NEOTECTONIC SIGNIFICANCE REVEALED BY STREAM LENGTH – GRADIENT INDEX OF THE DAXI RIVER BASIN IN THE SOUTHERN MARGIN OF ORDOS, CHINA

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ABSTRACT:

Since the late Cenozoic era, due to the impact of the Indo- Eurasian plate collision and the northeasterward compression of the Tibetan Plateau, a series of extensional sub-basins and tectonic belts have been formed at the periphery of the Ordos block. Watershed geomorphology plays an important role in studying the formation of rock uplift and river erosion, and are recording the surface evidence on landforms evolution. In this paper, twenty-eight sub-basins and tributaries around Daxihe River, locating at the southern margin of Ordos, were extracted from SRTM1 DEM data. Combined with Hack profile and related river parameters, the tectonic and geomorphic morphology were evaluated synthetically. The results show that (1) The mean SL of this area is 93.9, indicating that the tectonic activities are strong in Daxihe River Basin; (2) The SL values of the northern and southern are 58.9 - 152 and 66 - 137.4, respectively, showing that the uplift rate of eastern margin larger than the southern margin; (3) There are positive power functions between K and drainage area, also between landform relief and slope. This study plays an auxiliary role in regional geological background, structural activity analysis and disaster prediction.

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1. INTRODUCTION

As an evolution result of combined effects of climate, lithology, tectonic and river erosion, the watershed geomorphology plays an important role in studying the formation of rock uplift and river erosion, and recording the surface evidence of landforms. The longitudinal section of the rivers indicates the fluctuation and variation of the river along the direction of water flow, which is an intuitive manifestation of the geomorphology of the basin. Its sensitive response to fault activity is more suitable for recording tectonic movement with time. A large number of scholars have achieved good results in the study of quantitative topographic characteristics and revealing tectonic activity on the basis of river longitudinal profile (Cheng, 2003; Ji et al., 2011; Pirasteh et al., 2018).

Hack (1973) defined a quantitative index, stream length-gradient index, to directly reflect the relationship between flow energy and resistance in the study of Shenandoah Valley river longitudinal profiles. Brookfield (1988) pointed that the regions in southern Asia have higher stream length-gradient index, revealing corrosion resistant bedrock belt, differential uplift zone or unbalanced erosion zone, and considered that the interaction between uplift and climate in the Tibetan Plateau and its surrounding areas determines the development of the main water systems. In the upper reaches of Weihe River, Ji et al. (2011) used Hack curve and SL index pointed out that the river is affected by the tectonic active zone and the hack curve is convex, and proved that there are tectonic activities in many faults in the northeast margin of Tibetan Plateau. Based on SRTM1 DEM data, twenty-eight tributaries of Daxihe River Basin on the southern edge of Ordos block were extracted, and the statistical relationship between geomorphological parameters was discussed. With SL index and Hack curve, the tectonic morphology of the basin was comprehensively evaluated from two aspects in river longitudinal profile and horizontal distribution.

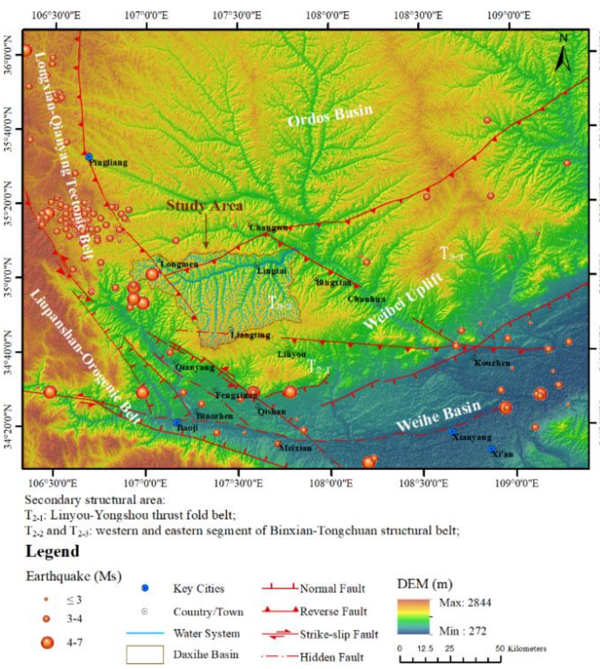

Figure 1. Regional geomorphic and active fault distribution map of study area. The faults and seismic data are from Fan et al., (2016). The SRTM1 data is available at https://earthexplorer.usgs.gov.

2. STUDY AREA

The study area is located in the southwest margin of Ordos block, Longxian-Qianyang fault zone and Weibei uplift (Figure 1). The area of the Daxihe Basin (106°54′-107°53′E, 34°41′-35°10′N) is about 2535.2 km^2, and elevation ranges from about 875 *m* to 1666 *m*. The surface slope is 0 - 57.9 °, and relief is 3.4 - 228.0 *m*. The main rivers in the area are Daxihe River, belonging to the first class tributary of Jinghe River, with a total length of 127 *km* and above 1400 *m* at source. It flows from west to east through Lingtai, Baili and other counties and towns in Gansu Province (Figures 1 and 2). The average annual precipitation and runoff in this basin are 555.9 *mm* and 160 million m^3.

On the basis of the basic tectonic framework formed by the movement of the Yanshan movement, the influence of the collision of the Eurasian plate and the northeast compression of the Tibetan Plateau has formed a series of tension-type fault basin and arc-shaped structural belts on the periphery of the Ordos block (Peltzer et al., 1985; Tapponnier et al., 2001; Yu et al., 2016). The area and its adjacent areas are divided into a series of geotectonic units with obvious topographic differences, such as northsouthward Longxian-Qianyang tectonic belt, eastwestward Weibei uplift structural belt and Weihe basin (Rao et al., 2015; Rao et al., 2017). According to the center of China Seismological Network, earthquakes occurred frequently in this area. Especially under the control of tectonic boundary faults on the west side, nearly 100 earthquakes occurred in Longxian-Qianyang tectonic belt (Figure 1).

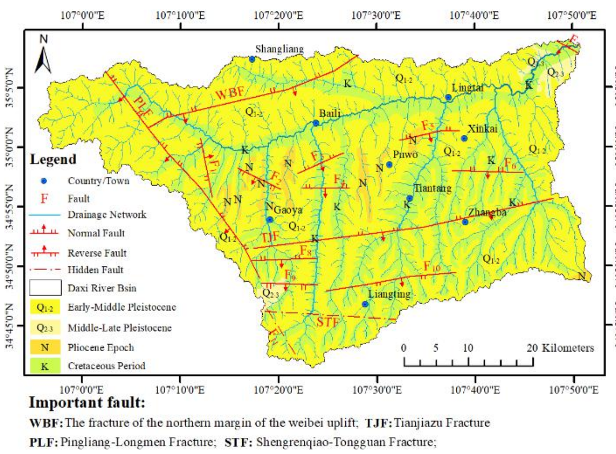

Figure 2. Geologic and fault distribution map of study area, the geological data were from Fan et al. (2016).

As shown in Figure 2, sandstone, conglomerate and clay are the main lithologies in this area. Stratigraphy along the river, from old to new including Cretaceous, Pliocene, Pleistocene and Cretaceous (Yang et al.,2009; Hao et al., 2011; Zhao,2011; Cheng et al., 2018). The surface malan loess has loose structure and large porosity, which is easy to be eroded and stripped. After long-term water system erosion, loess hills, valleys and other geomorphological types dominated by denudation accumulation are gradually formed, becoming a region with serious soil erosion (Yang et al., 2009; Ren et al., 2014).

3. METHODOLOGY

The river longitudinal profile responses the balance between erosion and uplift. When the erosion basis falls during fracture, headward erosion will occur in the valley from the point of fracture, and the slope of bed and the shape of the profile will change accordingly. This imbalance is often caused by the environment, climate, or neotectonic movement (Mackin, 1948; Brookfield, 1988; Zovoili et al., 2004). Hack (1973) connected the unit gradient with the river length, then put forward the stream length-gradient index (SL index), to characterize the relative steepness of the river longitudinal profile (Figure 3). The equation is shown as follows:

$$\mathrm{SL} = \left({}^{\Delta H}/_{\Delta L}\right) \times L \tag{1}$$

where ΔH = dispersion of unit reach
ΔL = stream length of unit reach
L = distance from source to middle point of the reach

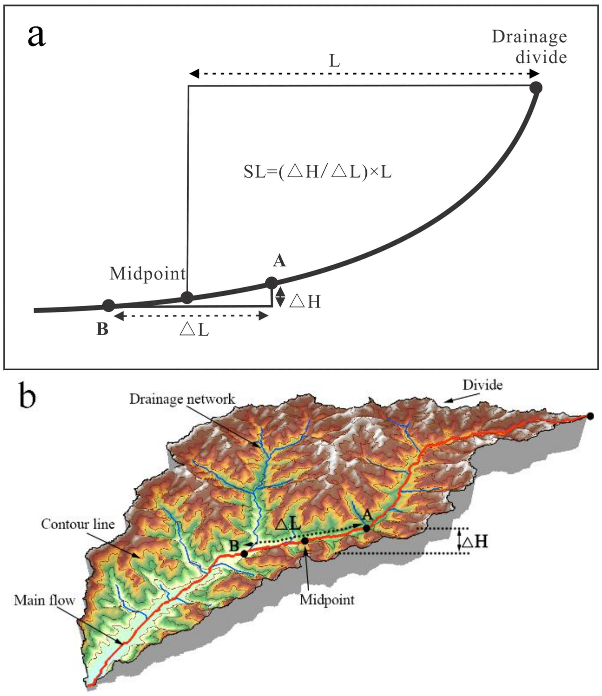

Figure 3. Parameters used in calculation of gradient index, modified from (Hack, 1973).

The value is caused by corrosion resistant rocks, tectonic uplift or unbalanced stream erosion, so the sensitive response of SL index to the basin landform is commonly used in the research of regional tectonic activity (Kaushal et al., 2017). In order to facilitate the analysis, the semi-logarithmic coordinate system is established to display the Hack curve with elevation as the longitudinal axis and logarithm of the distance from source to certain point in reach as the horizontal axis:

$$H = C - k \times lnL \tag{2}$$

where H = altitude at a point on the profile
L = stream length from the point to source
C = constant
k = SL, slope

In absence of external influence, erosion and accumulation form a balance in graded river, the profile is a smooth concave parabola and a straight line in semi-logarithmic coordinates, which is called steady-state channel profile (Chen et al., 2003). Unfortunately, the balance is damaged by the effects of climate, lithologies and tectonics. When bedrock uplift rate is greater than flow erosion rate, the elevation of bedrock channel gradually increases, the river longitudinal profile is raised upwards on the steady-state channel profile accordingly. On the contrary, when flow erosion rate is greater than baserock uplift rate, bedrock channel elevation is reduced, and the profile is concave downward under the steady-state channel profile (Whipple et al., 2000; Whipple et al., 2004). Therefore, the intensity of neotectonic movement can be proved by the concavity and convexity of Hack curve (Mackin, 1948).

4. RESULTS

Firstly, in order to deepen the study of connection between geomorphology and structure of the Daxihe Basin, twenty-eight sub-basins and tributaries around Daxihe River were extracted from SRTM1 DEM data in this study (Figure 4). Obviously, the southern rivers are longer than the northern rivers, and the drainage area has the similar visible results. Interestingly, there are three rivers (S7, S14 and S15) bifurcated at faults line (Figure 4). It is more obvious that the topographic is mainly controlled by the tectonic.

Secondly, the SL index, slope, river length and other relevant parameters were also calculated (Table 1). The twenty-eight tributary river lengths range from 4.6 *km* to 43.8 *km*, with an average length of 16.2 *km* and a dispersion of 154 - 497 *m* from the source to the estuary. The area of sub-basins in the study area is 7.8 - 424.7 km^2, with an average area of 73.3 km^2. The mean slope and relief are 4.5 °, and 96.2 *m*.

Thirdly, the tectonic and geomorphic morphology was evaluated synthetically with Hack profile (Figure 5) and SL grade distribution map (Figure 6). The SL index of 28 tributaries ranges from 58.9 to 152.0. The value of upstream reach is small, but the downstream reach is obviously increased. A large number of studies have shown that the concavity and convexity of Hack section is related to the uplift rate, and profile in the area of high lifting rate is convex (Merritts and Vincent, 1989; Marple and Talwani, 1993; Liu et al., 2016; Pirasteh et al., 2018). It can be seen from Figure 5 that all the Hack profiles are above the steady-state channel profile, showing the overall convex shape, which indicates that the Daxihe River Basin is affected by the structure and the tectonic activity is strong.

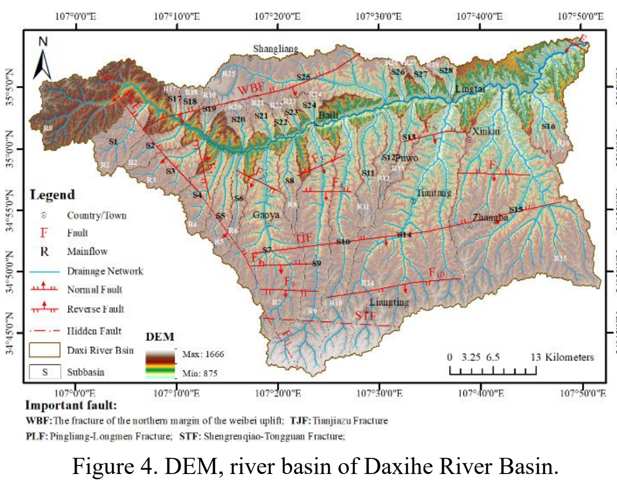

Figure 4. DEM, river basin of Daxihe River Basin.

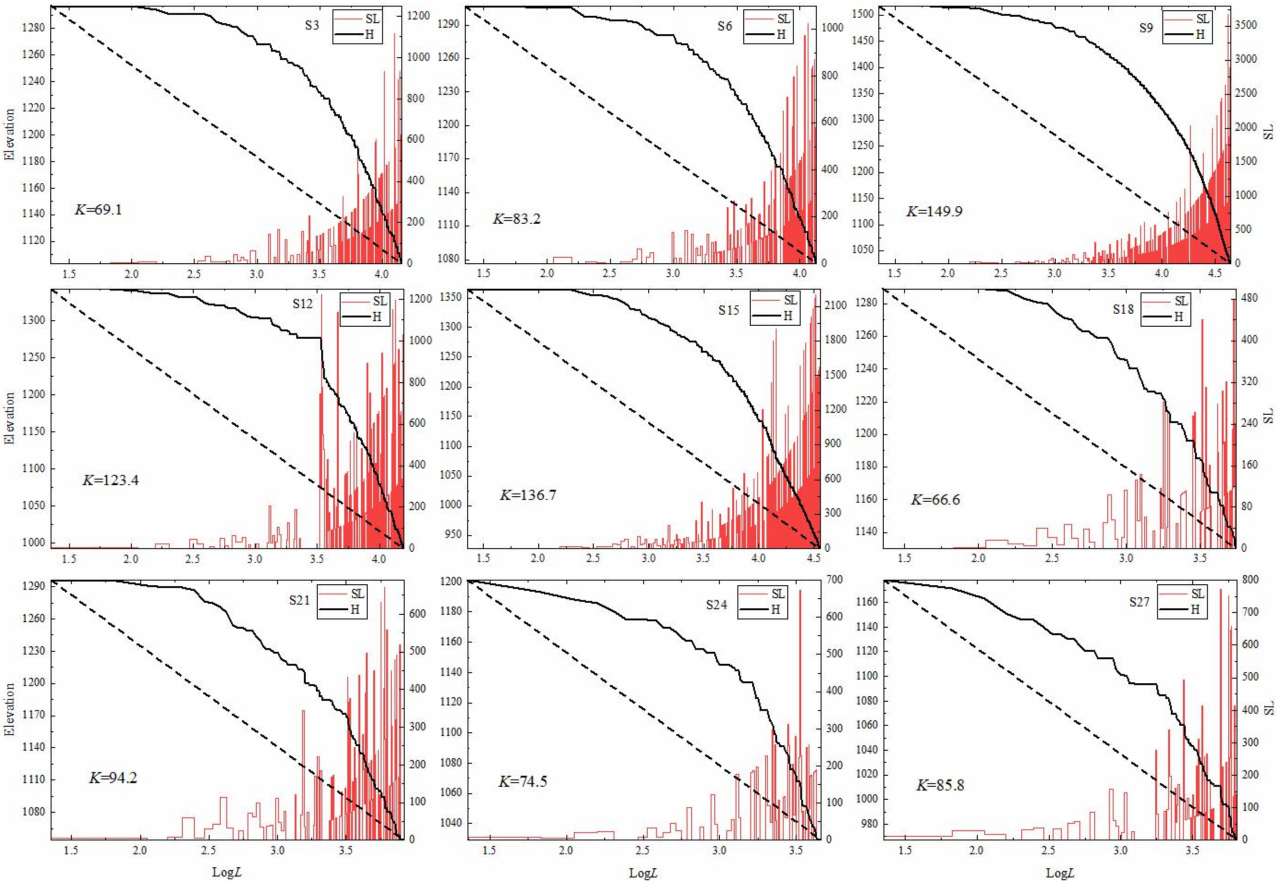

Figure 5. SL index and Hack profile of 9 major tributaries in the the Daxi river basin.

No.	Length	Head	Outlet	Dispersion	Area	Relief	Slope	K
	km	m	m	m	km^2	m	°	
S1	13.214	1324	1160	164	52.067	81.346	3.267	58.9
S2	11.236	1310	1128	182	28.878	90.574	4.356	67.5
S3	14.453	1297	1103	194	53.792	87.697	3.187	69.1
S4	13.629	1269	1089	180	41.883	92.6	2.876	64.7
S5	16.166	1291	1081	210	39.307	85.79	2.702	73.5
S6	13.485	1307	1076	231	22.89	99.55	3.341	83.2
S7	34.084	1375	1059	316	194.077	78.673	2.242	99.4
S8	14.212	1309	1040	269	29.679	109.193	4.218	96.1
S9	43.785	1518	1025	493	170.786	64.167	1.738	149.9
S10	41.822	1506	1009	497	129.101	72.255	1.8	152
S11	19.206	1345	995	350	52.059	95.943	3.739	119.4
S12	15.813	1343	991	352	27.865	107.534	4.799	123.4
S13	14.332	1289	976	313	27.565	106.134	5.291	111.7
S14	40.727	1418	956	462	394.064	75.219	2.147	141.8
S15	35.936	1364	927	437	424.656	88.559	2.598	136.7
S16	11.133	1186	911	275	48.385	126.267	5.364	102.1
S17	4.859	1291	1137	154	7.971	98.974	6.355	66
S18	5.54	1289	1130	159	14.071	106.188	5.117	66.6
S19	7.043	1286	1109	177	14.428	105.665	5.793	70.9
S20	8.047	1278	1075	203	18.884	100.553	5.661	79.5
S21	8.362	1296	1054	242	20.067	108.145	5.732	94.2
S22	4.926	1211	1046	165	7.774	103.096	6.272	70.6
S23	5.466	1214	1034	180	9.152	100.54	5.76	75.1
S24	4.599	1201	1029	172	11.588	98.952	5.836	74.5
S25	31.96	1421	988	433	170.816	105.696	4.708	137.4
S26	6.157	1158	981	177	11.866	103.798	7.182	72.7
S27	6.484	1178	967	211	14.027	105.727	6.892	85.8
S28	7.377	1174	956	218	14.758	94.829	5.861	86.7

Table 1. Parameters of sub-basins

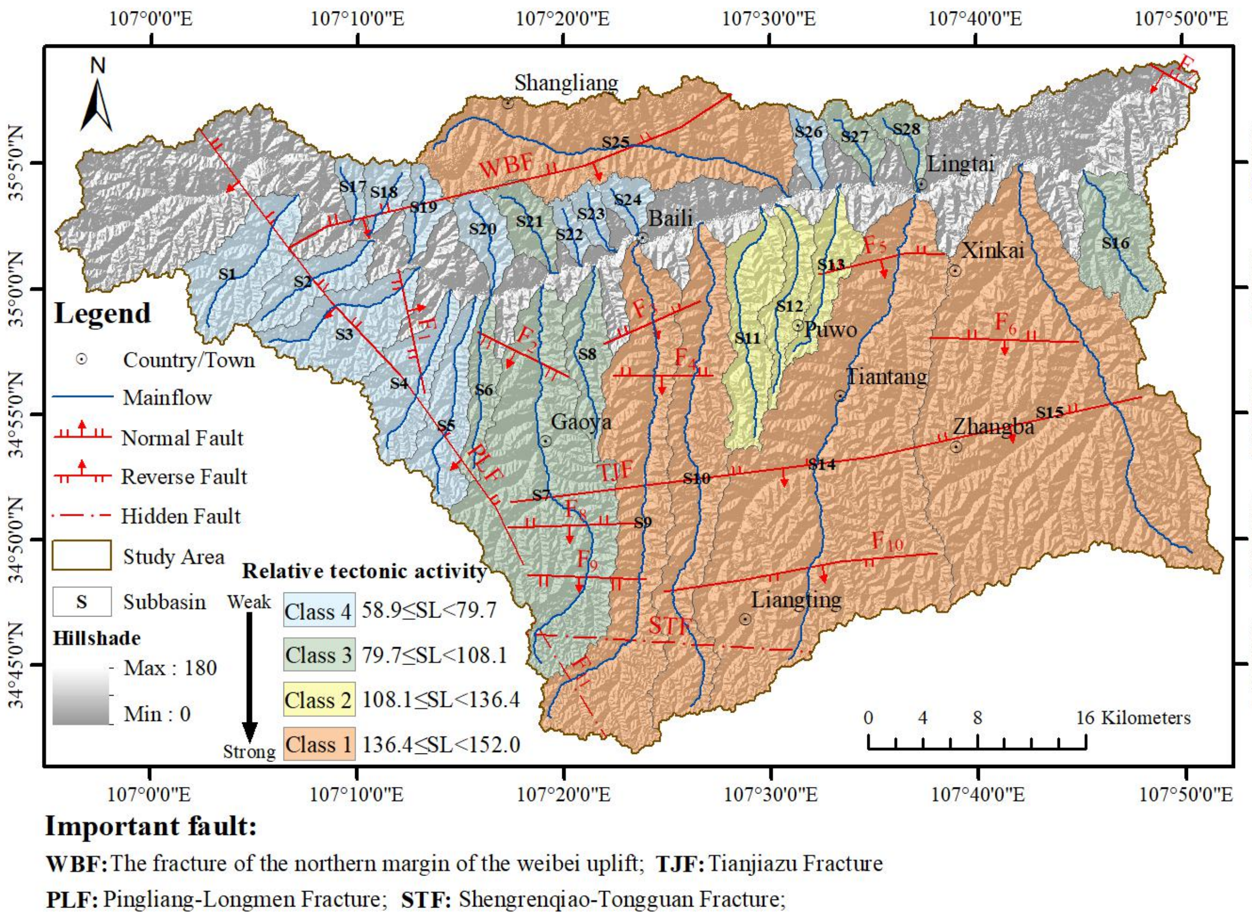

Figure 6. SL index grading distribution map of sub-basins.

Finally, the SL values of the sub-basins are divided into four classes by doubling the standard deviation, which is shown on the distribution map of the sub-basins (Figure 6). On the whole, the east side is higher than the west side, which is considered that there are regional differences in tectonic activity in this area, and the tectonic uplift rate is higher in the eastern margin than the western.

In summary, the northern margin has longer river channels than northern rivers, and the eastern margin have larger SL values, indicating that the tectonic uplift rate is higher in the eastern margin than the western.

5. DISCUSSION

From the view of Figure 2 and results above, it can be seen that the strata in this area are developed along the river with single lithology boundaries and the climate is perennial dry in this region (Brookfield, 1988; Zovoili et al., 2004), thus the geomorphology is mainly controlled by tectonic activity. The river system on the south bank presents obvious synchronous transition pattern, which is an important interpretation sign of the hidden structure. R9, R10 and R14 converge simultaneously in the main stream at the Shengrenqiao-Tongguan fault (STF) (Figure 2). The two points above prove the existence of STF. Meanwhile, R7, R14 and R15 flow synchronously near the Tianjiazu fault (TJF), indicating its structural control.

The river longitudinal profile is the superposition embodiment of the erosion and transport. Without the influence of the external boundary, as the catchment area of the graded river gradually increases from the upstream to the downstream, the kinetic energy of the water flow increases, the particle size of the accumulated gravel in the riverbed is reduced, and the slope tends to be gentle accordingly. However, as shown in Figure 7, the sub-basins are positively correlated with the corresponding K value ($y = 47.23\ x^{0.19}$, $R^2 = 0.54$), indicating that the external influence reacts on the channel in the opposite direction of erosion. That is, the lifting effect increases the potential energy at the channel fault and increases the local slope, and the strong structural uplift weakens the effect of the flow erosion on the surrounding geomorphic form.

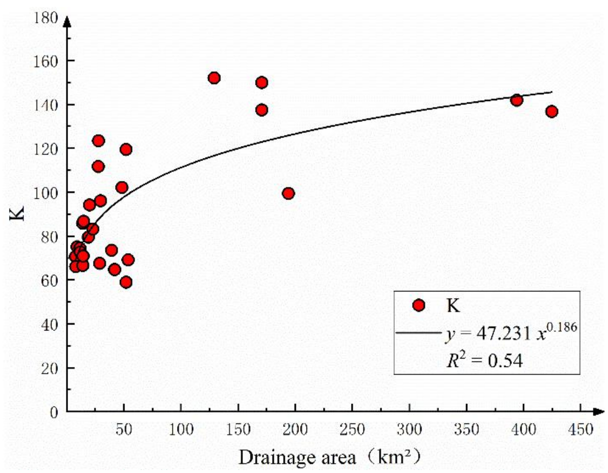

Figure 7. Relationship between K and drainage area.

The terrain relief amplitude is used to characterize the relative relief of surface and the result of uplift and decline of the internal structure of the block (Chen et al., 2016). The slope is the expression of the steep degree of the surface unit, which is expressed by the ratio of dispersion and horizontal distance on slope surface. Generally, the steep channel has a greater kinetic flow energy, and erosion capacity is more intense. In the case of a gentle slope, river length is approximately regarded as horizontal distance, and then the equal relationship between slope, river length and terrain relief amplitude are established. As shown in Figure 8, the mean slope and relief of tributaries in the study area show a positive power function (y = 64.92 $x^{0.27}$, R^2 = 0.66), which suggesting that the uplift in this area is stronger than the erosion. Along with the increase of slope, the increase of the terrain relief amplitude on the contrary is slow, which is due to mutual suppression of the elevation of tectonic uplift and erosion decline in block.

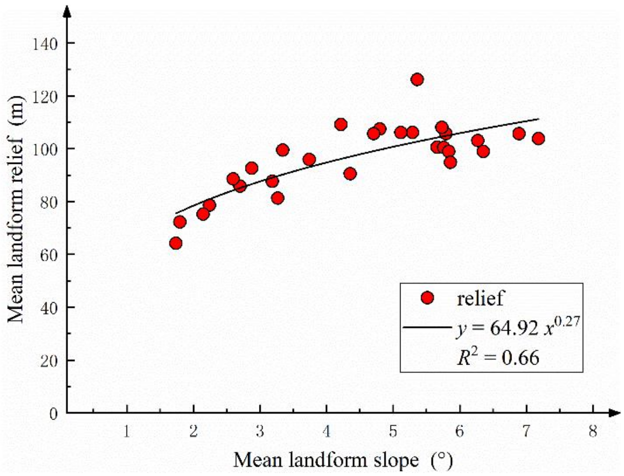

Figure 8. Relationship between relief and slope.

6. CONCLUSION

In Daxihe River Basin, twenty-eight main channels were extracted to analysis tectonic activities by using SL analysis and SRTM1 data. The geomorphology is mainly controlled by tectonic activity in this area. (1) SL index and Hack profile showed that the tectonic activities are strong and uplift rate is higher in the eastern margin than the western margin in Daxihe River Basin; (2) There is a positive power function between K and drainage area, indicating that the drainage area will be enlarged with K values; (3) The mean landform relief is positively correlated with the corresponding slope, showing that the steeper slope, the more obvious relief. This study enriches the research on regional geological background, structural activity and geological disaster.

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REFERENCES

Brookfield M.E., 1988: The evolution of the great river systems of southern Asia during the Cenozoic India-Asia collision: rivers draining southwards. *Geomorphology*, 22(3/4), 285-312. doi.org/10.1016/S0169-555X(97)00082-2.

Chen X.X., Zhang X.J., Chang Q.R., 2016: A Study on Optimal Statistical Unit for Relief Amplitude of Land Surface in Shaanxi Province. *Bulletin of Soil & Water Conservation*, 36(03), 265-270+370. doi.org/10.13961/j.cnki.stbctb.2016.03.046. (in Chinese with English abstract).

Chen Y.C., Sung Q., Cheng K.Y., 2003: Along-strike variations of morphotectonic features in the Western Foothills of Taiwan: tectonic implications based on stream gradient and hypsometric analysis. *Geomorphology*, 56(1/2), 109-137. doi.org/10.1016/s0169-555x(03)00059-x.

Cheng Y.L., He C.Q., Rao G., Yan B., Lin A.M., Hu J.M., Yu Y.L., Yao Q., 2018: Geomorphological and structural characterization of the southern Weihe Graben, central China: Implications for fault segmentation. *Tectonophysics*, 722, 11-24. doi.org/10.1016/j.tecto.2017.10.024.

Hack J.T., 1973: Stream-profile analysis and stream-gradient indices. *U.S. Geological Survey Journal of Research*, 1, 421-429.

Hao S.L., Sun D., Bu J., Wu C.Y., Huang X.D., 2011: Sedimentary facies of middle ordovician pingliang stage in southern margin of ordos basin. *Gansu Geology*, 20(01), 16-23. (in Chinese with English abstract).

Ji Y.P., Gao H.S., Pan B.T., Li Z.M., Guan D.S., Du G.Y., 2011: Implication of active structure in the upper reaches of Weihe river basin from stream length-gradient index (SL index) and Hack profile. *Journal of Lanzhou University (Natural Science Edition)*, 2011(4), 1-6. (in Chinese with English abstract).

Kaushal R.K., Singh V., Mukul M., Jain V., 2017: Identification of deformation variability and active structures using geomorphic markers in the Nahan salient, NW Himalaya, India. *Quaternary international*, 462(Dec.30), 194-210. doi.org/10.1016/j.quaint.2017.08.015.

Liu X.L., Li X., Liu Z.M., Chen X.L., Li S.L., 2016: Implication of active structure in Ebinur Lake basin by stream length-gradient index and Hack profile. *Geoscience & Remote Sensing Symposium*. doi.org/10.1109/IGARSS.2016.7730584.

Mackin J.H., 1948: Concept of the graded river. *Geological Society of America Bulletin*, 59(5), 463-512. doi.org/10.1130/0016-7606(1948)59[463:COTGR]2.0.CO;2.

Marple R.T., Talwani P., 1993: Evidence of possible tectonic upwarping along the South Carolina coastal plain from an examination of river morphology and elevation data. *Geology*, 21(7), 651-654. doi.org/10.1130/0091-7613(1993)021<0651:EOPTUA>2.3.CO;2.

Merritts D., Vincent K.R., 1989: Geomorphic response of coastal streams to low, intermediate, and high rates of uplift, Medocino triple junction region, northern California. *Geol.soc.am.bull*, 101(11), 1373-1388. doi.org/10.1130/0016-7606(1989)1012.3.CO;2.

Peltzer G., Tapponnier P., Zhitao Z., Xu Z.Q., 1985: Neogene and Quaternary faulting in and along the Qinling Shan. *Nature*, 317(6037), 500-505. doi.org/10.1038/317500a0.

Pirasteh S., Li J., Chapman M., 2018: Use of LiDAR-derived DEM and a Stream Length-Gradient Index Approach to Investigation of Landslides in Zagros Mountains, Iran. *Geocarto International*, 33(9), 912-926. doi.org/10.1080/10106049.2017.1316779.

Rao G., Cheng Y.L., Yu Y.L., Yan B., Lin A.M., 2017: Tectonic characteristics of the Lisha Piedmont Fault in the SE Weihe Graben (central China), as revealed by the geomorphological and structural analyses. *Geomorphology*, 282, 52 - 63. doi.org/10.1016/j.geomorph.2017.01.014.

Rao G., Lin A.M., Yan B., 2015: Paleoseismic study on active normal faults in the southeastern Weihe Graben, central China. *Journal of Asian Earth Sciences*, 114, 212 - 225. doi.org/10.1016/j.jseaes.2015.04.031.

Ren X.Z., Shen P.X., Chen F.L., 2014: Analysis on the geological features and ore-forming conditions at the southern margin of Erdos basin. *World Nuclear Geoscience*, 31(03), 514 - 518. doi.org/10.3969/j.issn.1672-0636.2014.03.004. (in Chinese with English abstract).

Tapponnier P., Zhiqin X., Roger F., Meyer B., Arnaud N., Wittlinger G., Yang J.S., 2001: Oblique stepwise rise and growth of the Tibet plateau. *Science*, 294(5547), 1671 - 1677. doi.org/10.1126/science.105978.

Whipple K.X., 2004: Bedrock rivers and the geomorphology of active orogens. *Annual Review of Earth and Planetary Sciences*, 32(1), 151 - 185. doi.org/10.1146/annurev.earth.32.101802.120356.

Whipple K.X., Hancock G.S., Anderson R.S., 2000: River incision into bedrock: Mechanics and relative efficacy of plucking, abrasion, and cavitation. *Geological Society of America Bulletin*, 112(3), 490-503. doi.org/10.1130/0016-7606(2000)112<490:RIIBMA>2.0.CO;2.

Yang Q., Sun X.J., Wang A.J., Zhang J.Y., 2009: Situation and Prevention Measures of Geological Hazards in Lingtai County, Gansu Province. *The Chinese Journal of Geological Hazard and Control*, 20(4), 45-49. doi.org/10.3969/j.issn.1003-8035.2009.04.010. (in Chinese with English abstract).

Yu Y., Chen Y.J., 2016: Seismic anisotropy beneath the southern Ordos block and the Qinling-Dabie orogen, China: Eastward Tibetan asthenospheric flow around the southern Ordos. *Earth & Planetary Science Letters*, 455, 1-6. doi.org/10.1016/j.epsl.2016.08.026.

Zhao D.H., 2011: Evaluating on Surface Water Resources in Daxi River Basin in Lingtai County, Gansu Province. *Gansu Metallurgy*, 33(06), 82-84+118. doi.org/10.16042/j.cnki.cn62-1053/tf.2011.06.007. (in Chinese with English abstract).

Zovoili E., Konstantinidi E., Koukouvelas I.K., 2004: Tectonic geomorphology of escarpments: the cases of Kompotades and Nea Anchialos faults. *Bulletin of the Geological Society of Greece*, 36(5), 1716-1725. doi.org/10.12681/bgsg.16579.