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Morphotectonic Characteristics of the Iponan River Watershed in Cagayan de Oro City, Philippines

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Abstract

Using the Advanced Land Observing Satellite Phased Array type L-band Synthetic Aperture Radar (ALOS PALSAR) digital elevation model, morphometric parameters were derived and utilized in the morphotectonic analysis of the Iponan River Watershed. Morphometric analysis of the area revealed that the watershed is in the early maturity of geological stage. Its mountain front sinuosity index indicates that portions of the watershed area are slightly and tectonically active. Other parameters suggest that the area is experiencing rapid uplift and undergoing ground tilting that may be influenced by tectonic activity. The presence of a tectonic line running through the extent of the Iponan River could be a potential source of tectonic activity and influence morphological processes in the watershed area. Its channel concavity suggests that the watershed has rapidly rising slopes as may be caused by the uplift. Overall, the Iponan River Watershed area is generally tectonically active and that its morphotectonic processes may be moderately controlled by tectonic activity.

Keywords: morphotectonic, ground tilting, uplift, channel concavity, tectonically active

1. Introduction

Mountain rivers are the primary source of water supply among many places on the planet and are responsible for the formation of drainage basins. Understanding river basin dynamics require determination of various basin characteristics such as morphotectonic parameters (Biswas *et al.*, 2014). Interpreting various features of the drainage basin can provide critical information on how geomorphic processes and tectonic activities have influence the formation of geomorphic features (Lone, 2017). The last few decades have experienced the rise in the application of satellite-based imageries and other geospatial technologies in ground surface analyses. Three-dimensional images such as digital elevation models (DEMs) and other surface methods such as remote sensing have been widely used to provide critical information and interpretation of geomorphic processes and tectonic activities of certain drainage basins (Dar *et al.*, 2013; Badura and Przybylski, 2005). These geomorphic features resulting from tectonic and surficial processes can be best described by tectonic geomorphology analysis (Burbank and Anderson, 2001). Morphotectonic analysis can be carried out employing a variety of thematic maps. Digital elevation models form the basis of performing morphotectonic analysis and facilitates analysis of surface evidences of tectonic processes much easier (Silva *et al.*, 2007). Tectonic activities most often produce and modified landforms. Evaluation of these landforms, particularly those that are generated by active faults, e.g. mountain fronts, provide relevant information for the estimation on how tectonic activities gradually deform land features (Verrios *et al*., 2004).

The Iponan River Watershed is the second largest watershed in Barangay Iponan, Cagayan de Oro City. Its major tributary, the Iponan River, extends 147 kilometers to the river mouth. It is also among the river systems in Cagayan de Oro City and Misamis Oriental that cause catastrophic damage as flood waters swift through villages along its path. Recently, the Philippine Institute of Volcanology and Seismology (PHIVOLCS) discovered new active faults within Misamis Oriental, one of which was found in Barangay Iponan. The discovery of the Iponan fault line undermines the local government units' existing priority programs and management plan in terms of preparedness and response to potential future hazards brought about the fault line in addition to the threat of flood hazard. The study evaluates the different morphotectonic parameters of the Iponan Watershed using available digital elevation model and how these parameters will influence morphometric processes and tectonic activities of the study area and lastly generate considerable information that can be used in the formulation of disaster risk reduction and management plan.

2. Methodology

The morphotectonic analysis of Iponan River Watershed was carried out with the use of a 12.5m by 12.5m resolution ALOS PALSAR digital elevation model from the Alaska satellite facility. Processing of the digital elevation model was performed under a geographic information system (GIS) platform.

The use of specific toolbox within the GIS platform were also used for particular DEM processing and calculation. The study also employed spreadsheets for manual calculations.

2.1 Study Area

The Iponan River Watershed was delineated using GIS. The watershed area is situated between longitudes 124.40°N and 124.63°N and latitudes 8.20°E and 8.53°E (Figure 1a). The watershed has a total estimated area of 41750 hectares that comprise portions of the cities of Cagayan de Oro and Iligan, and four other municipalities of Misamis Oriental. The north-south elongation of the watershed is marked by its highest elevation of 1176 masl along the eastern and southern portions and the lowest part is at its northern portion at 68 masl. The geologic formation of the watershed area was extracted from the Mines and Geosciences Bureau (2014) (Morrison, 2014) (Figure 1b). The Iponan River Watershed consisted of at different geologic formation as part of the geologic units of Mindanao including uplifted Jurassic and Miocene marine sediments, tertiary volcanics and metamorphosed basement units with sedimentary basins between uplifts making up the rest of the formation in the island (Morrison, 2014). Extending a few kilometers from downstream to the river mouth are recent alluvial, lacustrine or beach deposits covering an estimated area of 2,096 hectares. A Pliocene-Quaternary formation running about 18 kilometers from north to south is enclosed within a Miocene-Pliocene formation that also extend from north to south of the watershed. The Pliocene-Quaternary formation is described as non-volcanic cone, generally pyroxene andesite, with dacitic or andesitic plugs. The Miocene-Pliocene formation is depicted as marine clastic overlain by extensive, locally transgressive pyroclastic and tuffaceous sedimentary rocks. The Pliocene-Pleistocene formation is the formation within the watershed area primarily composed of marine and terrestrial sediments. The undifferentiated part is represented largely by graywacke and metamorphosed slate interbedded/intercalated with phyllitic, basic and intermediate flow and/or pyroclastic. The delineation of the fault line was taken from the Japan International Cooperation Agency (JICA) Survey Team (DPWH, 2014) for the flood risk management project of Cagayan de Oro River. From Figure 1c, the Iponan tectonic line runs through the Iponan River, extending approximately 36 kilometers to the south.

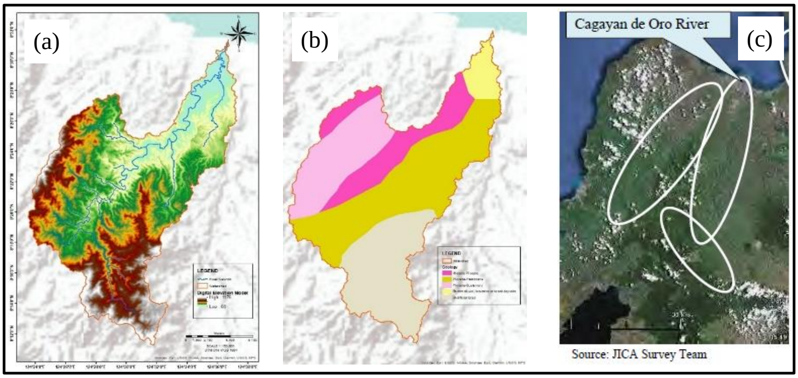

Figure 1. a) Location of Iponan River Watershed; b) Geologic Formation and c) Tectonic Lines delineated (white) by the JICA survey team showing Iponan River adjacent to Cagayan de Oro River

2.2 Morphometric Analysis

The basin geomorphic characteristics have long been believed to be important indices of surface processes. These parameters have been used in various studies of geomorphology and surface-water hydrology. The morphometric parameters for each basin were directly computed from the vector data extracted from the topographic maps.

2.2.1 Hypsometric Analysis of Iponan River Watershed

Using the 12.5m x 12.5m resolution DEM, different morphometric parameters were generated using a hypsometry tool within the GIS platform – drainage network, geometry, drainage texture and basin relief. Each of these parameters has their components. A hypsometric analysis of the watershed area including the hypsometric integrals were carried out with respect to the location of the catchment and stream order (Figure 2a). In the calculation of hypsometric integrals, the basis was the subwatershed areas of the entire Iponan River Watershed. Using the elevation-relief ratio, the following equation is used:

$$E \approx HI = \frac{Elev_{mean} - Elev_{min}}{Elev_{max} - Elev_{min}} \quad (1)$$

where:

E = The elevation relief ratio equivalent to the hypsometric integral
HI = The hypsometric integral
$Elev_{mean}$ = The weighted mean elevation of the watershed;
$Elev_{max}$ = The maximum elevation of the watershed; and
$Elev_{min}$ = The minimum elevation of the watershed.

2.2.2 Mountain Front Sinuosity

As the degree of tectonic activity influence mountain morphology along the front, this index determines the profiles of mountain fronts (Sarp *et al.*, 2011). Mountain front sinuosity is defined by the equation:

$$Smf = \frac{Lmf}{Ls} \tag{2}$$

where:

Smf = The mountain front sinuosity;
Lmf = The true distance along a contour line; and
Ls = The straight line distance along the contour line (Figure 2b).

2.2.3 Valley Floor Width to Height Ratio

As areas within the watershed undergoes rapid uplift, such tectonic activities are marked by incised streams having narrow valley floor and v-shaped valley features. The determination of *Vf* would show how tectonic activities influence valley floors and shapes. The index can be expressed as:

$$Vf = \frac{2Vw}{(Eld-Esc) + (Erd-Esc)} \tag{3}$$

where:

Vf = The valley floor width to height ratio;
Vw = The width of the valley floor;
Eld Erd = The left- and right-hand valley divides going down stream; and
Esc = The elevation of the stream channel or valley floor (Figure 2c).

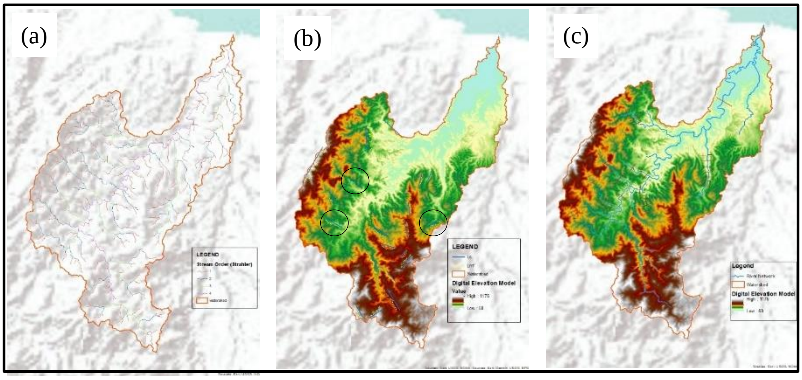

Figure 2. a) Strahler stream order; b) delineation of *Lmf* and *Ls* (in circles) for *Smf* calculation; c) cross-sections for valley floor width to height ratio determination

2.2.4 Asymmetry Factor

To determine if the watershed area is experiencing tectonic tilting, the asymmetry factor was considered. Determination of the different parameters of the asymmetry factor has been carried out within the GIS platform and manually calculated in a spreadsheet. The *AF* is calculated using the equation:

$$AF=100\frac{A_r}{A_t} \quad (4)$$

where:

A_r = The area on the hydrographic right; and
A_t = The total area of the sector.

2.2.5 Transverse Topographic Symmetry Factor

The determination of transverse topographic symmetry factor was carried out for assessment of basin asymmetry and active tectonics in Iponan Watershed. Measurement of *TTSF* was prepared within the GIS environment by quantifying the deviation of the drainage basin centerline from the centerline of the active meander belt as well as the deviation of the basin centerline from the basin divide (Figure 3). The factor is expressed as:

$$TTSF=\frac{D_a}{D_d} \quad (5)$$

where:

D_a = The space from the centerline of the drainage basin to the centerline of the active belt; and

D_d = The space from the centerline to the basin divide.

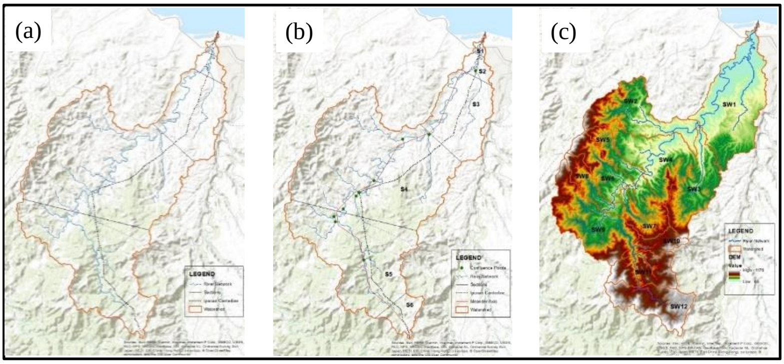

Figure 3. a) Centerline of the Iponan River Watershed; b) sectioning of the watershed area; c) location of subwatersheds

2.2.6 Stream Length Gradient Index

The aim of the stream length gradient index is to identify morphometric anomalies of the stream's longitudinal profile and how it correlates the factors influencing lithology and tectonics of the study area. For a particular reach of interest, the stream length gradient index is expressed as:

$$SL_{section} = \frac{\Delta h}{\Delta l} \times L \tag{6}$$

where:

SL = The stream length gradient index;

Δh = the difference between the highest and lowest section of a channel;

Δl = The horizontal projection of the channel section; and

L = The length of the farthest point of the channel section to the headwaters of the basin.

A relationship between $SL_{section}$ and SL_{TOTAL} is also carried out to identify anomalies within the drainage basin by dividing $SL_{section}$ by SL_{TOTAL} where SL_{TOTAL} is represented as:

$$SL_{TOTAL} = \frac{\Delta h}{ln\, L} \tag{7}$$

where:

Δh = The total change in elevation; and
$ln\, L$ = the logarithm of the total length L of the channel.

For this study, however, only the main stream trunk was sampled.

2.2.7 Channel Concavity

Channel concavity is the longitudinal change in slope of a certain reach. For this study, a concavity index theta (θ) was calculated, representing the slope of a line regressed through a log-log plot of channel slope (percent rise) vs. drainage area. The whole process of generating topographic features was carried out within the GIS platform using a number of GIS tools to extract and convert features and finally create a concavity graph using a spreadsheet.

2.3 Tectonic Analysis

Tectonic analysis for the Iponan River Watershed were based on the calculated morphometric parameters. Geomorphic indices were used in identifying areas that have undergone tectonic deformations or relative variations of tectonic activities. While these morphometric parameters do not entirely make up the analysis requirement for geomorphological analysis, their computation, common relationship and potential for statistical evaluation are valuable support for morphotectonic assessment (Pánek, 2004).

3. Results and Discussion

The use of various approaches based on satellite imagery and topographic maps have been instrumental in the assembling information relevant to the study. Geomorphic parameters like hypsometric curve and integral, mountain front sinuosity, asymmetry factor, transverse topographic symmetry factor and others were also derived from these satellite-based imagery and topographic maps.

3.1 Hypsometric Analysis

Figure 4a is the hypsometric curve of Iponan River Watershed showing a knickpoint. The hypsometric feature of a drainage basin can be primarily influenced by tectonic, lithologic and climatic factors. For the Iponan River Watershed, its hypsometric curve suggest that the watershed area is in a mature in reference to Figure 4b. It also worthy to note that knickpoints such as the one in hypsometric curve of the watershed can be used as geormorphic markers for non-uniform and unsteady uplift as well as unsteadiness in watershed divides in an actively deforming setting (Pavano *et al.*, 2016) .

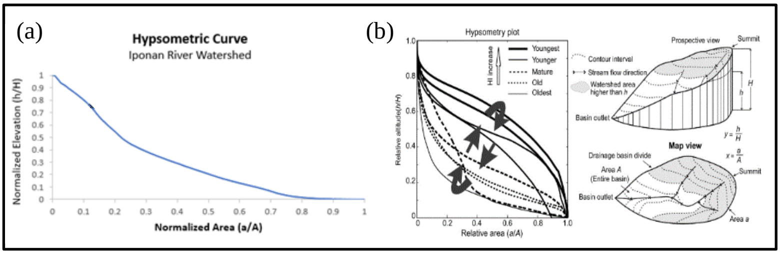

Figure 4. a) Hypsometric curve of Iponan River Watershed and b) geomorphic cycle development showing changes in hypsometric curves (Pérez-Peña *et al.*, 2009)

Calculation of the hypsometric integral among the 12 subwatershed areas shows that all subwatersheds have a consistent HI value of 0.5, suggesting that Iponan River Watershed is in a geological stage of early maturity (Table 1). The HI values of 0.5 is also possibly related to slight to moderate erosion and moderately impacted by tectonic activities. It is documented that HI values are

Table 1. Hypsometric integrals of Iponan River Watershed

Subwatershed	HI	Geological Stage	Subwatershed	HI	Geological Stage
SW1	0.50	Early Maturity	SW7	0.50	Early Maturity
SW2	0.50	Early Maturity	SW8	0.50	Early Maturity
SW3	0.50	Early Maturity	SW9	0.50	Early Maturity
SW4	0.50	Early Maturity	SW10	0.50	Early Maturity
SW5	0.50	Early Maturity	SW11	0.50	Early Maturity
SW6	0.50	Early Maturity	SW12	0.50	Early Maturity

influenced by tectonic activity is evident in large scale basins (≥1000km^2) and lithology at small scales (≤100 km^2) (Lifton and Chase, 1992). Other studies also show using numerical modes that upliftment activities in the basin scale is strongly related to HI (Saha and Pal, 2016).

3.2 Mountain Front Sinuosity

Calculation and classification for the nineteen fronts of Iponan River Watershed was based on Bull and McFadden (1977). Accordingly, *Smf* values less than 1.4 indicates tectonically active areas; *Smf* values between 1.4 and 3 denotes areas that are slightly active; and *Smf* greater than 3 suggest inactive areas. Table 2 shows the calculated values of *Smf* with values ranging from 1.03 to 1.60, revealing that the Iponan River Watershed is generally a tectonically active area.

Table 2. Mountain front sinuosity of Iponan River Watershed

Lmf	*Ls*	*Smf*	Interpretation	*Lmf*	*Ls*	*Smf*	Interpretation
6608.50	4836.53	1.37	Tectonically Active	1806.66	1444.18	1.25	Tectonically Active
2468.79	1835.50	1.35	Tectonically Active	2513.47	1951.59	1.29	Tectonically Active
2731.83	2261.43	1.21	Tectonically Active	4071.64	3037.72	1.34	Tectonically Active
2242.10	1847.65	1.21	Tectonically Active	2405.79	1728.36	1.40	Slightly Active
2196.14	1935.40	1.13	Tectonically Active	2322.49	1836.33	1.26	Tectonically Active
2046.62	1728.20	1.18	Tectonically Active	1821.08	1139.39	1.60	Slightly Active
2353.51	1925.40	1.22	Tectonically Active	2512.82	2011.22	1.25	Tectonically Active
1718.02	1537.20	1.12	Tectonically Active	4637.71	3160.36	1.47	Slightly Active
1489.76	1323.88	1.13	Tectonically Active	3475.43	3036.10	1.14	Tectonically Active
1426.72	1349.46	1.06	Tectonically Active				

3.3 Valley Floor Width to Height Ratio

Calculation for *Vf* has been carried out in the different tributaries and parts of the main channel of the Iponan River. A total of 48 measurements have been made. Table 3 below shows the various *Vf* values from these tributaries. The valley floor width to height ratio is used to differentiate mountain features carved by glaciers (broad, U-shaped valleys) and those carved by streams (tight, V-shaped valleys). However, this index has also been used to identify parts of mountain front that is experiencing or undergoing tectonic activities.

Table 3. Valley floor width to height ratio of Iponan River Watershed

Tributary	*Vf*	Inferences	Tributary	*Vf*	Inferences	Tributary	*Vf*	Inferences	Tributary	*Vf*	Inferences
T1	0.41	Experiencing rapid uplift	T13	0.33	Experiencing rapid uplift	T25	0.32	Experiencing rapid uplift	T37	1.93	Less Active
T2	0.61	Experiencing rapid uplift	T14	0.29	Experiencing rapid uplift	T26	0.15	Experiencing rapid uplift	T38	5.23	Less Active
T3	0.20	Experiencing rapid uplift	T15	0.30	Experiencing rapid uplift	T27	0.52	Experiencing rapid uplift	T39	0.31	Experiencing rapid uplift
T4	0.36	Experiencing rapid uplift	T16	0.16	Experiencing rapid uplift	T28	0.26	Experiencing rapid uplift	T40	0.30	Experiencing rapid uplift
T5	0.13	Experiencing rapid uplift	T17	0.11	Experiencing rapid uplift	T29	0.25	Experiencing rapid uplift	T41	0.42	Experiencing rapid uplift
T6	0.25	Experiencing rapid uplift	T18	0.67	Experiencing rapid uplift	T30	1.52	Moderately Active	T42	0.53	Experiencing rapid uplift
T7	0.05	Experiencing rapid uplift	T19	0.11	Experiencing rapid uplift	T31	1.33	Moderately Active	T43	0.89	Experiencing rapid uplift
T8	0.29	Experiencing rapid uplift	T20	0.65	Experiencing rapid uplift	T32	0.30	Experiencing rapid uplift	T44	0.27	Experiencing rapid uplift
T9	0.22	Experiencing rapid uplift	T21	0.47	Experiencing rapid uplift	T33	0.32	Experiencing rapid uplift	T45	1.79	Less Active
T10	0.24	Experiencing rapid uplift	T22	0.57	Experiencing rapid uplift	T34	0.34	Experiencing rapid uplift	T46	10.43	Less Active
T11	0.18	Experiencing rapid uplift	T23	0.24	Experiencing rapid uplift	T35	1.71	Less active	T47	0.29	Experiencing rapid uplift
T12	0.33	Experiencing rapid uplift	T24	0.08	Experiencing rapid uplift	T36	1.93	Less active	T48	0.26	Experiencing rapid uplift

High *Vf* values correspond to wide, flat valley floors while lower values are seen as steep narrow valleys. The index is also indicative of whether stream is actively down cutting or primarily eroding laterally into adjacent hill slopes with *Vf* values <1 classified as V-shaped valleys, *Vf* values between 1 and 1.5 suggest moderately active regions and *Vf* values greater than 1.5 are classified as U-shaped valleys.

Resulting *Vf* values indicate that a large portion of the watershed area have relatively active mountain fronts and are experiencing rapid uplift. These values also suggest recent tectonic movements. The values also indicate that the watershed has mostly V-shaped valleys and that streams are actively down cutting or eroding horizontally into contiguous hill slopes. Values between 1 and 1.5 indicate moderately active mountain fronts and are transitioning from a narrow to a broader valley floor. Large values of *Vf* suggest broader U-shaped valleys and is suggestive of areas having dormant tectonic activities due to availability of lateral erosion (Mayer, 1986).

3.4 Asymmetry Factor

Resulting values of the asymmetry factor was taken from partitioning the watershed area into six sections (Figure 3b). An asymmetry factor value of 50 indicates a symmetric catchment. Table 4 shows the various AF from the six sections of the Iponan Watershed indicating that tectonic tilting.

Table 4. Asymmetry factor of Iponan River Watershed

Section	A_r	A_t	Asymmetry Factor
S1	1,261,827.11	2,214,039.89	57.0
S2	4,987,505.64	8,267,819.51	60.3
S3	50,270,985.98	59,656,477.84	84.3
S4	91,471,101.62	212,677,731.05	43.0
S5	53,136,445.74	119,875,605.85	44.3
S6	9,905,645.40	14,797,837.21	66.9

Figures 5a and 5b show the asymmetry of the Iponan River Watershed and the different asymmetry classification and color coding, indicating the direction of the tilt. For the Iponan Watershed the trunk stream flows from south to north. Individually, each section of the watershed exhibits relatively different *AF* values. An *AF* close to 50 shows no or slight tilting perpendicular to the direction of the trunk stream. However, *AF* values that are less (tilting to the right of downstream) or greater than 50 (tilting to the left of downstream) denote significant tilting of the catchment area owing to either active tectonics or lithologic control (Roy and Sahu, 2015; Cox, 1984). For the entire watershed area, however, an *AF* value of 50.55 percent was computed at the right bank of the basin. The *AF* values of both banks may be indicative that the watershed area is highly dissected, eroded and that recent tectonic activity may have impacted the area. The values also suggest that the watershed area is tilting right downstream and could have been caused by lithological factors rather than tectonic.

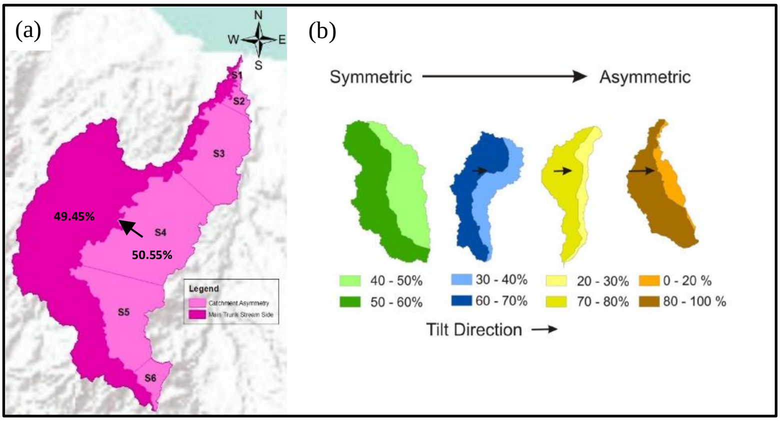

Figure 5. a) Asymmetry of the Iponan River Watershed (showing sections); b) Asymmetry classification and color coding (Ries, 2013)

The *AF* value of the right bank of the watershed area would also indicate that the Iponan River flows close to the left of the watershed. The difference between the absolute *AF*-50 and the right bank value of 50.55 is 0.55 which could indicate that the watershed has influence of recent tectonic activity.

3.5 Transverse Topographic Symmetry Factor

A symmetrical basin has a *TTSF* value of 0, with asymmetry increasing as the value approaches to 1. For the Iponan Watershed, sampling points taken from the digital elevation model shows *TTSF* values ranging from 0.04 to 0.62, indicating that the watershed area is generally asymmetrical (Table 5). While both the asymmetry factor (*AF*) and *TTSF* does not confirm direct indication of a possible ground tilting, the result from the study suggest that ground tilting may be related to active tectonics within the watershed area.

Table 5. *TTSF* values of Iponan River Watershed

Points	D_a	D_d	*TTSF*
P1	298.38	2041.43	0.15
P2	2062.42	3387.35	0.61
P3	2856.54	4610.71	0.62
P4	537.5	6913.13	0.08
P5	353.63	8122.29	0.04
P6	1020.2	7737.04	0.13
P7	2815.15	6876.68	0.41
P8	3043.63	6562.98	0.46
P9	3050.92	6704.69	0.46
P10	848.83	3772.94	0.22

3.6 Stream Length Gradient Index

The calculation of the stream length gradient index would determine if the study area is tectonically or lithologically controlled. Since this parameter is a sensitive indicator to changes in channel slope, it allows evaluation of relationship among possible tectonic activity in the area. From the measurement of the *SL* (Table 6), the Iponan Watershed has an *SL* range of 105.31 to 356.60. These low *SL* values ($SL < 300$), maybe indicative that the watershed area have alluvium rock types with less tectonic influence. Higher values of *SL* are suggestive of areas with hard rock features and are moderately controlled by tectonic activities. For total watershed *SL* value is 516, suggesting that the whole watershed area may be moderately controlled by tectonic activities.

Table 6. Stream length gradient index of Iponan River Watershed

Station	*Δh*	*Δl*	*L*	*SL*
S1 – S2	100	3000	3500	116.67
S2 – S3	100	4700	8200	174.47
S3 – S4	140	5300	13500	356.60
S4 – S5	80	10000	23500	188.00
S5 – S6	60	9500	33000	208.42
S6 – S7	40	15200	48200	126.84
S7 – S8	20	11300	59500	105.31

3.7 Channel Concavity

Data manipulation within the GIS platform has generated a log-log scatter plot and a power-type trendline. From Figure 6 below, the concavity index theta (θ) is the exponent from the power trendline equation. Theta (θ) for Iponan River Watershed is -0.244. While channels exhibiting moderate concavities near 0.5 as having uniform uplift regimes, anomalously high or low concavities channels can occur particularly when channel segments cross spatially varying rock uplift rates, depending on the direction of flow relative to the gradient in uplift rate. Channels having negative concavity may indicate rapidly increasing slopes (Wobus *et al.*, 2006). Accordingly, channels having θ < 0 values are channels having convex-upward profile (Kirby and Whipple, 2001).

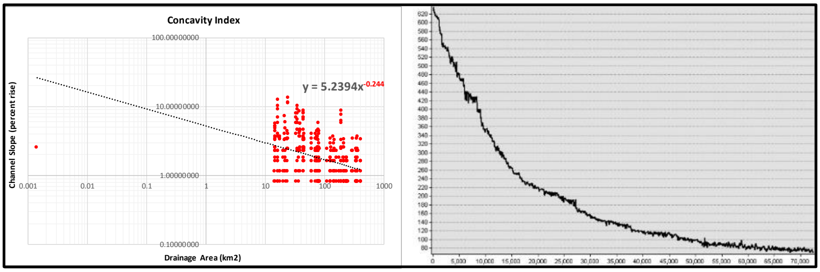

Figure 6. a) Concavity index of Iponan River Watershed;
b) River profile of Iponan River

4. Conclusions and Recommendation

The determination of morphotectonic parameters in the Iponan River Watershed provide critical information of the distribution of various land features and indicators to better understand geomorphic processes and tectonic activity in the area. The morphometric analyses of the watershed area suggest that both geomorphic processes and tectonic activity (such as ground tilting and uplift) are influencing catchment morphology. Accordingly, the soil mantle along the Northern Mindanao corridor consisted mainly of sedimentary rock units and may have concealed obvious manifestation of other significant geologic structures, e.g. faults and fractures within these corridors (DPWH, 2014). Such is probably the case of the tectonic line that runs through the Iponan River. Such fault line and other existing fault lines within the vicinity of the watershed could indicate that tectonic activity may have the major control within the watershed area. As this may be the case, it is also sensible to consider other critical factors that may have influenced the entire watershed area. Factors such as the interaction of climate, earth surface and tectonic processes as well as the river system properties can provide substantial information on the morphotectonic features of the Iponan River Watershed. While there had already been geologic-tectonic-related studies in Northern Mindanao, a specific and detailed study of the watershed's morphological and tectonic features can reinforce information utilization, disaster risk planning and management and decision making.

5. Acknowledgement

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