SYSTEMATIC ASSESSMENT OF WATERSHED GEOMORPHOLOGY USING DIGITAL TERRAIN ANALYSIS FOR DETECTING GULLIES, RIPARIAN AREAS, AND UPLAND DEPRESSIONS

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ABSTRACT: Digital terrain analysis (DTA) is a remote-sensing methodology integrating analyses of digital elevation data in a geographic information system (GIS) with imagery, field-based observations, and study of landscape processes. Using DTA, landforms such as gullies, riparian areas, and upland depressions can be identified. Gullies are erosive trenches formed by running water, riparian areas are zones adjacent to streams and rivers, and upland depressions are locations in upland areas that store or accumulate water from runoff. Identification of these landforms is crucial in water quality protection due to the fact that these landforms may be sources of nonpoint source contaminants if no management practices are applied. This study was applied to three watersheds in Southern Philippines – Talomo, Matiao, and Pilan Watersheds. Results showed that in Talomo Watershed, 1.1324 km^2 are gullies; 5.23 km^2 are riparian areas, while 5.23 km^2 are upland depressions. In Matiao Watershed, 0.1029 km^2 are gullies, 8.30575 km^2 are riparian areas, and 8.30575 km^2 are upland depressions. In Pilan Watershed, .0562 km^2 are gullies, 1.6148 km^2 are riparian areas, and 1.6148 km^2 are upland depressions. Field visits showed that the results were able to pinpoint locations of actual gullies, riparian areas, and upland depressions.

INTRODUCTION

In watershed management, it is often crucial to detect landforms that may have negative effects to the river system in terms of siltation and pollution as an effect of overland runoff. Some identified landforms that may pose these effects are gullies, riparian areas, and upland depressions (Mulla et al., 2007). Gullies are erosive trenches formed by running water, riparian areas are zones adjacent to streams and rivers, and upland depressions are locations in upland areas that store or accumulate water from runoff. Many studies have used various methods in delineating the said landforms.

Surface water hydrology is dictated by watershed geomorphology, i.e., terrain shape. For this reason, many studies have analyzed watershed geomorphology to pinpoint certain target landforms – as suggested by Mulla et al. (2007), specifically, using digital terrain analysis (DTA). Geomorphology affects surface hydrology – e.g., shape of surface affect the convergence and divergence of overland flow, and also overland flow are directed to portions of the terrain with lower elevations (Creed and Sass, 2011).

With the use of modern techniques like remote sensing methodologies such as light detection and ranging (LiDAR) and data acquisition via interferometric synthetic aperture radar (IfSAR) processed in a geographic information system (GIS) integrated with DTA, the landforms can be detected easily. Using only the geomorphic information of a watershed landscape derived from digital elevation models (DEM), a method employing DTA to assess watershed geomorphology for detecting gullies, riparian areas, and upland depressions was developed.

Using DTA to assess watershed geomorphology, primary terrain attributes, i.e., slope, flow direction and accumulation, and secondary terrain attributes, i.e., stream power index (SPI) and topographic wetness index (TWI), are analyzed in detecting the said landforms (Mulla et al., 2007). Once identified, the landforms can be mapped to identify areas that may need watershed management practices.

Objectives of the Study

This study aimed to identify the gully, riparian area, and upland depression landforms in Talomo, Matiao, and Pilan Watersheds by assessing the watershed or terrain geomorphology using DTA methods. Specifically, this study aimed to:

1. Calculate the primary terrain attributes of the watersheds – slope, flow direction, and flow accumulation;
2. Calculate the secondary terrain attributes of the watersheds – stream power index (SPI) and topographic wetness index (TWI); and
3. Identify the gullies, riparian areas, and the upland depressions in the watersheds.

MATERIALS AND METHODS

Study Area

Talomo Watershed, located in 7° 8'4.87"N 125°26'35.66"E and also the largest of the three, houses the Talomo River which is the second major drainage basin of Davao City. Talomo Watershed houses the Talomo River which is the second major drainage basin of Davao City. Talomo Watershed also recharges the city's primary source of clean water for domestic and industrial uses. Matiao Watershed, located in 7° 9'57.18"N 126° 1'22.14"E, houses the silted Matiao River which supplies irrigation water to rice plantations. Pilan Watershed, located in 6°52'28.11"N 125°23'6.45"E, the smallest of the three, houses the Pilan River which drains to the Davao Gulf. Figure 1 shows the location of the study areas.

Data

Two datasets per watershed were used in this study – LiDAR (1-meter resolution) and IfSAR (5-meter resolution) DTMs. The LiDAR DTMs were used in identifying gullies and the IfSAR DTMs were for riparian areas and upland depressions. It is also important to note that the LiDAR data only covers the floodplain of the watersheds, hence, the results for the identification of gullies are only limited within the floodplains of each watershed. However, in the case of Talomo Watershed, instead of using IfSAR DEM, the 5-meter resolution DEM used was resampled from its 1-meter LiDAR DEM. This was opted due to the unavailability of the 5-meter IfSAR DEM of the watershed.

Methodology

In detecting gullies, riparian areas, and upland depressions, the 1-meter resolution LiDAR DTM was used in identifying the gullies, while the 5-meter resolution IfSAR DTM was used in identifying the riparian areas and the upland depressions. The GIS processes were carried out using the ESRI's ArcMap version 10.2.2 and the percentile rankings were executed using R software. Figure 2 shows the general workflow of the study.

In identifying the gullies, the 1-meter resolution DTM was pre-processed before calculating the primary terrain attributes. Pit-filling and low-pass filtering was employed to correct flow routing and analysis (Danielson, 2013). After calculating the primary terrain attributes, the SPI and TWI were calculated. According to Wilson and Gallant (2000), SPI represents the erosive power of runoff on certain surfaces, while TWI describes the extent of saturation in the landscape. Both assume uniform edaphic properties. Also, both can be used to predict net erosion and deposition in certain areas, and zones of saturation (Wilson and Gallant, 2000). The SPI is given by the formula

$$SPI = \ln(flow\ accumulation \ \times slope). \quad [1]$$

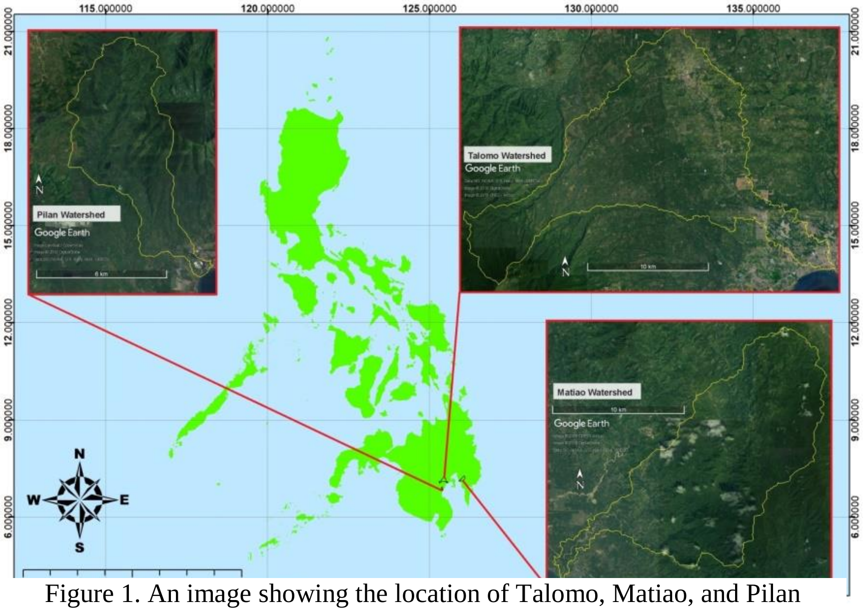

Figure 1. An image showing the location of Talomo, Matiao, and Pilan Watersheds.

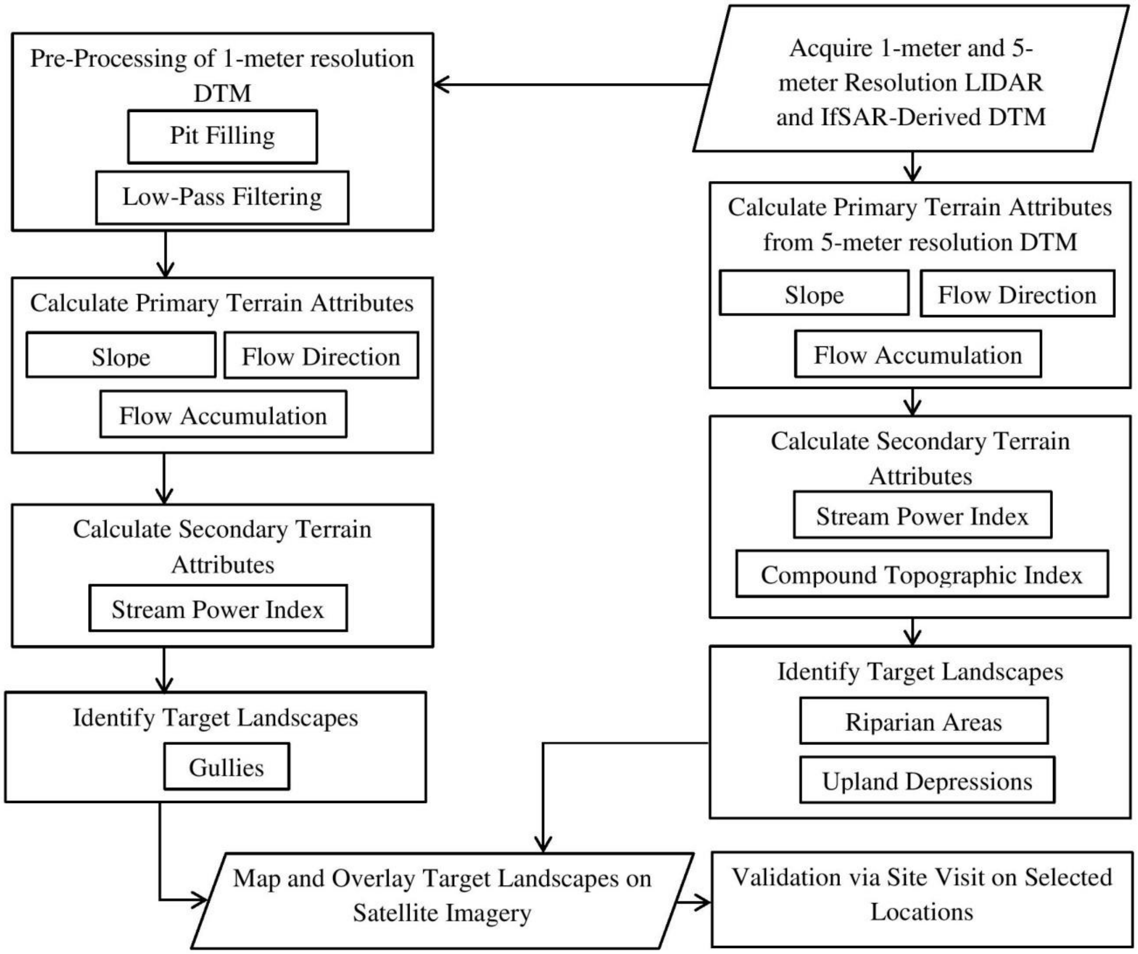

Figure 2. General workflow of the study.

SPI values were ranked, and areas on the watershed with SPI greater than or equal to the 99th percentile of the SPI values were classified as gullies (Mulla et al., 2007). In identifying the riparian areas and upland depressions, the primary terrain attributes and the secondary terrain attributes, SPI and TWI, were calculated using the 5-meter resolution DTM. TWI is given by the following equation

$$TWI = \ln\left(\frac{flow\ accumulation}{slope}\right). \qquad [2]$$

The SPI and TWI values were subjected to low-pass filtering. After filtering, the SPI and TWI values were ranked. Areas with SPI and TWI values on or above the 95th percentile were classified as riparian areas and upland depressions, respectively (Mulla et al., 2007). After identifying the landforms, the resulting maps were overlaid on satellite imagery which was extracted from Google Earth Pro.

RESULTS AND DISCUSSION

For the Talomo Watershed 1-meter and 5-meter resolution DTM, results after calculating and ranking the secondary attributes showed that the 99th percentile of 1-meter resolution SPI is 8.276085, the 95th percentile of the 5-meter resolution SPI is 3.875047, and the 95th percentile of the 5-meter resolution TWI is 0.01202967. The top 0.1% SPI values of the 1-meter resolution DTM was also calculated to detect gullies with higher potential for erosion and it was found that the infimum is given by the value 10.081537. For Matiao Watershed, after calculating the secondary attributes, it was found out that the 99th percentile for the 1-meter resolution SPI values is 9.387105. The infimum of the top 0.1% of the 1-meter resolution SPI values for Matiao Watershed was found to be 11.85034. Also, the 95th percentile for the 5-meter resolution SPI and TWI values are 8.059478 and 1.484203, respectively. After identifying the CSAs, their areal extents were calculated. The results for Pilan Watershed showed that the value at the 99th percentile of the 1-meter resolution SPI values is 10.43971 and the infimum of the top 0.1% of all 1-meter resolution SPI values is 12.44459. The 95th percentile of the 5-meter resolution TWI and SPI values are 1.659930 and 8.430665, respectively. Table 1 shows the summaries of the areal extents of the gully, riparian area, and upland depression CSAs of the watersheds. Also, Figures 3 through 11 show data samples of the identified gully, riparian area, and upland depression CSAs overlaid on the satellite imagery of the watersheds.

Table 1. Summary of the areal extent of gullies, riparian areas, and upland depressions in Talomo, Matiao, and Pilan Watersheds.

Watershed	Landform	Areal Extent (in 10,000 sq. m.)	Proportion of Watershed
Talomo	Gullies	113.24	~0.49%
	Riparian Areas	523.00	~2.27%
	Upland Depressions	523.00	~2.27%
Matiao	Gullies	10.29	~0.01%
	Riparian Areas	830.57	~5.00%
	Upland Depressions	830.57	~5.00%
Pilan	Gullies	5.62	~0.17%
	Riparian Areas	161.48	~5.00%
	Upland Depressions	161.48	~5.00%

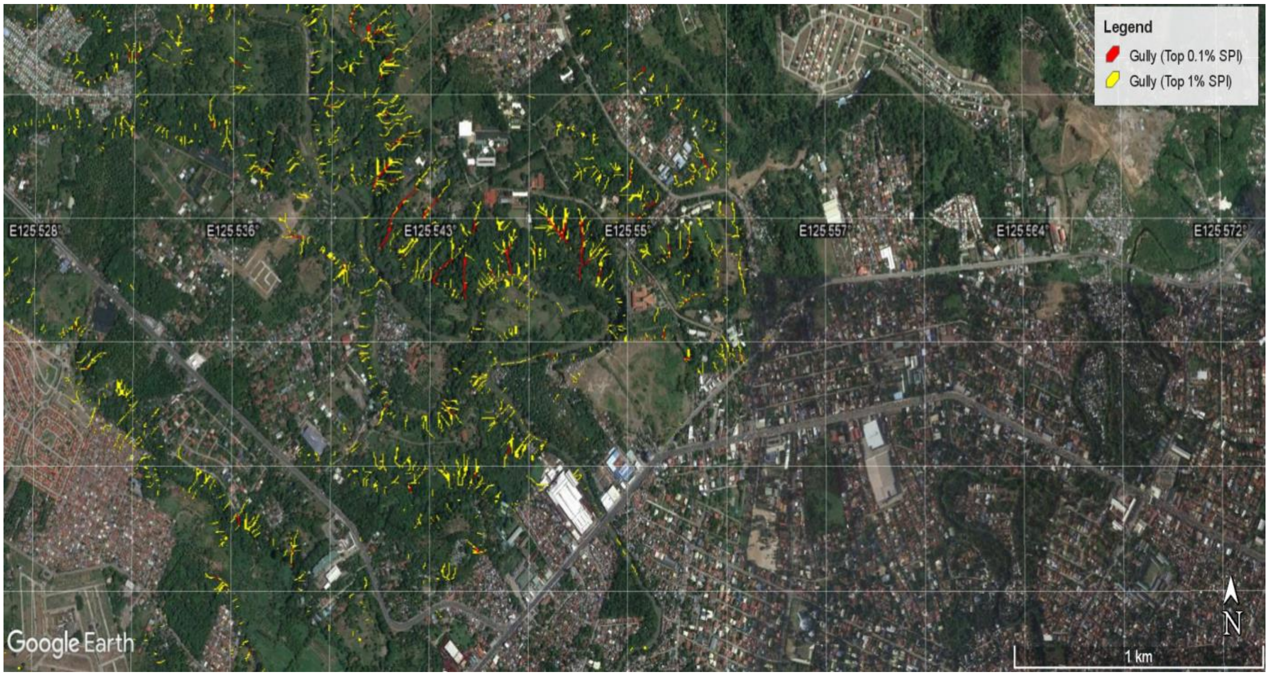

Fig. 3. A satellite imagery of a data sample of identified gully landforms in Talomo Watershed.

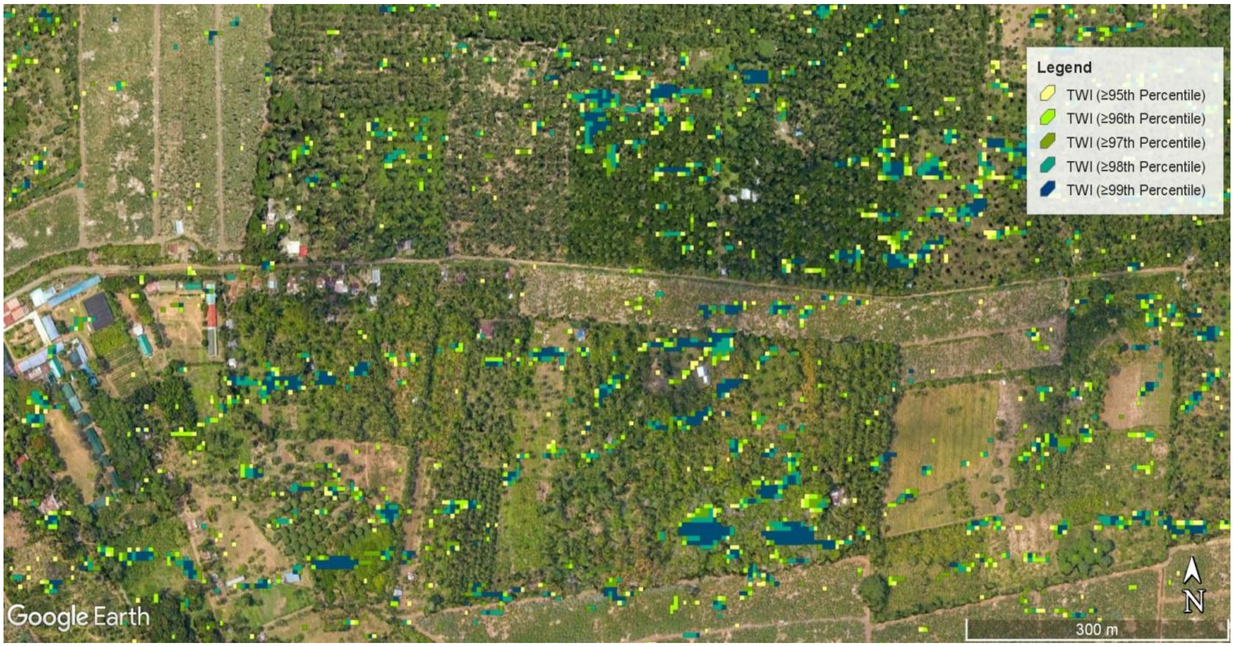

Fig. 4. A satellite imagery of the identified upland depression landforms in Talomo Watershed.

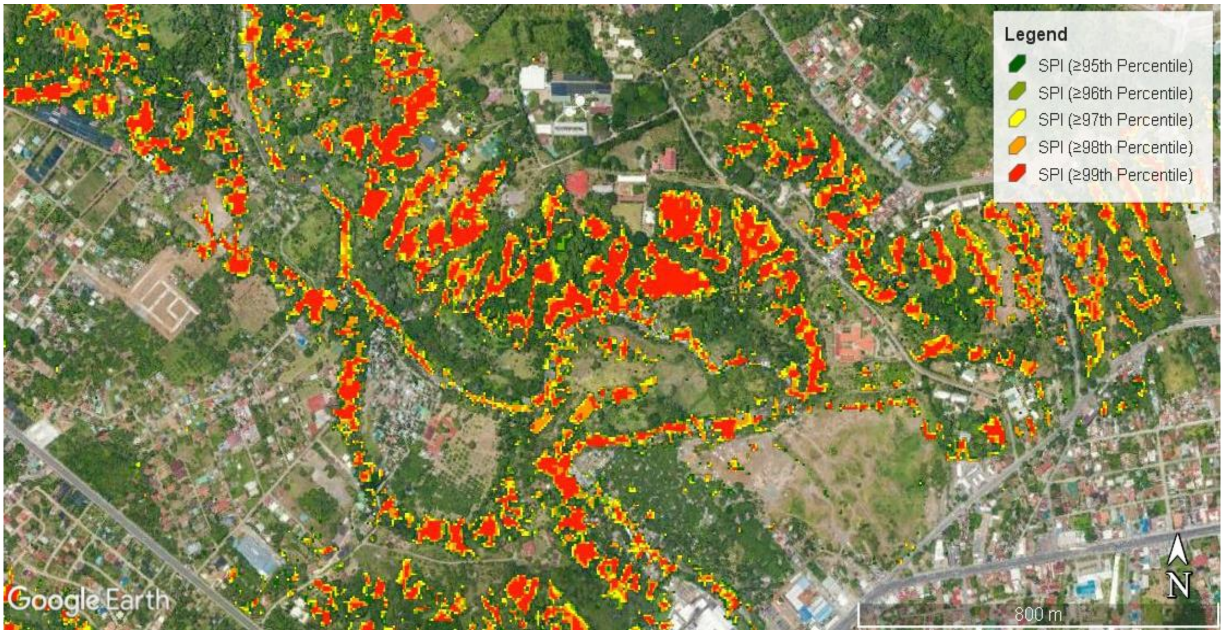

Fig. 5. A satellite imagery of the identified riparian area landforms in Talomo Watershed.

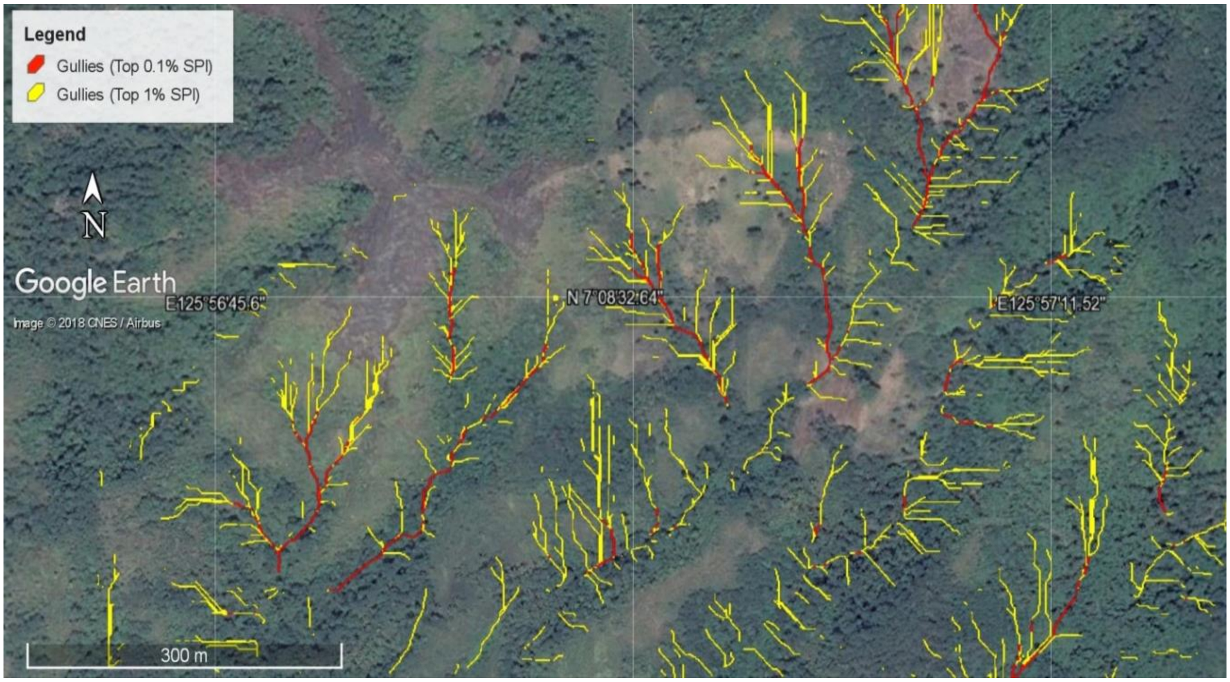

Fig. 6. A satellite imagery of a data sample of identified gully landforms in Matiao Watershed.

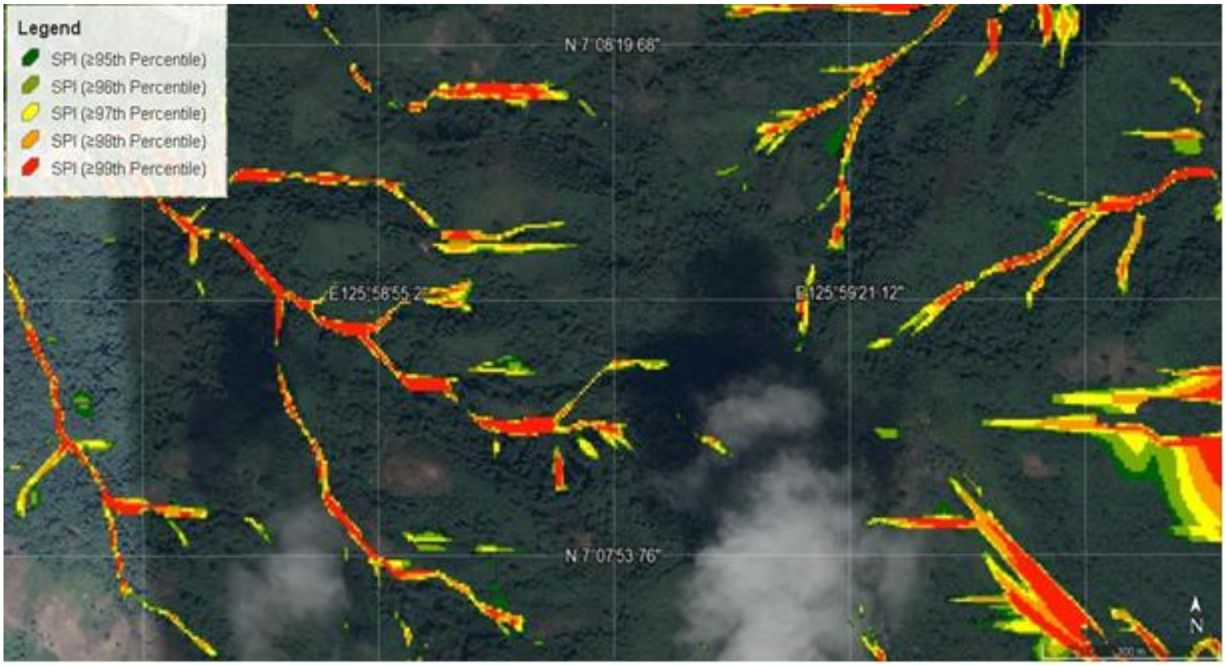

Fig. 7. A satellite imagery of a data sample of identified riparian area landforms in Matiao Watershed.

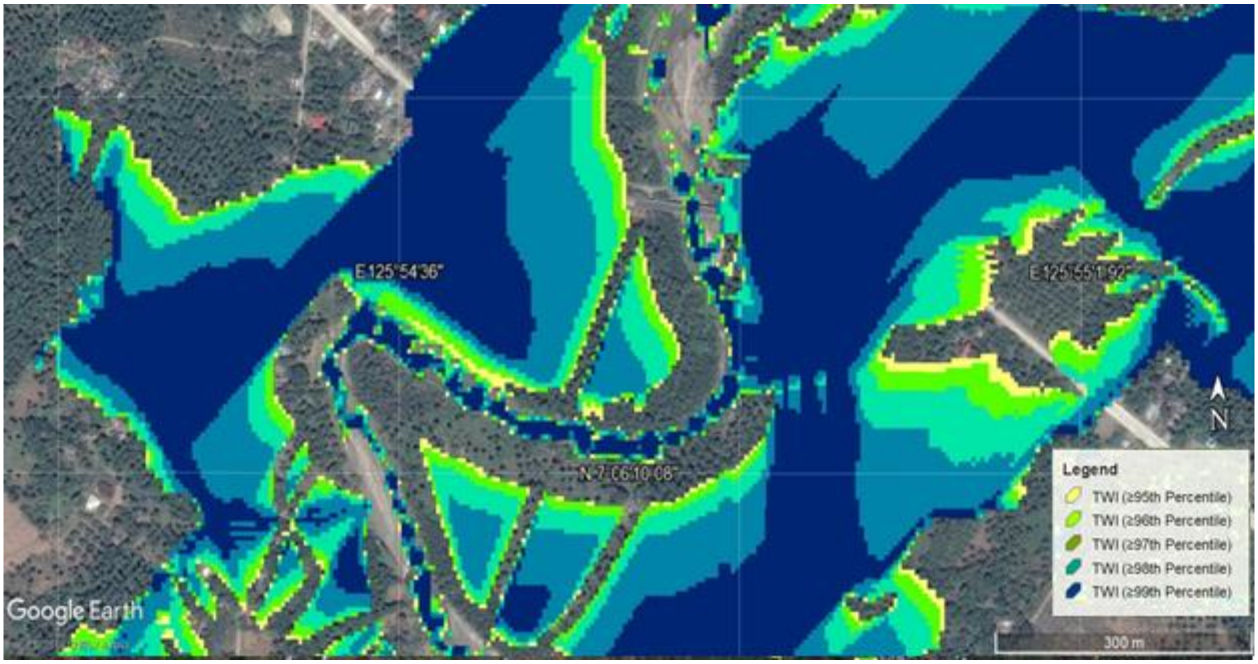

Fig.8. A satellite imagery of a data sample of identified upland depression landforms in Matiao Watershed.

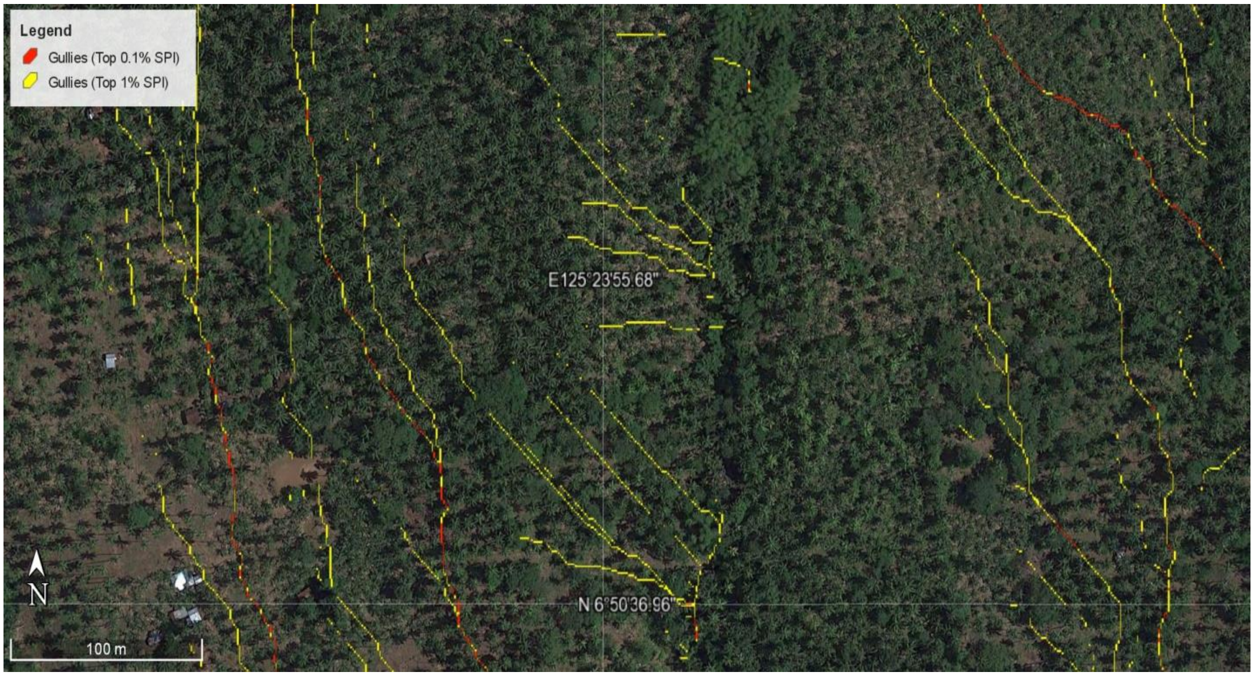

Fig.9. A satellite imagery of a data sample of identified gully landforms in Pilan Watershed.

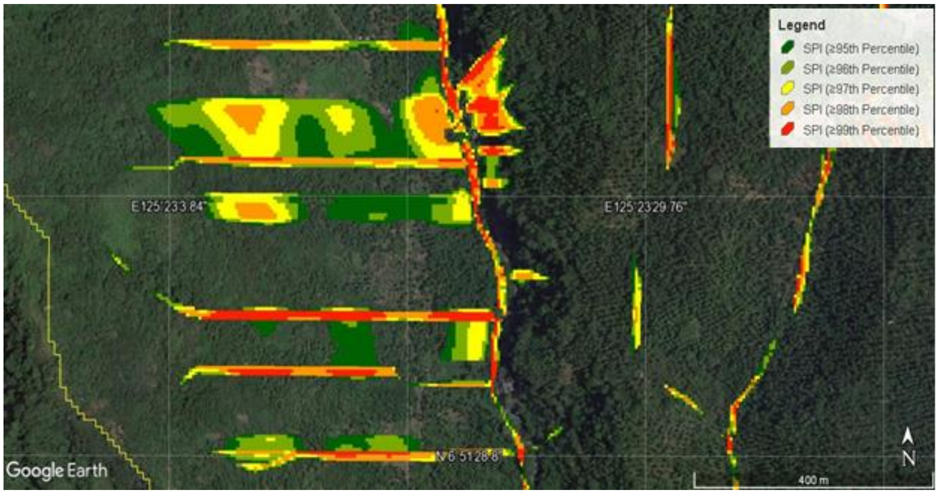

Fig.10. A satellite imagery of a data sample of identified riparian area lanforms in Pilan Watershed.

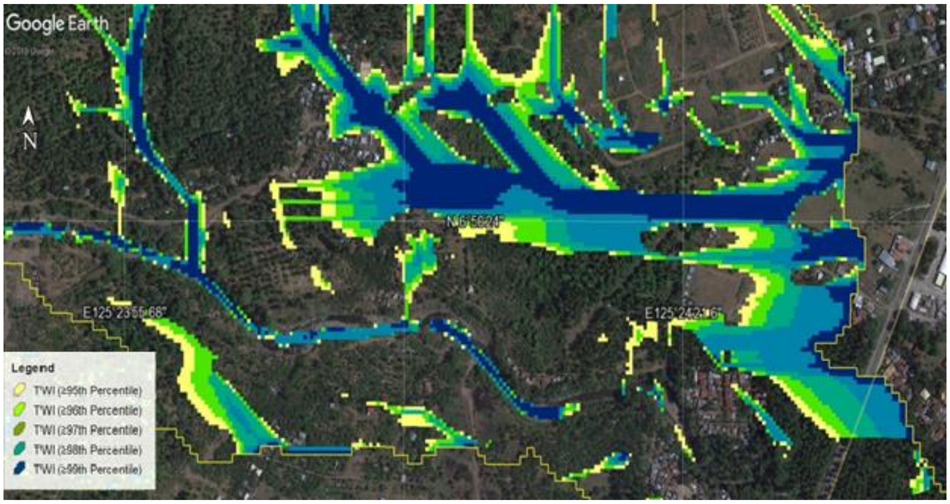

Fig. 11. A satellite imagery of a data sample of identified upland depression landforms in Pilan Watershed.

Initial field visits were conducted to see the actual landforms the results represent. Two sites per landform classification per watershed were selected based on their SPI and TWI values and accessibility. All the visited landforms were confirmed as gullies, riparian areas, and upland depressions. Figures 12, 13, and 14 show several images from the field visits.

During the field visits, it was found out that other identified gully and riparian areas or landforms, other than the selected verification sites, were already altered. These cases are common in areas with various anthropogenic activities. Although findings during the verification of this study revealed possible conditions of the results in the field, increasing the number of the field verification would yield a better understanding of the results from this study.

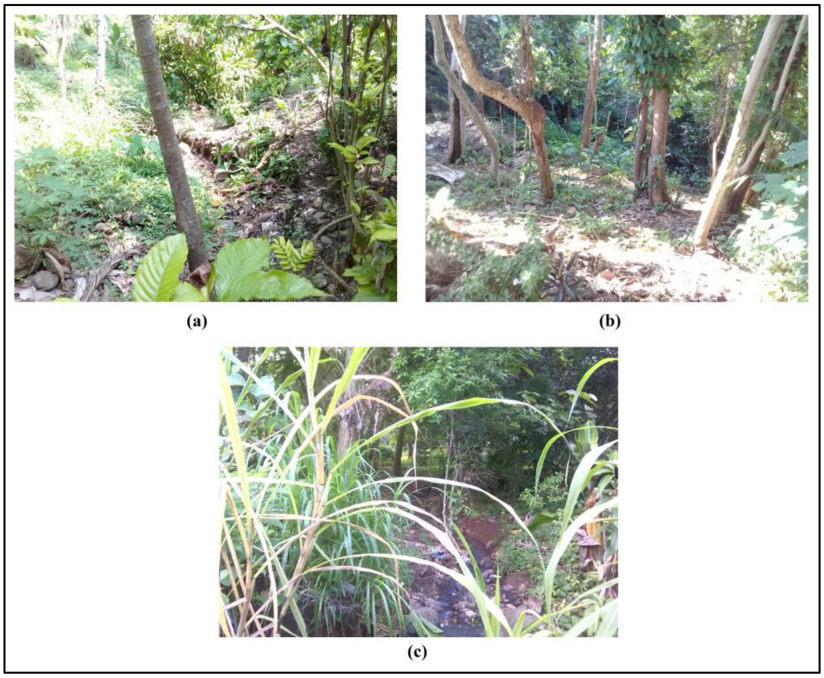
(a)
(b)
(c)

Fig. 12. Images taken at the verification sites of (a) gullies, (b) riparian areas, (c) upland depressions within Talomo Watershed. Photos were taken at (a) 7° 3'57.98"N 125°32'53.91"E , (b) 7° 4'14.49"N 125°31'48.37"E , and (c) 7° 6'22.00"N 125°29'0.20"E.

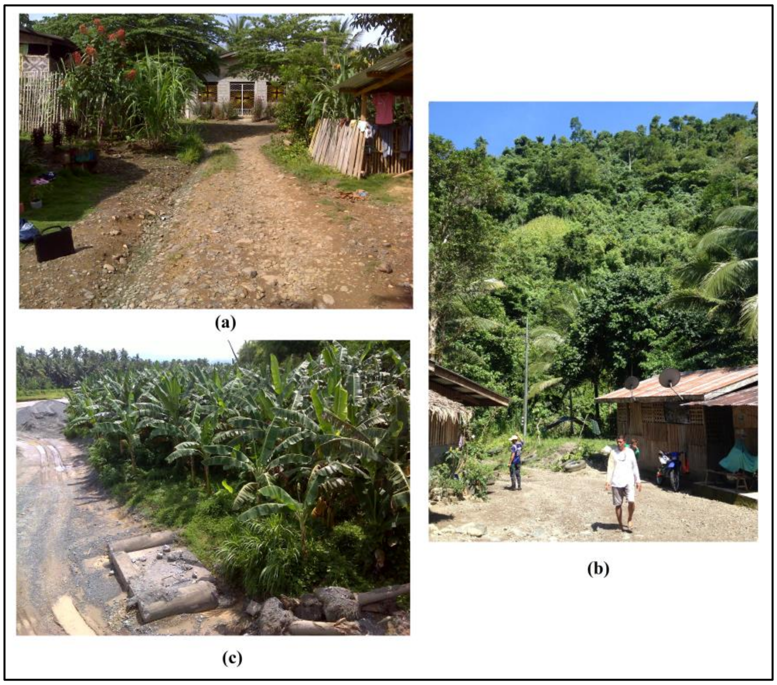
(a)
(b)
(c)

Fig. 13. Images taken at the verification sites of (a) gullies, (b) riparian areas, (c) upland depressions within Matiao Watershed. Photos were taken at (a) 7° 7'35.80"N 125°57'7.39"E , (b) 7° 9'45.19"N 125°59'52.47"E, and (c) 7° 6'20.00"N 125°54'48.51"E.

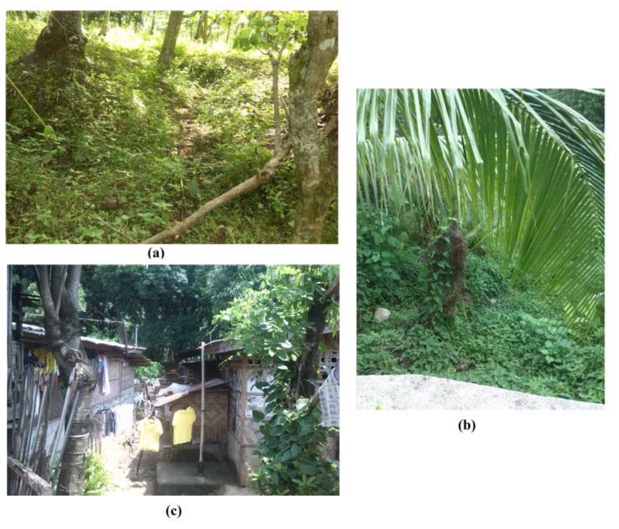

Fig. 14. Images taken at the verification sites of (a) gullies, (b) riparian areas, (c) upland depressions within Pilan Watershed. Photos were taken at (a) 6°50'34.40"N 125°24'4.00"E, (b) 6°51'58.39"N 125°23'8.60"E, and (c) 6°50'11.08"N 125°24'21.74"E.

SUMMARY AND CONCLUSION

This study made use of digital terrain analysis methods to assess the watershed geomorphology of Talomo, Matiao, and Pilan watersheds in order to detect landforms such as gullies, riparian areas, and upland depressions. The input datasets were 1-meter resolution LiDAR-derived digital terrain models of the three watersheds and 5-meter resolution IfSAR DTMs of Matiao and Pilan. The 5-meter resolution DTM of Talomo Watershed was derived using resampling methods in ArcMap 10.2.2. After identifying the landforms, it was found out that gullies cover up to 1.1324 sq. km. of Talomo Watershed, riparian areas and upland depressions each cover 5.23 sq. km. Results also showed that in Matiao Watershed, 0.1029 sq. km. were gullies, riparian areas and upland depressions each cover 8.30575 sq. km. For Pilan Watershed, 0.0562 sq. km. are gullies, riparian areas and upland depressions each cover 1.6148 sq. km. of the watershed. The threshold values for the identification of landforms, i.e., 99th and 95th percentile for the gullies, and riparian areas and upland depressions, respectively, were set without field calibration, thus, to obtain more accurate results, necessary calibration techniques must be applied.

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