively higher order tends to form an increasing geometric progression in which the first term is the average area of first-order basins and the ratio is the ratio of successive average areas. This assertion shows that the average areas of progressively greater basins increase in a geometric progression, a very important law according to which the drainage areas of river basins develop. The definitive formulation of this law was done by Schumm [73] and it was confirmed by Leopold and Miller [74], and Morisawa [75]. The ratio of averaged area, which indicates the growth rate of average area from one order to the other, is affected by tectonics, structure and lithology and is very important in determining greater

Table 4. Basin shape parameters of the 26 sampled drainage basins.

Code	Rivers	Elongation ratio	Circularity ratio	Compactness	Form factor
N01	Xiangxi	0.80	0.25	2.01	0.51
N02	Liantai	0.49	0.20	2.22	0.19
N03	Xietan	0.66	0.34	1.72	0.34
N04	Caoliangxi	0.76	0.36	1.66	0.45
N05	Shennongxi	0.76	0.30	1.84	0.46
N06	Bianyuxi	0.68	0.27	1.91	0.37
N07	Daning	0.61	0.21	2.18	0.29
N08	Caotangxi	0.92	0.37	1.64	0.67
N09	Liujia	0.65	0.22	2.12	0.33
N10	-	0.53	0.27	1.92	0.22
N11	Tanxi	0.61	0.13	2.82	0.29
N12	Xiaojiang	0.99	0.15	2.56	0.77
N13	-	0.72	0.30	1.83	0.40
N14	-	0.76	0.23	2.11	0.45
S01	Jiuwanxi	0.80	0.25	2.01	0.50
S02	Tongzhuang	0.64	0.25	2.00	0.32
S03	Qinggan	0.78	0.39	1.61	0.47
S04	Lianzixi	0.63	0.30	1.82	0.32
S05	Xiaoxi	0.53	0.19	2.31	0.22
S06	Baolong	0.74	0.24	2.05	0.43
S07	Guandu	0.64	0.30	1.81	0.33
S08	-	0.74	0.35	1.68	0.43
S09	-	0.65	0.32	1.77	0.33
S10	Moxi	0.65	0.25	2.00	0.33
S11	Silu	0.53	0.14	2.64	0.22
S12	Modaoxi	0.63	0.25	2.02	0.31

"-" represent the unknown river names.

relief fragmentation. In mountainous areas such as the Three Gorges the ratio should be higher. In this section the average areas were plotted for all streams order of the different drainage basins to check their conformity to this law. The results appear in the charts below (Figure 7).

The plot of Horton law of average areas expressing the optimal development of river shows that many rivers in the area are not optimal (Figure 8). They deviate somehow from the law. 4 drainages in the northern part of the area (N12 and N07), the first and second largest rivers of the area fits well the law while in the south S12 and S10 fits the law well. It should be noted that all those rivers are located in the west of the Wu Gorge. Therefore it can be said that the area west

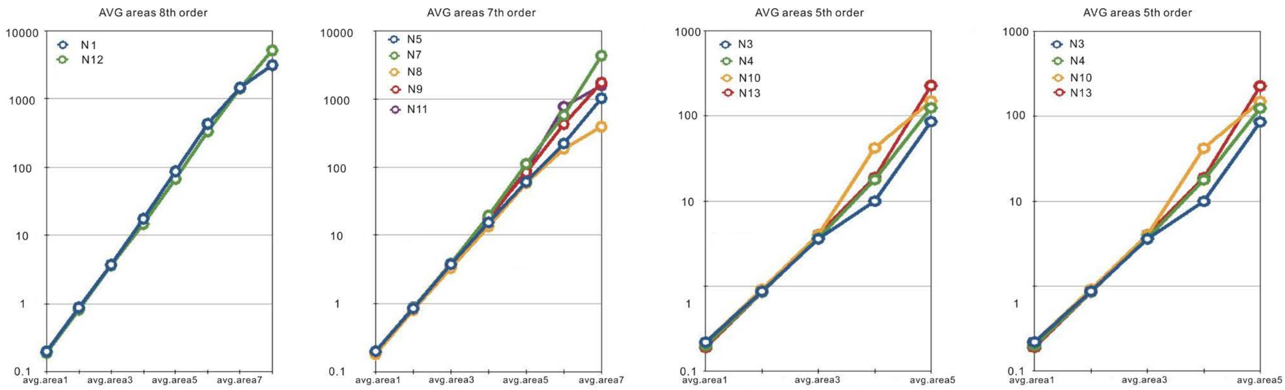

Figure 7. Horton laws of averaged area, northern basins.

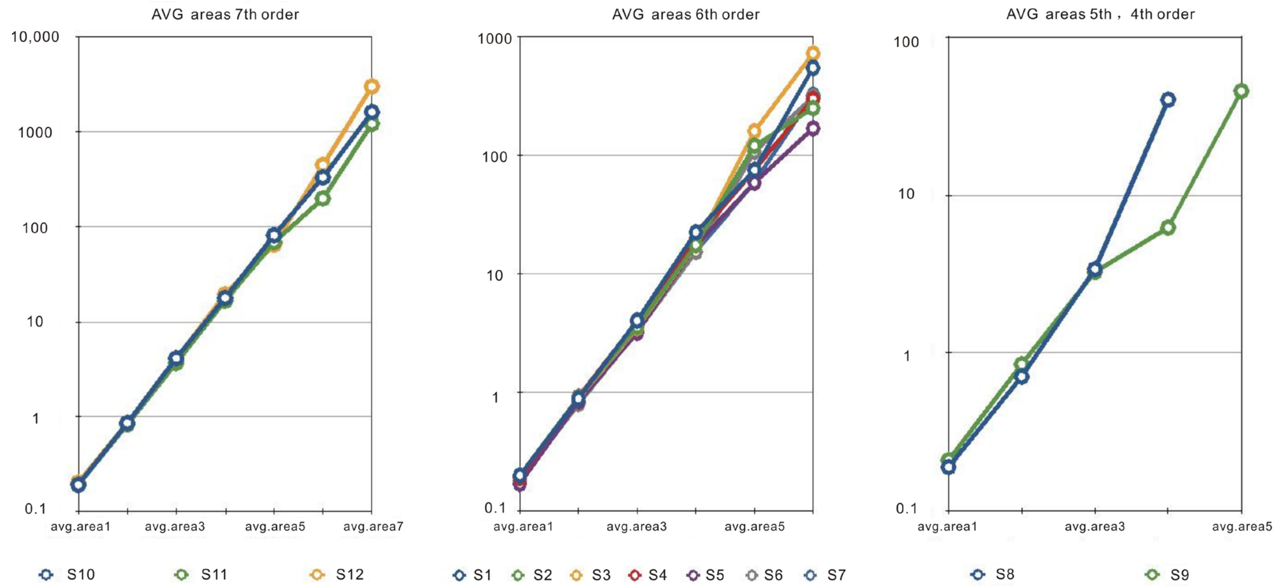

Figure 8. Horton Laws of averaged area, southern basins.

of the Wu Gorge developed large well-optimized drainage basins while the part East of the gorge did not reach such state of development.

3.5. Stream Junction Angle

The angle of the river flowing to the Yangtze River from the Daba Mountains between the Xiling gorge and the Wu gorge is high between 70 degrees and 85 degrees (Figure 9). The river from the south flows at low angle but in the direction SW-NE. In this context the angle of the different rivers are quite normal, but 3 rivers: the Daning, the Xiaojiang and the Guandu rivers shows abnormal stream junction angle with the Yangtze River. The Daning and Xiaojiang River's angle of connection is opposite to the flows of the Yangtze River that is quite exceptional as river angle of connection is usually conform to the flows of the main trunk and is influenced by the Coriolis force [30]. The Guandu River flows to the Yangtze at no angle, like its channel is the natural prolongation of the river on the Guandu syncline toward the higher elevations of the Hengshixi anticline.

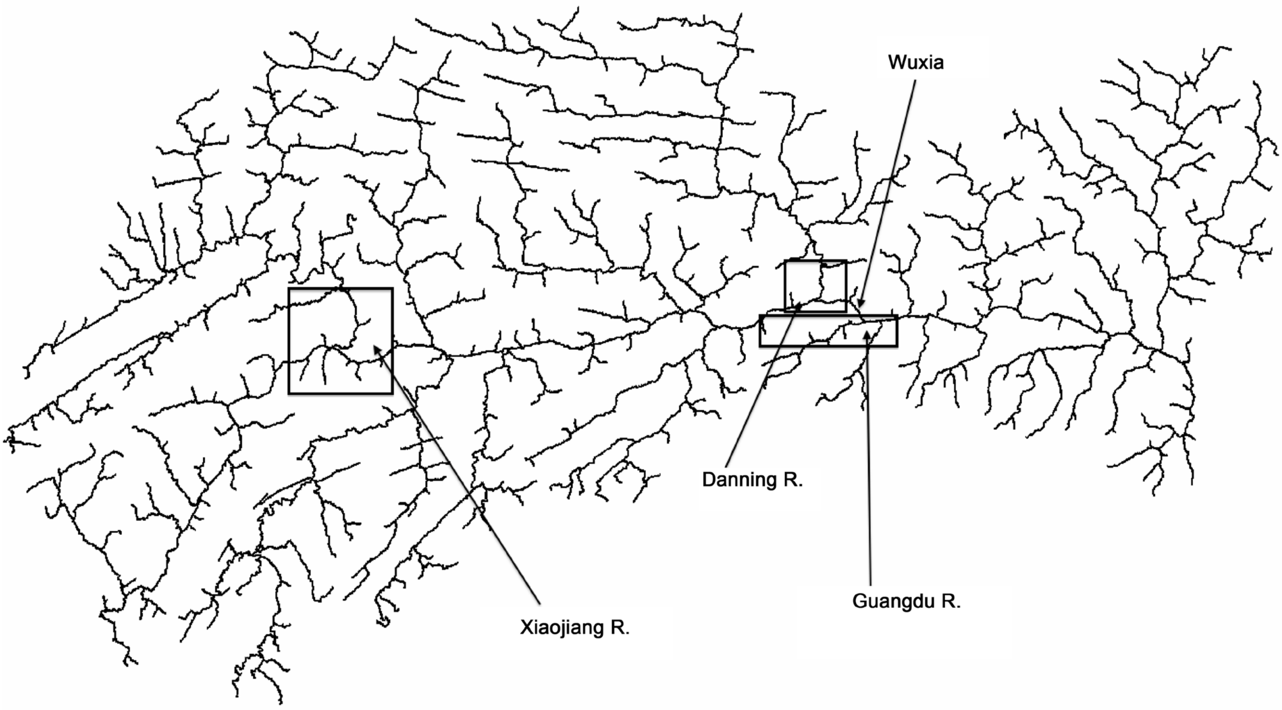

Figure 9. Map showing the angle of junction of the rivers.

This two abnormal river flows give a clue to what happened to the area. It implies that the Daning River used to flow west and the Guandu River was the upper stream of the River flowing east. This idea proves that the Hengshixi anticline used to be the water divide of the two rivers that gave birth to the present day Changjiang.

3.6. Drainage Asymmetry

The asymmetric factor (A_f) can be used to evaluate tectonic tilting at the scale of a drainage basin [76] [77] [78] [79]. A_f is defined as:

$$A_f = 100\left(A_r / A_t\right)$$

where A_r is the area of a part of a watershed on the right of the master stream (looking downstream) and A_t is the total area of the watershed. A_f is close to 50 if there is no or little tilting perpendicular to the direction of the master stream. A_f is significantly greater or smaller than 50 under the effects of active tectonics or strong lithological control. Since the asymmetry factor is susceptible to any tilting perpendicular at the trunk of the stream, any A_f values greater or less than 50 indicate the possibility of tilting. Any drainage basin with a flowing trunk stream that was subjected to a tectonic rotation will most likely have an effect on the tributaries' lengths. Assuming the tectonic activity caused a left dipping to the drainage basin, the tributaries to the left of the main stream will be shorter compared to the ones to the right side of the stream with an asymmetry factor greater than 50, and vice versa [76] [79]. If the values of A_f are superior to 50 means a tilt of the basin to the left and lower values a tilting to the right.

The chart of the asymmetry factor shows that many of the drainage basins are subjects to tilting, meaning surely that tectonics is present in the area (**Figure 10**). To know more how far the basins tilts to the left or to the right, a new concept was introduced that we call asymmetry degree or tilting degree.

The tilting degree is given by the formula:

$$AD = A_f - 50$$

The tilting degree expresses better the asymmetry of the drainage basins. Basins without tilting will have a value 0, while basins subject to tilting will differentiate from 0 with positive values showing tilting to the left and negative values tilting to the right.

The degree of tilting shows that most of the rivers of the area, which are subject to tilting, are moving to the left. 6 basins are tilting to the right (**Figure 11**). It should be noted that many of the drainage basins have tilting degree values close to 0 meaning usually no tilting or very slight tilting. The basins showing high degree of tilting are mainly located in south part between the Xiling gorge and the Wu Gorge and also on the Hengshixi anticline. In the northern part

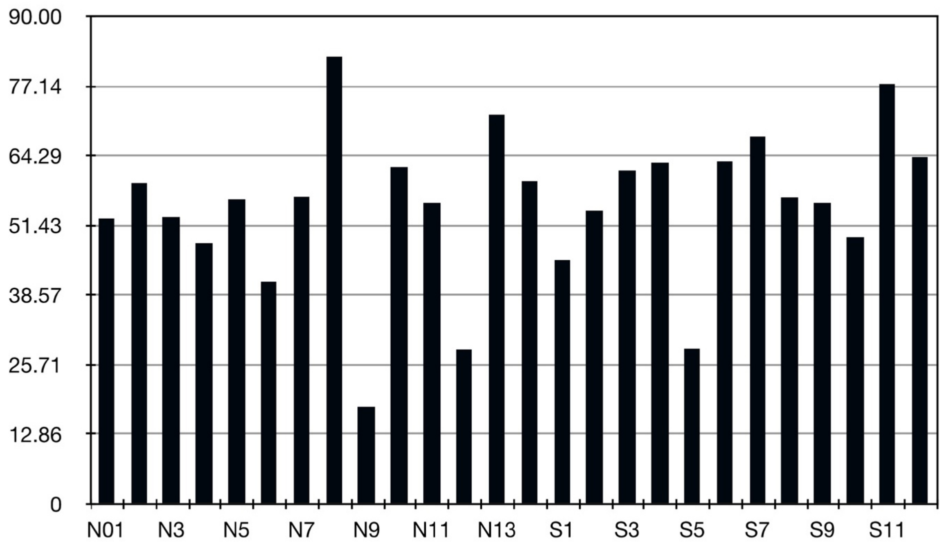

Figure 10. Asymmetry factor data plot for the 26 sampled drainage basins.

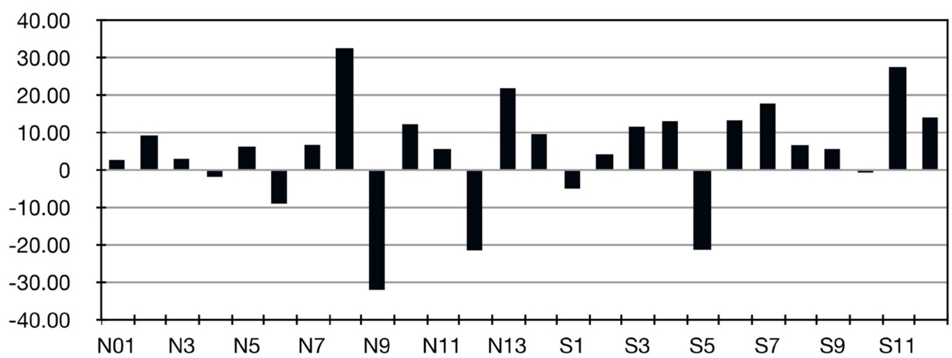

Figure 11. Basin asymmetry degree.

N08, N09, N10, N12 are subject to high tilt. It should be noted that the Huangling anticline area is very stable because the rivers located to this anticline namely the Xiangxi and Jiuwanxi Rivers have very low values of tilting degrees.

4. Discussion

The drainage network of the Three Gorges area as described above has been under the control of structure, lithology and tectonics. The drainage pattern, the shape of the basin, the drainage asymmetry reveal such controls that has been very important during all the development history of the drainage network of the area and the Yangtze River is just part of that history. As described, the Wu Gorge located on the Hengshixi anticline appears to be the line of separation of the different drainage patterns and also of the level of organization of the basin areas. The west of the Wu Gorge is characterized by parallel and trellis drainage patterns and also locates large well-optimized river basins. The two largest and well organized drainage basin in the north of the Yangtze river and west of the Wu gorge has a stream junction angle contrary to the flows of the Yangtze river showing that they used to flow west. Those evidence added together help to understand more the pattern and location of capture of the two paleo-rivers which linked the upper and lower Yangtze River. The evidence gathered reveal that the capture seems to have occurred at the Wu Gorge as the difference of stream junction angles, the optimal organization of drainage basins, the difference of drainage pattern seems to be different from that gorge when looking east or west. A model explaining the pattern of river capture can easily be made. In this pattern, the structure of the area constituted of succession of asymmetric anticlines and synclines seems to have played a major role. This process involved 3 steps: the initiation and development inside the synclines, the extension of drainage from the synclines to the sides of the anticlines and the capture of two streams on the anticline.

- Firstly, because of the morphotectonic structure of the Three Gorges constituted by a succession of anticlines and synclines, strike streams started to develop and extend on the synclines as it happens in such areas [39] [53] [80].
- Secondly, headwater erosion started to develop on the side of the different anticlines. Because of the difference of sloping between the two sides of the anticlines, dip streams formed on the right side while anti-dip streams developed on the right side. That explains why the right side stream has cut very deep valley as it can be seen on the 3D surface map (**Figure 12**).

Finally, an anti-dip stream captured one of the dip stream's head and the two rivers started to flow east. The capture site just lowered down under the forces of riverbed erosion to give the deep and steep Wu Gorge.

The elbow of capture related to such type of capture is a "Z" shape still visible on the course of the Yangtze River at the Wu Gorge. Since the capture happened, the beheaded stream dried up and was replaced later by new drainage basin that is currently higher than the Yangtze River and can be considered as wind gaps.

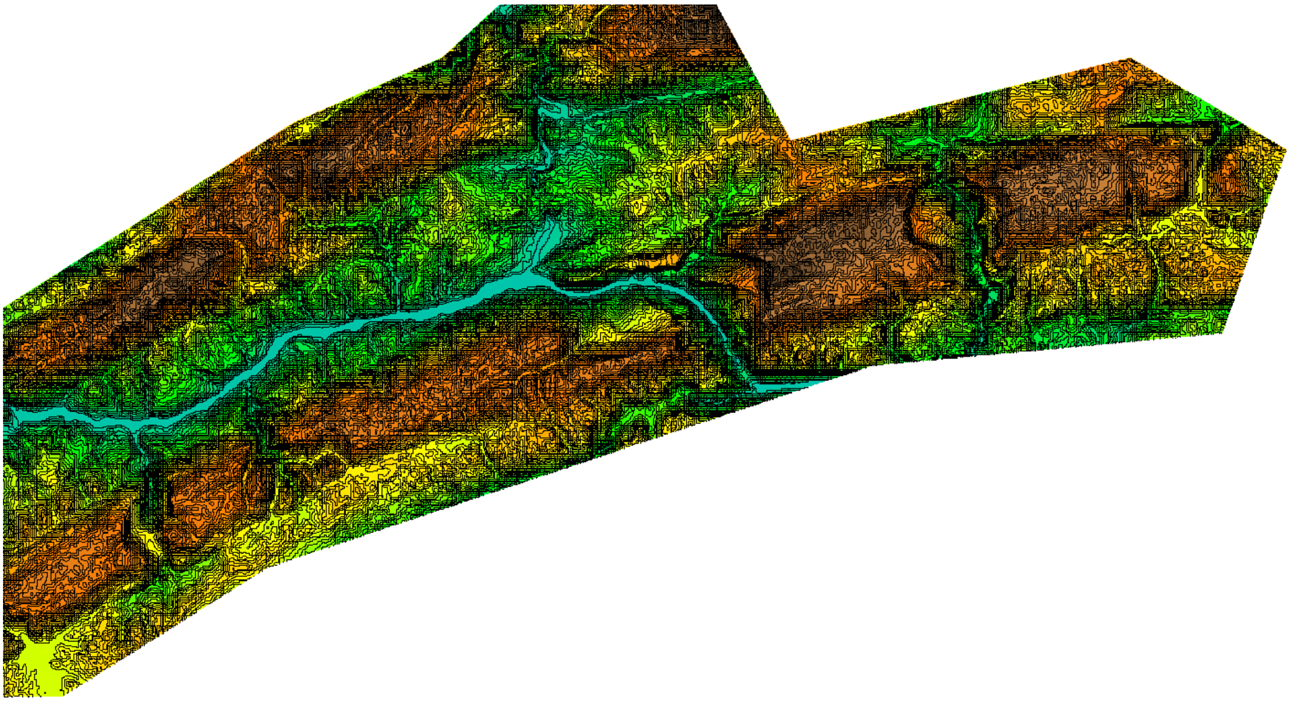

Figure 12. DEM map draped with 30 meters contour lines showing this type of erosion on the Hengshixi anticline.

The largest river west of the Wu gorge (The Xiaojiang River: N12 and the Daning River: N07) still did not adjust their stream junction angle to the new direction of flow resultant from the river piracy. The Guandu River still remains and connects at low angle to the Yangtze River as it used to the head of the middle reaches before the river piracy.

After the river piracy, the down cutting of the gorge went faster because of the large discharge of water from the upper reaches but also because of tectonic uplift as shown by the analysis of basin asymmetry.

5. Conclusion

The present-day Yangtze River is the result of river piracies occurred at different locations along its course especially in its upper reaches. Nowadays, 2 river piracies, at Shigu and at the Three Gorges have been recognized. In the international geomorphological literature, the first river piracy is well documented because it has been the focus of multiple researches as it must be younger and datable materials are easier to retrieve as the area has not been as disturbed as the Three Gorges area where the building of the dam flooded all the river terraces and Quaternary sediments. The high occurrence of rock falls and landslides makes surface cosmogenic dating quite impossible. The result has been that for the area hypotheses formulated since the 1930 such as antecedence, superimposition and some very improbable such as underground river roof collapse triggered by an earthquake are still used to explain the river piracy. However, the Three Gorges is the region where the first capture between the middle and the upper Yangtze occurred enabling the river to develop upwards and extend while integrating numerous other drainage systems and the capture of the Jinsha River seems to have been the last of them during the history of the river. In this paper, we stated that the river capture occurred at the Wu Gorge and that the Hengshixi anticline has long been the drainage divide between the upper and the middle Yangtze. We also defined a model that explains the pattern of capture of the two paleo-rivers under structural and tectonic controls. The time of the river capture will still be a debate as datable materials are very scarce and the analysis of heavy minerals from the sediments in the Jianghan plain have still not revealed its results.

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