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Geomorphologic Characterization of Dingalan Town Proper and Barangays in its Proximity: Implications for Infrastructure Development and Sustainable Land Usage

by

Khelly Shan C. Sta. Rita

A Thesis submitted to the School of Civil, Environmental, and Geological Engineering
in partial fulfillment of the requirements for the Degree

Bachelor of Science in Geological Science and Engineering

Mapúa Institute of Technology

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SLHS CERTIFICATION

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This certifies that the thesis/dissertation entitled GEOMORPHOLOGIC CHARACTERIZATION OF DINGALAN TOWN PROPER AND BARANGAYS IN ITS PROXIMITY: IMPLICATIONS FOR INFRASTRUCTURE DEVELOPMENT AND SUSTAINABLE LAND USAGE

authored by KHELLY SHAN C. STA. RITA

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Guillerma Jayne T. Atienza, M. Sc.
Thesis Adviser

As members of the Oral Examination Committee, we certify that we have examined this thesis, presented before the committee on December 3, 2017, and hereby recommend that it be accepted as fulfillment of the thesis requirement for the degree in **Bachelor of Science in Geological Science and Engineering.**

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ABSTRACT

Areas located near the equator and adjoining plate margins are commonly imperiled by different geologic hazards brought about by tectonics, geography, and climate. Engineering developments must undergo comprehensive planning to diminish geohazard risks, economic requirements, and environmental disruption while maximizing the functionality of an area. Geomorphology plays a vital role in the planning process such that landforms and geomorphologic processes will indicate the feasibility of structure placement and how it will affect the environment. Providing this interrelationship for the study area in Dingalan, Aurora was the immediate objective of this study. Accelerated erosion, high wave energy, active fault network, rugged terrain, and riverine influence, comprise the chief surficial delimiters in formulating the urban plan for the municipality. Aerial images and IfSAR-derived elevation models coupled with ground-truth investigations constituted the steps accomplished in the geomorphological survey. ESRI® ArcGIS™ 10.3 was utilized in generating the geomorphologic map and in correlation with the land use map. Results mainly showed the four geomorphologic provinces, that is, fluvial, tectonic, denudational, and coastal forms, imposing several hazards to most of the structures, namely, numerous houses, roads, schools, commercial zones, industrial zones, and other minor structures were observed to traverse the fault line and active river channel. Some structures were and will be founded on unstable materials, others will be placed on the rugged areas, the coastal region is purported to be reclaimed, and the waste disposal poses groundwater contamination. Suggested countermeasures involved river diversion, bank heightening, avoidance, use of breakwaters, relocation, application of earthquake-resistant designs, slope drainage, and slope reduction, among others. Areas of geomorphologically similar characteristics as well as future construction endeavors in the municipality can make use of these findings to create a more sustainable community.

Keywords: Geomorphology, GIS, land use, geologic hazards, sustainable development

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I would like to give my deepest gratitude to the Lord for the blessings, wisdom, and willpower you have given me and for leading me to the following persons who have been vital in the accomplishment of this thesis study of mine.

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My family, Mama, Papa, Kylie, Mommy, Tatay, and Mommy Belle, for their unceasing love and support. They are my inspiration in giving all best I could in everything I do.

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For this achievement, I give back all the glory and praises to the omnipotent Father Almighty.

Khelly Shan C. Sta. Rita

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Chapter I

INTRODUCTION

Third world countries, located almost entirely within the tropical regions, are currently undergoing industrialization and urbanization at an extremely rapid pace (Gupta & Ahmad, 1999; Chin, 2006; Hara et al., 2008; Dai et al., 2001). To accommodate the growing need to construct more buildings and other structures, most urban planners often neglect viewing a certain development project on a wider scale, especially when the planner does not a have a thorough knowledge of geology. This will bring about complications in the long run as the designer might have overlooked some important geological factors that will degrade the integrity and service life of the structure if left unmitigated.

These regions are located near active plate margins and tropical cyclone belts, and for this reason, such problems are magnified. The study area, located in Dingalan, Aurora, is definable by the aforementioned cases. Land use planning and necessary supporting data are crucial to developing countries that are usually under severe environmental and demographic constraints. Similarly, the government generally lacks the funding which results in a difficulty in meeting the lavish costs of controlling the natural hazards through major engineering works and rational land use planning (Bocco et al., 2000).

As a definitive example, the Department of Public Works and Highways (DPWH) is presently constructing a replacement for the Langawan Bridge along the Dingalan-Gabaldon Road in the province of Aurora as a consequence of the thick accumulations of bed material. That being said, the original bridge is no longer compliant with the required vertical clearance to accommodate flooding events. The structure will be implemented thru the Bridge Construction and Replacement Program I (BRCP I) of the Department. Geologically, the project is situated in a tectonically active denudational landscape, and in that respect, this geomorphologic characterization is undertaken to ensure structural longevity. Similar concepts were and can be applied to other engineering infrastructures for the study area, to minimize geohazards and environmental disturbance.

This study primarily conducted geomorphologic mapping for the purpose of assessing the feasibility of the projected land use map for the municipality. The findings lent sizable recommendations on the mitigation measures to address geologic hazards that would interfere with local development plans, as well as optimization of the plan for environmental sustainability. Categorization of the various landforms acted as the baseline data to provide the underlying information on the geomorphologic processes which are at play. A closer look at the generated map permitted the identification of the associated risks. Earlier mapping activities for the area were done in an undeniably larger scale, often encompassing the whole Region 3 or the whole island of Luzon (e.g. Nakata, 1977; Allen 1962; Daligdig, n.d.), and focused only on a single landform classification (i.e. tectonic landforms).

The process of geomorphologic mapping was accomplished with the use of Geographical Information Systems (GIS). The method was proven to be increasingly capable of handling more intensive tasks as the technology is continually being improved. Several studies (e.g. Siart, 2009; Lopez, 2014; Fuller, 2013; Napieralski et al., 2013; Bocco & Mendoza, 2001; Ginesu et al., 2016; Haryana et al., 2013; Dai et al., 2001; Livingstone et al., 1999; Arrowsmith, 2009) utilized the system to its maximum potentials and were successful in delineating geomorphologic features in their respective localities and provided numerous applications exemplifying the versatility of the discipline.

The municipality of Dingalan is located on a rugged coastal region in an active tectonic landscape with elevated erosion rates, hence, various geologic hazards are anticipated to take place. Studies on the seismic-induced hazards, weather-induced hazards, as well as the interrelationship between landforms and geologic hazards have already been undertaken (e.g. IRIS, 2013; Lancion, 1995, Mukherjee & Jha, 2012; Ginesu et al., 2016; Haryana et al., 2013; Petre et al., 2012; Soykan et al., 2014; Whitney & Hengesh, 2015; Daligdig, n.d.), but were accomplished with less details and/or on a different location. The comparatively smaller area of interest, therefore requires keen observation and critical analysis.

Insufficient research on the subject compelled the author to produce a geomorphologic map of the study area with the utilization of a standardized mapping and survey technique. A correlation between the geomorphology of the study area to the currently mapped and probable geologic hazards was established. Conclusively, assessments towards the practicality of infrastructure development via the proposed land use map of the area were conceptualized. The results of the study can also serve as a reference for property development in other areas of comparably akin geologic character.

1.1 Statement of the Problem

What are the different geomorphological units of the study area in Dingalan, Aurora and their connection to infrastructure development as directed by the municipality's proposed land use zoning?

1.2 Objectives

This research specifically intends to:

1. Determine and analyze the different morphological features and landforms in a specified segment of Dingalan, Aurora, the study area;

2. Delineate various morphological features using aerial photo interpretation and digital elevation model manipulation; and,

3. Provide a site specific relationship between the geomorphologic units, existing geologic hazards, and proposed land use map towards infrastructure development.

1.3 Significance of the Study

The results fundamentally gave recommendations on the suitability of the covered sector to function as planned, hence, identification and appraisal of the different morphologic units in the area acted as input for assessing the development zoning and determining the perils coupled with every infrastructure and their respective environmental consequences. The geomorphological map provided information on the geological and geomorphological processes relative to the anthropogenic intervention and their mutual affinity. Aside from its involvement in the field of engineering, the map will also serve as a premise for applications in both the fields of theoretical and applied sciences.

1.4. Scope and Limitation

The central intent of the research was the delineation of geomorphological features in the study area (see Figure 1.1) in Dingalan, Aurora. Recognition of the various landforms of the study was based on geomorphological mapping with the use of aerial photographs, anaglyph images, and Interferometric Synthetic Aperture Radar (IfSAR) derived digital elevation models (DEMs). Ground truthing was limited to accessible areas and distinct landforms, accomplished to substantiate the results obtained in the preliminary geomorphological delineation. Remotely sensed data were used to observe and identify landforms, structures, and landscape morphology. DEM files were utilized in morphometric analyses in support for the description and identification of geomorphological units. IfSAR DEMs and land use map employed for correlation were limited to the province, thus, areas outside Aurora as shown in the aerial photographs were not analyzed

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and were voided on the resulting geomorphological map. Also, as a result of the datasets being taken at separate years, adjustments on some non-rigid forms were perceived, thus, the need for compromises in the final output (e.g. the river has already migrated, therefore, the river channel was not shown in the map, only the thalweg; alluvial fan was discernible in the DEM but not in the aerial photographs).

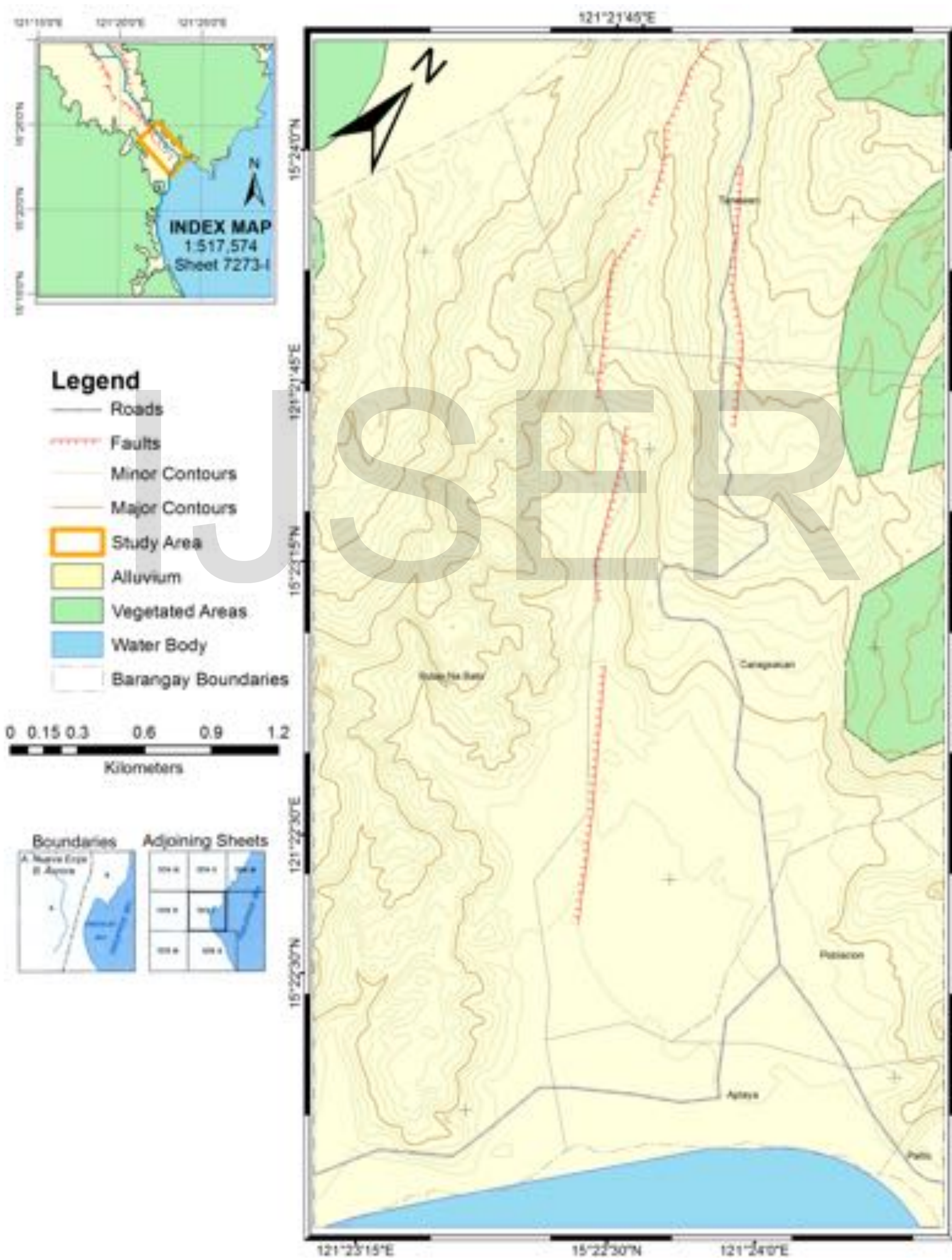

Figure 1.1 Location map of the study area.

1.5 Conceptual Framework

The study aims to create a pragmatic geomorphologic map which is geared for land use zonation assessment for sustainability and mutual benefit between the structures and the natural environment. These applied geomorphologic maps intended for specific purposes are derived from analytic and synthetic data.

Analytic data consists of purely scientific information, inclusive of morphogenesis, morphostructure, morphometry, and morphochronology. Morphogenesis denotes the mode of formation of landforms. This information is represented in the form of geomorphologic units, and in the study, includes forms of denudational, structural, fluvial, and coastal origins. Morphostructure deals with the nature of bedrock as this affects the landforms carved and processes developed. The basis on pedology and sedimentology in the context of parent materials can be accounted for, allowing for determination of their intrinsic properties. In digital data, lithology is commonly indicated by the drainage patterns. Morphometry provides quantitative information on the relief, aspect, elevations, curvature, etc. Specified factors such as slope angle may be used for additional subdivision. This, however, contributes minor essential information and fortifies map plasticity. Relative and absolute time of formation and development are drawn from morphochronology. Age distinction is important, particularly to forms between recent and those inherited from earlier periods when climatic conditions and other factors are different.

Synthetic factors add environmental and biological factors, effectively increasing the practicality of the mapping activity. Morphological units are mapped at various scales and are coined terrain provinces at the larger scale, and simply terrain mapping units during more detailed analysis. Terrain provinces are the largest units in which associations and complexes of terrain are combined. On the other hand, terrain mapping units are differentiated on the basis of origin, form, density, etc.

As stated by Verstappen and Zuidam (1991), such undertaking requires preliminary image interpretation to gather an overview of the general geomorphology of the study area and their relationships to the adjacent areas. Remotely-sensed data commonly take part in the accomplishment of the stage, coupled with the simultaneous review of other information resources such as literature, thematic maps, etc. Topographic maps are required in preparation for the field survey, to be used for positioning in the field. Field data are then suggested to be stored in a GIS system, in this case, ESRI® ArcGIS™ 10.3 was used. Subsequent detailed interpretation of the preliminary data with the collected field data should be done to create detailed and accurate maps. The conceptual framework of the study is presented below in figure 1.2.

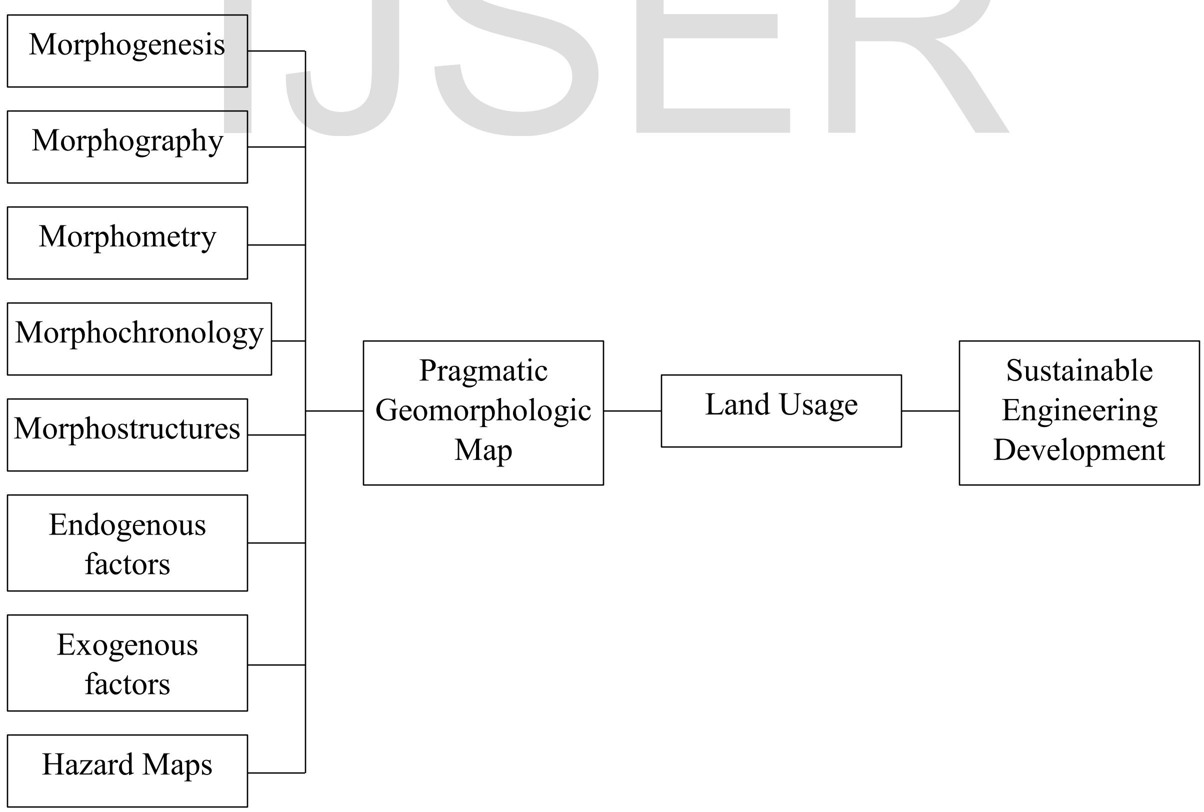

Figure 1.2 Conceptual framework of the study.

Chapter II

REVIEW OF RELATED LITERATURE

Geomorphology is a branch of geology defined as the science which pertains to the study of surficial landforms, materials, and their respective governing forces (Thornbury, 1968). The discipline is further subdivided into different domains based on the geological environment. Briney (2013) stated that geologic processes controlling the morphology of an area are all interconnected and goes hand in hand with one another.

Among the techniques done in a geomorphological undertaking is geomorphological mapping. This provides valuable baseline data for geomorphological practice, as well as initial insights towards urban planning, geologic hazard studies, surficial dynamics, landscape evolution, landform mapping, hazard forecasting, inventory, planning/management, and ecological analyses (Napieralski et al., 2013). This is also important in other branches of natural sciences (Otto et al., 2013). Geomorphological mapping is undergoing a resurgence - with the science proving to be a crosscutting discipline, integrating academic and professional applications, the positive impacts upon the society are remarkable. Knowing where a landform is, why it is there, what it is made of, and how it has changed are incredibly useful pieces of information to managing society's interaction with these surficial features.

Geomorphologic maps can be considered graphical data banks of a landscape depicting its landforms and surface as well as subsurface materials. Sketches and maps of terrain units (Dykes, 2008) have been fundamental methods for the analysis and visualization of the surface features ever since the incipience of geomorphological research. Lopez (2014) described the mapping process as relatively straightforward, depressions and elevations can be represented by points;

linear features are best represented by lines. The map will acquire geographical properties, thus, suitable methods of spatial representation must be employed.

Landforms can be mapped using either field or entity data models. Raster-based DEMs can be used to generate land surface parameters, and topographic information can be overlaid with other raster layers to assign each pixel to a particular landform class. Morphometric information (e.g., slope, slope, azimuth, curvature) is fundamental for identifying and mapping landforms, in fact, contemporary terrain analysis approaches permit unique characterization of the topography. Decrepit as it may seem, aerial photographs remain as valuable resources to study morphological units at a local scale and are commonly used to augment field mapping, or applied in conjunction with other data (Hall et al., 2009). As described by Livingstone et al. (1999), the method is not left untouched as it is still being upgraded for better efficiency.

Geographical Information Systems (GIS) have advanced to this point such that it is presently much more capable of handling more tedious tasks, in other words, complex functionalities are integrated. Several authors (e.g. Siart, 2009; Lopez, 2014; Fuller, 2013; Napieralski et al., 2013; Bocco & Mendoza, 2001; Ginesu et al., 2016; Haryana et al., 2013; Dai et al., 2001; Livingstone et al., 1999; Arrowsmith, 2009) were able to tap into the program's full capabilities, demonstrating the effectivity of the tool in the field of geomorphology.

This research was focused on several barangays of Dingalan, Aurora, due to it being the chosen field of study. The Province of Aurora is located in an active tectonic denudational landscape composed of rugged mountains grading to a more recumbent coastal region. It is bounded on the north by the Northern Sierra Madre, on the west by the Central range of the Sierra Madre, on the south by the Umiray River, and on the east by the Philippine Sea, which is opening to the Pacific Ocean. The province is topographically dominated by the Sierra Madre Mountain

Range, and only about 14% of its land area is flat (Lancion, 1995). The Gabaldon segment of the Philippine fault governs the structural aspect of the area (see Figure 2.1).

The Philippine Fault Zone (PFZ) is an approximately 1,250-kilometer sinistral fault extending NNW, parallel to the Philippine archipelago (Tsutsumi & Perez, 2013). Historically, the fault has been very active, as characterized by several destructive earthquakes in the past 200 years coupled with surface rupture. Fitch (1972) described that this motion is a manifestation of the oblique subduction of the Philippine Sea Plate beneath the Sunda Plate. GPS surveys rendered 30 mm/yr sinistral motion on the fault (Duquesnoy et al., 1994; Bacolcol et al., 2005). Allen (1962) conducted initial geomorphic studies on the PFZ to assess the relative fault motion. Several geomorphic evidence such as fault-line scarps, fault troughs and valleys, side-hill ridges, numerous faults sag and sag ponds, as well as consistent stream offsets provided additional information on the sinistral motion of the fault. He also described the tectonic landforms throughout the fault zone. The northeast side of the fault zone is uniformly higher, making an obvious topographic contrast between the mountains – Cordillera Central and Central Sierra Madre – and the Central Luzon Basin. The fault zone branches into two, the one which traverses the study area is the NW-SE trending Gabaldon Segment, across the Sierra Madre between Dingalan Bay and Laur.

A more comprehensive study conducted by Nakata (1977) described the tectonic landforms throughout the PFZ segments in Central Luzon. Between Dingalan Bay and Gabaldon, he stated that the fault zone consists of roughly NNW trending parallel active breaks about 2 km wide, and several left-handed offset streams albeit none is sharply displaced. The northeastern part of the area has several depressed troughs and sags, the largest one of which is 400-m long, 50-m wide, and 25-m deep. Similarly, Rutland (1967) conducted preliminary geologic mapping in the area and resulted in the recognition of synclinal folding in the Lubingan Formation. Debris avalanche deposits from the Mingan Mountains characterized by ill-sorted boulders and gravels were also outlined.

The active tectonic landscape of Dingalan, coupled with its highly rugged topography, dynamic mass wasting processes, and hostile coastal nature, subjects the area to hazards due to the tides, earthquakes, and landslides. Wooten et al. (2009) enumerated the hazards that the group has mapped in the tectonically active region of Western and North Carolina. Hazard maps of earthquakes, landslides, tropical storms, debris flow mechanics, and slope instabilities were accomplished.

These natural calamities generally cause fatalities and destruction of man-made structures, thus, mitigation measures are important to be met. Lunina et al. (2014) quantified the extent of earthquake-induced hazards that may occur after an earthquake. The results of their study showed that the distance that a hazard might occur is located within a range, which is proportional to the magnitude of the earthquake. On the other hand, Ulusay et al. (2002) described earthquake-induced hazards according to the type of structure from the Düzce earthquake in Turkey. Likewise, Zhou (2014) enumerated the geologic hazards that China faced during the 2008 Wenchuan earthquake. This included landslides, rock avalanche, landslide damming, barrier lakes, debris flows, widespread liquefaction, and severe structural damages. Climate and geographically-induced calamities are also predominant. Eco et al. (2015) quantified debris flows and expanse of destruction brought about by Typhoon Koppu. Sustained winds of 185 km/hr with precipitation of up to 400-mm saturated the alluvial cover of the Sierra Madre Mountain Range causing landslides, the materials of which converged into the stream network. Cascading rainfall events remobilized the accrued colluvium as debris flows, destroying numerous properties in the process. Several flooding events were also reported along the foothills and valley basins.

The geomorphology of the area will administer foremost insights with respect to the geologic hazards that an area might be susceptible to, therefore, understanding the discipline is vital in providing countermeasures to the imminent geologic hazards, risks associated with natural landforms, surficial processes, and environmental conditions (Lopez, 2014). Because geomorphology is the science about the changes in the land features, and geomorphic planning helps us devise the best solutions for present land use problems (Adeli and Khorshiddoust, 2011), the two disciplines must both be considered to design an effective and feasible urban plan for a certain locality. With this in mind, a site-specific interrelationship between geomorphology and land use should be conceptualized in infrastructure site selection and land use zoning.

Environmental problems are being aggravated as a consequence of urbanization and increasing population due to the anthropogenic landform modifications that are required to satisfy the need for more concrete structures (Hara et al., 2008). Failure to take local geomorphology into consideration either in the planning or management stage leads to increased tendencies of having casualties and property damage (Gupta & Ahmad, 1999).

Evidences signifying the reciprocity between anthropogenic geomorphology and construction engineering are relatively sparse, but continues to gain attention from several authors (e.g. Bocco et al., 2001; Haryana et al., 2013, Petre et al., 2012; Adeli & Khorshiddoust, 2011; Hara et al., 2008; Dai et al., 2001; Gupta & Ahmad, 1999; Ulusay et al., 2002) in the past decades. Ample qualitative and quantitative assertions regarding the geomorphologic controls were discussed. The consensus view seems to be that areas with flat to gentle slope, fluviatile zones, minimal tectonic disturbance, cohesive underlying material, low denudation rates, and deep water table constitute the favorable characteristics for construction of most engineering developments.

With the municipality's approximately 24,000 and still increasing populace as well as the continuing rural-urban transformation, it is important to determine the geomorphologic attributes of the municipality, and how we can take advantage of this understanding to counter the consequent detrimental effects. Moreover, intricate geomorphological studies intended exclusively for the study area are inexistent. Henceforth, geomorphological assessment is a compelling mechanism in managing the innate risks and hazards, augmenting the assurance with respect to structural integrity for environmentally sustainable development.

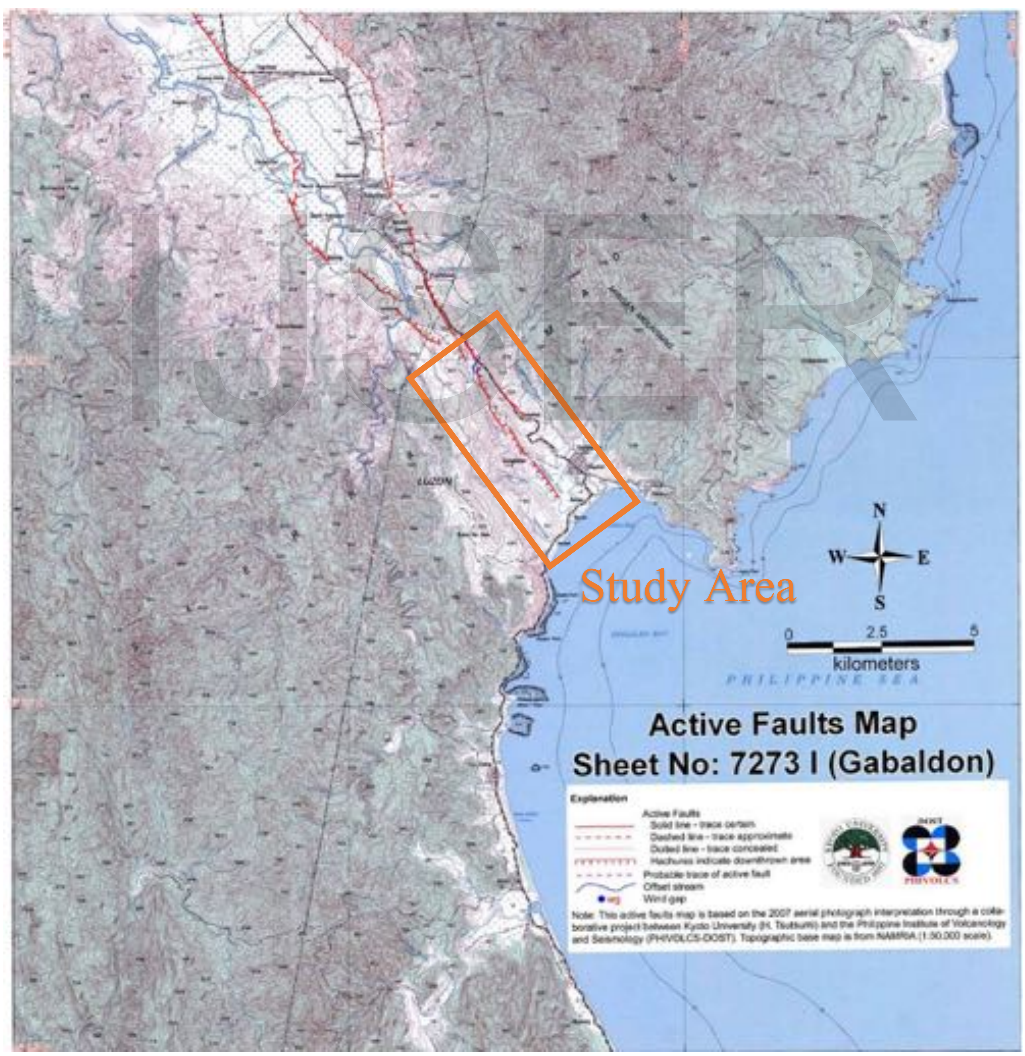

Figure 2.1 Active Faults Map of the Gabaldon Quadrangle. (source: PHIVOLCS)

Chapter III

Geomorphologic Characterization of Dingalan Town Proper and Barangays in its Proximity: Implications for Infrastructure Development and Sustainable Land Usage

ABSTRACT

Areas located near the equator and adjoining plate margins are commonly imperiled by different geologic hazards brought about by tectonics, geography, and climate. Engineering developments must undergo comprehensive planning to diminish geohazard risks, economic requirements, and environmental disruption while maximizing the functionality of an area. Geomorphology plays a vital role in the planning process such that landforms and geomorphologic processes will indicate the feasibility of structure placement and how it will affect the environment. Providing this interrelationship for the study area in Dingalan, Aurora was the immediate objective of this study. Accelerated erosion, high wave energy, active fault network, rugged terrain, and riverine influence, comprise the chief surficial delimiters in formulating the urban plan for the municipality. Aerial images and IfSAR-derived elevation models coupled with ground-truth investigations constituted the steps accomplished in the geomorphological survey. ESRI® ArcGIS™ 10.3 was utilized in generating the geomorphologic map and in correlation with the land use map. Results mainly showed the four geomorphologic provinces, that is, fluvial, tectonic, denudational, and coastal forms, imposing several hazards to most of the structures, namely, numerous houses, roads, schools, commercial zones, industrial zones, and other minor structures were observed to traverse the fault line and active river channel. Some structures were and will be founded on unstable materials, others will be placed on the rugged areas, the coastal region is purported to be reclaimed, and the waste disposal poses groundwater contamination. Suggested countermeasures involved river diversion, bank heightening, avoidance, use of breakwaters, relocation, application of earthquake-resistant designs, slope drainage, and slope reduction, among others. Areas of geomorphologically similar characteristics as well as future construction endeavors in the municipality can make use of these findings to create a more sustainable community.

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Introduction

Third world countries, located almost entirely within the tropical regions, are currently undergoing industrialization and urbanization at an extremely rapid pace (Gupta & Ahmad, 1999; Chin, 2006; Hara et al., 2008; Dai et al., 2001). To accommodate the growing need to construct more buildings and other structures, most urban planners often neglect viewing a certain development project on a wider scale, especially when the planner does not a have a thorough knowledge of geology. This will bring about complications in the long run as the designer might have overlooked some important geological factors that will degrade the integrity and service life of the structure if left unmitigated.

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Insufficient research on the subject compelled the author to produce a geomorphologic map of the study area with the utilization of a standardized mapping and survey technique. A correlation between the geomorphology of the study area to the currently mapped and probable geologic hazards was established. Conclusively, assessments towards the practicality of infrastructure development via the proposed land use map of the area were conceptualized. The results of the study can also serve as a reference for property development in other areas of comparably akin geologic character.

Methodology

A standard and long-standing process requiring the use of traditional stereoscopic photo interpretation to minimize technical difficulties, supplemented with various GIS clients to produce an accurate and detailed geomorphologic map, was employed in this study. Relevant data for geomorphological assessment consisted of aerial photographs, IfSAR-derived DEMs, and topographic maps. Existing studies, reports, published journals, and other references were reviewed to gain a grasp on what to expect with the geomorphologic framework of the area. The software, including, but not limited to, ESRI® ArcMap™ 10.3, ESRI® ArcScene™ 10.3, Quantum GIS (QGIS), Global Mapper 15, and Agisoft Photoscan Pro 1.2.4 were extensively used in producing the geomorphologic map in this research.

Unpublished and published studies, journal articles, books, reports, and online references were collected during this initial stage. Aerial photographs, topographic maps, and IfSAR derived DEMs were obtained from the National Mapping and Resource Information Authority (NAMRIA). Existing geologic hazard maps were acquired from the READY Project from the joint efforts of the Philippine Institute of Volcanology and Seismology (PHIVOLCS), Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA), and the Mines and Geosciences Bureau (MGB) as initiated by the National Disaster Coordinating Council (NDCC). The land use map for correlation was secured from the municipal planning office. The geology of the area of interest was acquired from the MGB Region 3 headquarters.

Upon its completion, a preparatory insight on the lithology, structures, morphology, and other geologic factors were developed. This allowed hypotheses formation which is useful in devising a preliminary geomorphologic analysis.

Figure 3.1 depicts the landforms generally found in an active strike-slip fault landscape. For this reason, these land features are projected to flourish in the study area. Careful inspection and analysis of the aerial photos were exercised to ascertain accurate interpretations.

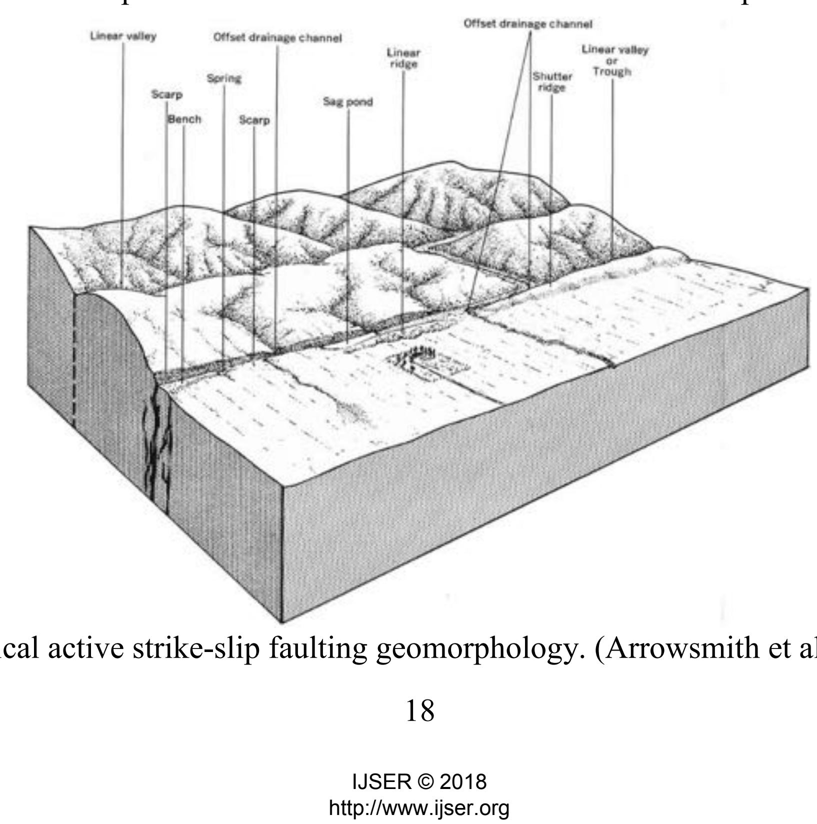

Figure 3.1 Typical active strike-slip faulting geomorphology. (Arrowsmith et al., 2009)

Five (5) pieces of remotely sensed aerial photographs (Figure 3.2a) covering Dingalan Bay up to a section of Nueva Ecija Province were delineated manually with the use of a mirror stereoscope, acetate films, and acetate pens. A hand-operated approach was preferred due to the relatively low resolution of the photographs which made it difficult to decipher miniscule details on a computer screen. Digital stereographic manipulation of the photos was also hindered by the lack of perpendicular alignment among the datasets as a result of the curved flight path upon taking the imagery. Manual interpretative annotation is comparatively simpler than digital methods.

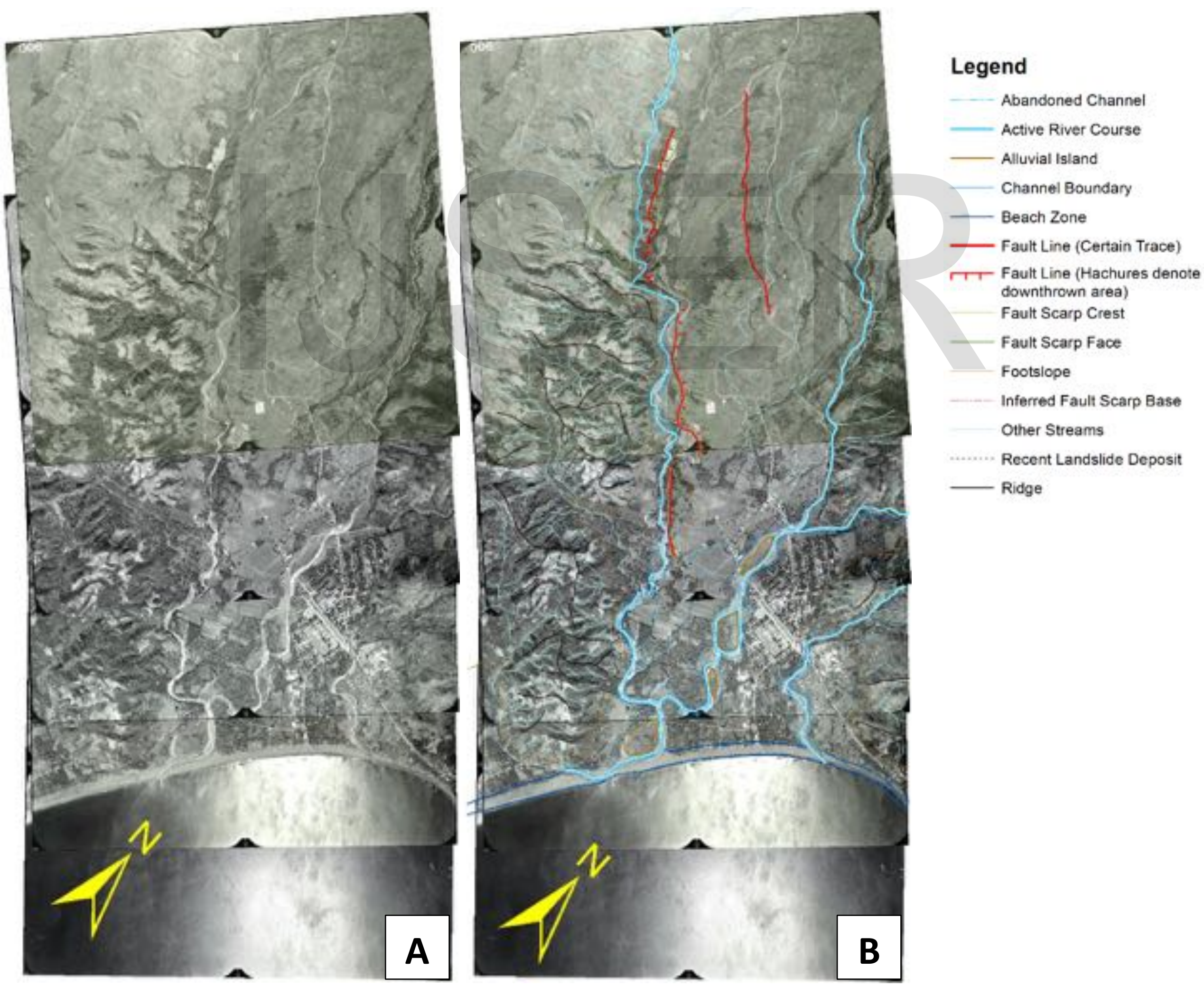

Figure 3.2 (a) Georeferenced aerial imagery used in the study covering Dingalan Bay to a segment of Nueva Ecija with fiducial lines removed to show continuity (courtesy of Dr. T. Bacolcol). (b) Digitized preliminary delineations overlaid on the aerial photos.

Delineations done on the acetate film were scanned for digitization purposes. Modifications were undertaken to ensure that the scanned delineation aligned with the aerial photos with the use of the warp tool in Adobe Photoshop CS5. Georeferencing was then conducted to set the spatial reference of the scanned document. The scanned was then digitally traced on ArcMap as seen in Figure 3.2b.

A ground-truth investigation was undertaken last 19^{th} of September 2017. Prior to this, the preliminary delineations were overlaid above an OpenStreetMap layer and was plugged into the OruxMaps GPS app for convenient field tracking. Other field equipment included field notebook, pencil, Brunton® TruArc™ 20 baseplate compass, and a digital camera. Only approximate measurements were taken due to the very steep slopes in the area prohibits close range inspection of each individual landform.

Each morphological feature delineated in the preliminary interpretations were sought after, though some (i.e. fault scarp and offset stream on top of the debris avalanche deposits) were unsuccessfully found due to the lush vegetation, consisting of shrubs and trees, obscuring them. Whereas some areas were barred to be entered by local government officials (i.e. the two deltas), and some were being modified for construction purposes (i.e. river terrace by the Langawan River). In contrary, some features (i.e. several incised meanders on the levees and alluvial islands of the Dingalan River, multiple small recent rotational landslides on the slopes northwest of the study area) not seen on the aerial photos themselves were observed upon the field visit, thus, the amount of details and landforms incorporated in the final geomorphologic map was increased.

The bearing and facing direction as well as the coordinates of each observation point were recorded for simpler input in the map workspace. Detailed field observations and quantitative estimations for each landform are discussed herein.

At this point, the DEM was further re-examined to provide additional details for inclusion in the map. Morphometric analyses (slope, aspect, curvature, elevation, and ruggedness) using the spatial analyst tools of ArcMap and specialized functionalities of Global Mapper 15 and QGIS regarding this endeavor were utilized. The resulting morphometric maps provided additional reinforcement to the interpretations, as well as further characterization of the study area. The combine tool under the local toolset of ArcMap proved to be suitable for overlaying the rasters to the geomorphology vector dataset.

Visual evaluation of the hillshaded DEM was completed upon exporting to ArcScene for interactive manipulation in three-dimensional space. Some more additional landforms were detected on this re-examination. Not all features were in just a single data type. The age discrepancy of the DEM and aerial photos provided metamorphological information such that some landforms have already undergone changes. To provide auxiliary information, the aerial photos were converted to anaglyph stereo pairs and viewed in 3D using Agisoft Photoscan Pro 1.2.4. Circumscribed digital assessment of the aerial photos is permitted for convenience.

Simultaneous review of the aerial photos and DEM in the map workspace granted a wider array of reference for digitization into shapefiles. Polygons (for features best represented in two-dimensions upon projection into a horizontal plane) and lines (for linear features) were used in mapping the geomorphic units in the area. Due to their contextual dissimilarities, two shapefiles capturing both had to be created. The vector datasets are then draped over a hillshaded DEM to simulate relief.

Tools and functionalities (i.e. local toolset, spatial analyst, data management) embedded in ArcMap engine were harnessed to create qualitative and quantitative overlay correlations between the geomorphological units, various geologic hazards, and land use map. This permits the determination of overlapping zones and their respective spatial coverage. The percentages as well as areas (in square meters) for land use are presented in tabular form placed in the appendices. Overlaying the geologic hazards to the land use zones and geomorphologic map warranted the cognizance of the repercussions of the planned zoning to a certain land feature and vice versa. Scientifically, each geomorphologic unit has its own accompanying inherent risk, and was considered in assessing the land use zonation proposed by the concerned municipal component.

The above stated process implemented to accomplish this study is summarized in a methodological framework shown in figure 3.3.

Description of the Study Area

The study area, consisting of the barangays Poblacion, Tanawan, Butas na Bato, Caragsacan, Aplaya, and Paltic, is situated in the northern portion of Dingalan. Geographically, it is approximately bounded by the coordinates 15°22' to 15°24' N and 121°22'30" to 121°24' E, with a total surface area of 13.91 sq. km. was evaluated. The Gabaldon-Dingalan Road serves as the main access road to reach the area. It takes a 3 to 4-hour commute from Metro Manila via North Luzon Expressway (NLEX) passing through Cabanatuan City.

Several physiographic features surround the location. On its southeastern side, situated is the Dingalan Bay, which opens to the Philippine Sea. Its northeast and southeast boundaries consist of the Sierra Madre Mountain Range (SMMR). The Mingan Mountains (MM), a portion of the SMMR, flank the study area on its southeastern piedmont. The central domain is characterized by a gentle to flat topography. Generally, the rivers of the area trend NW-SE, with Dingalan River being the largest one, has headwaters on the MM. Four other rivers (Langawan River, Pisoh Creek, Subsob River, and Davildavilan River) originate from the same particular direction. Sapinit Creek

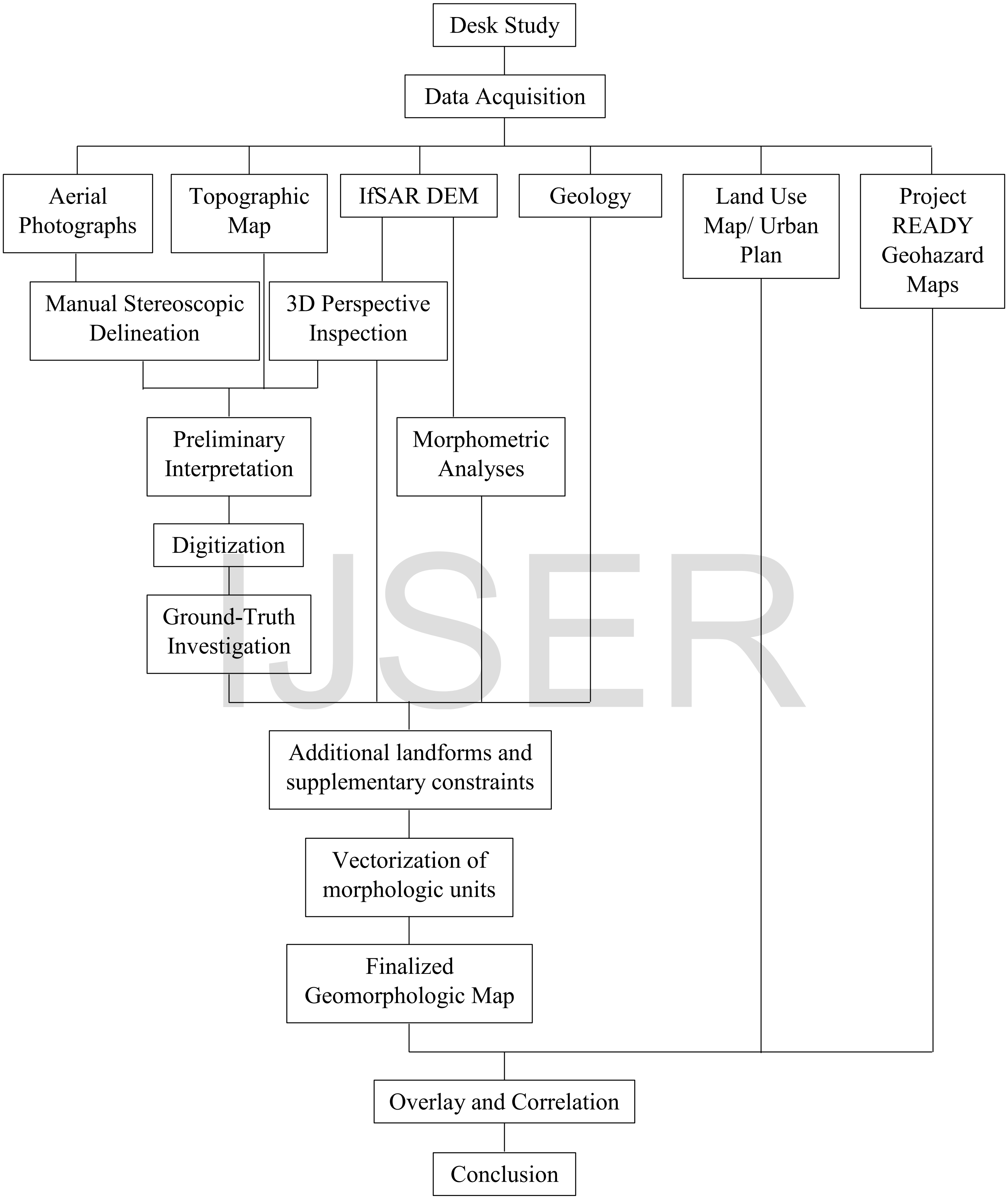

Figure 3.3 Methodological framework of the study.

and Amil Creek emerge from the southwest portion of the area, opposite the aforementioned streams. According to Rutland (1967), the area belongs to the Laur-Dingalan Fault Zone. The sinistral Gabaldon segment of the Philippine Fault (PF) runs NW-SE alongside Dingalan River. Near the coast, the fault branched out into two segments manifested by oppositely plunging normal faults. The fault trace converged near the source of Dingalan River. The flat central portion of the study area can be interpreted as a depression due to faulting from the structural geology of the area. A hillshaded elevation model is shown in figure 3.4 to visualize the topography.

According to the geologic map (yet to be published by the Bureau) as shown in figure 3.5, Barenas Baito Formation and Caraballo Formation constitute the lithology of the area. The Late Cretaceous Barenas Baito Formation, composed of spilitic and basic to intermediate volcanic flows and breccias with intercalated metasedimentary rocks (consisting of thin to medium bedded, varicolored indurated sandstones, siltstones, argillites, chert and local lenses of conglomerate), underlies the southwestern slopes in the study area. On the other hand, the Middle to Late Eocene Caraballo Formation forms the MM. The said formation consists of basaltic and andesitic flows and breccia and associated pyroclastic rocks, volcanic sandstone, conglomerate, mudstone and chert (Peña, 2008). Lastly, recent unconsolidated alluvium overlays the floodplain.

Results and Discussions

Morphometric analyses (figure 3.7) permitted the categorization of the field of study into physiographic regions (figure 3.6). The area was classified into three domains, namely, lowlands/ plains, gentle slopes with rolling topography, and steep, rugged hills. The low-lying plains are characterized by recumbent inclinations with elevations between 0 to 45 meters above mean sea level (AMSL). The region corresponds to the fluvial landform regime, showing parallel and sub-

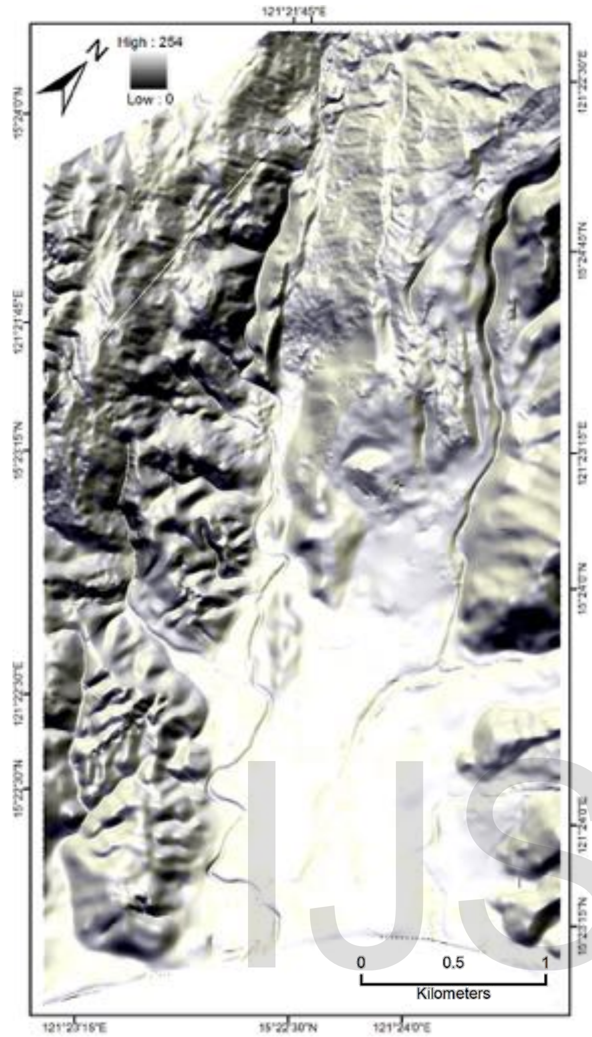

Figure 3.4 Hillshaded elevation model of the study area depicting its topographic relief. (Source: NAMRIA)

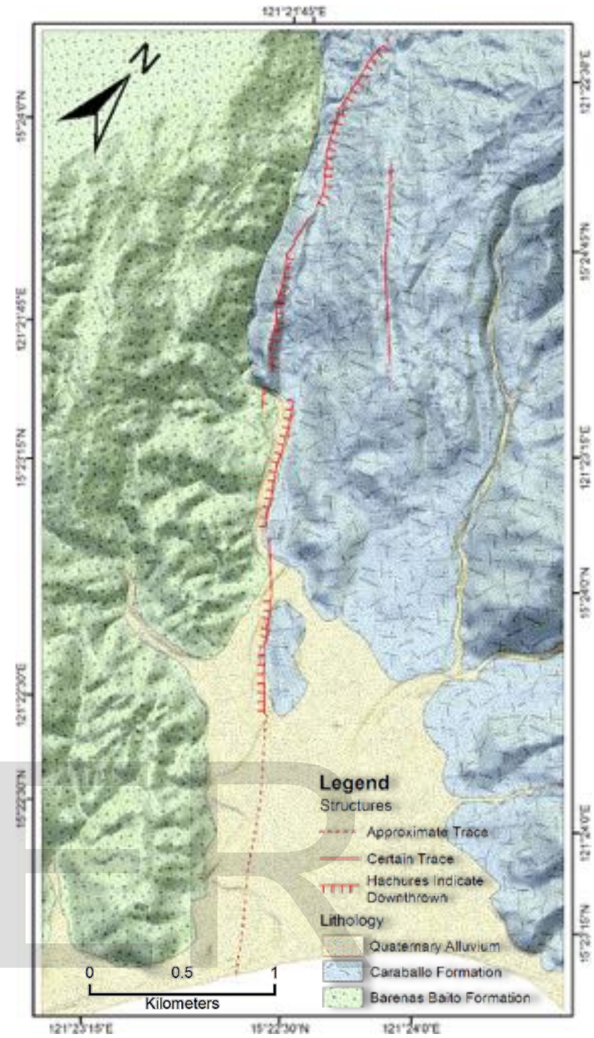

Figure 3.5 Geologic map of the study area showing the lithology, relief, and structures. (Source: MGB Region 3)

rectangular drainage pattern. Both the gentle slopes and steep hills are characterized by elevations ranging from 45 to 327 meters AMSL with dendritic to parallel drainage pattern. The disparity lies on ruggedness and slope. The hills are significantly steeper and more rugged. However, the morphometric aspect of the study area does not have a substantial link to the said regions, but interpretation of the dataset provides support to the general physiography of the location. Table 3.1 shows the morphometric physiognomies of each region.

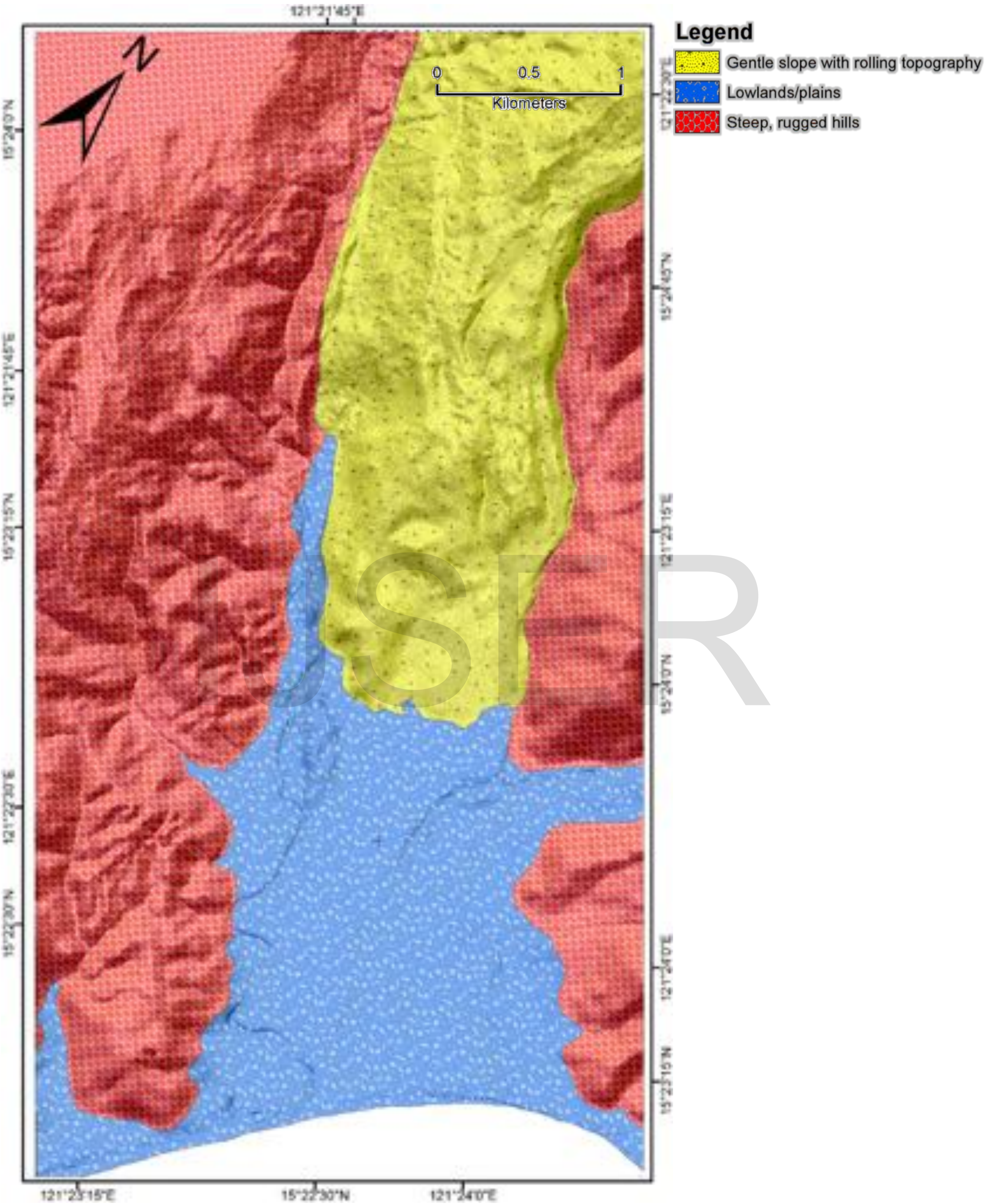

Figure 3.6 Map showing the three major physiographic regions in the coverage area.

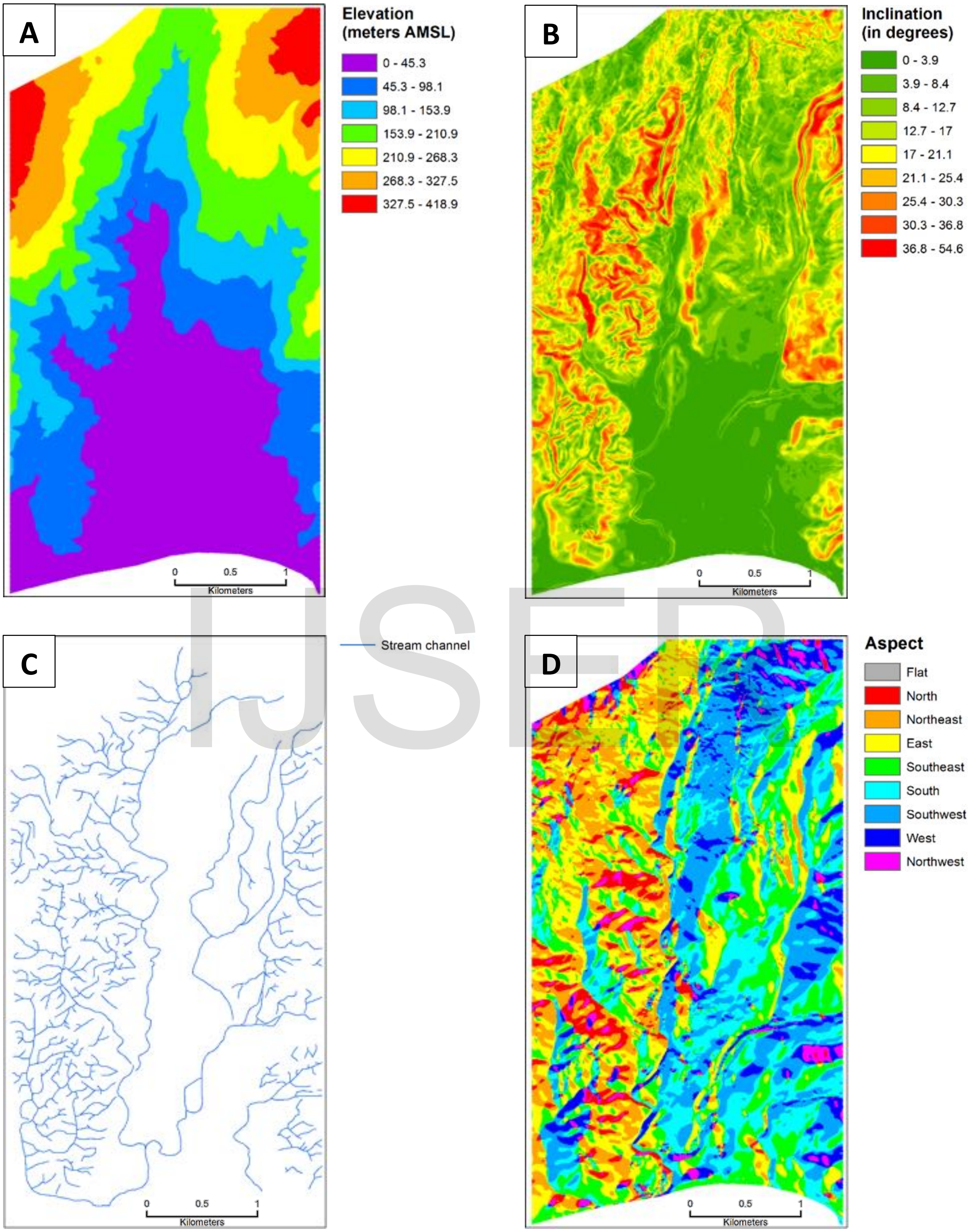

Figure 3.7 Results of morphometric analysis in the study area presented in cartographic form. (a) Elevation map presenting the selected elevation ranks. (b) Slope map illustrating pixel inclination. (c) River network map showing drainage patterns. (d) Aspect map for the bearing.

Table 3.1 Physiographic provinces with prominent relief expression and lithology

Physiographic Region/province	Elevation (meters AMSL)	Slope Steepness (degrees)	Drainage Pattern/s	Lithology/Formation
Steep, rugged hills	45.3 to 98.1	0 to 54.6	Dendritic, radial, trellis	Barenas Baito Formation
Gentle slopes with rolling topography	45.3 to 98.1	0 to 54.6	Parallel	Caraballo Formation
Alluvial plains and valleys	0 to 45.3	0 to 8.4	Parallel to sub-rectangular	Quaternary alluvium

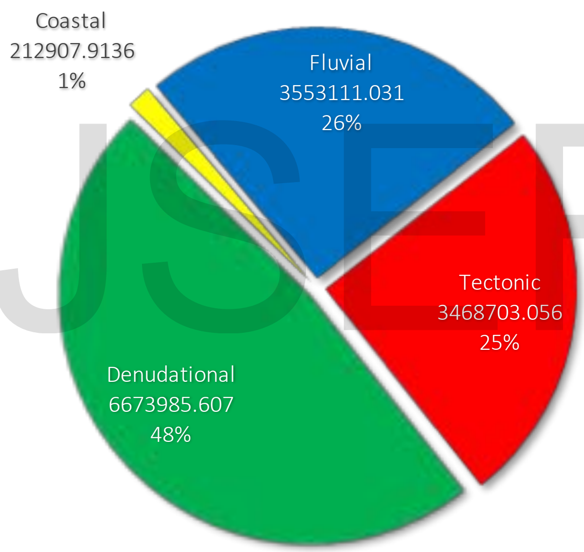

Figure 3.8 Statistical distribution of the geomorphic environments/classes in the study area.

Four geomorphic environments comprise the area of study. Categorically, these are coastal, fluvial, denudational, and tectonic landforms. From the calculated statistics (figure 3.8), denudational landforms are the most widespread, covering 48% or 6.68 sq. km. of the study area. Next are the fluvial landforms encompassing 26%, tectonic landforms at 25%, and the least are the coastal units at 1%. Table 3.2 enumerates the landform units under each group.

Table 3.2 Observed landform units under each geomorphic environment/class

Geomorphic Environment	Physiographic Region/s	Landform Unit
Denudational landforms	Steep and rugged hills; Gentle slope with rolling topography	Denudational slopes
		Denudational slopes with structural control
		Gully
		Highly eroded denudational slopes with structural control
		Rotational landslides
		Debris avalanche deposit
Tectonic landforms	Steep and rugged hills; Gentle slope with rolling topography	Fault scarps
		Fault-controlled terraces and benches
		Sag pond
		Structurally-controlled denudational slopes
		Offset ridges
		Eroded linear escarpment with fault scarps
		Structurally-controlled slopes with undulating topography
		Triangular facets
		Fault trace
		Pressure ridges
		Offset streams
Fluvial landforms	Alluvial plains and valleys; Steep and rugged hills	Alluvial fan
		Alluvial islands
		Floodplain
		Fluvial terraces
		Overbank deposits
		Point bar deposits
		Active river channels
		Cutbanks
		Wadis
		Abandoned channels
Coastal landforms	Alluvial plains	Beach
		Coastline

Geomorphological Features

Diverse mass wasting processes are expressively dominant in the study area. Sediment and colluvial dynamics are chiefly driven by gravity, moisture, and climatic conditions in the form of slope instability, rainfall, typhoons, and relative humidity. It is important to note that running water has little to no contribution to the erosional events that are at play, because most rivers are either ephemeral or abandoned (wadi), while some are slowly moving (bayou). Degradative mechanisms in the area are also observed to occur in a differential manner, with the sloping ground receiving greater rates of erosion in contrast to the lower erosion rates in the level zones. As a result, several geomorphic features indicative of these processes were identified in the field.

Gully

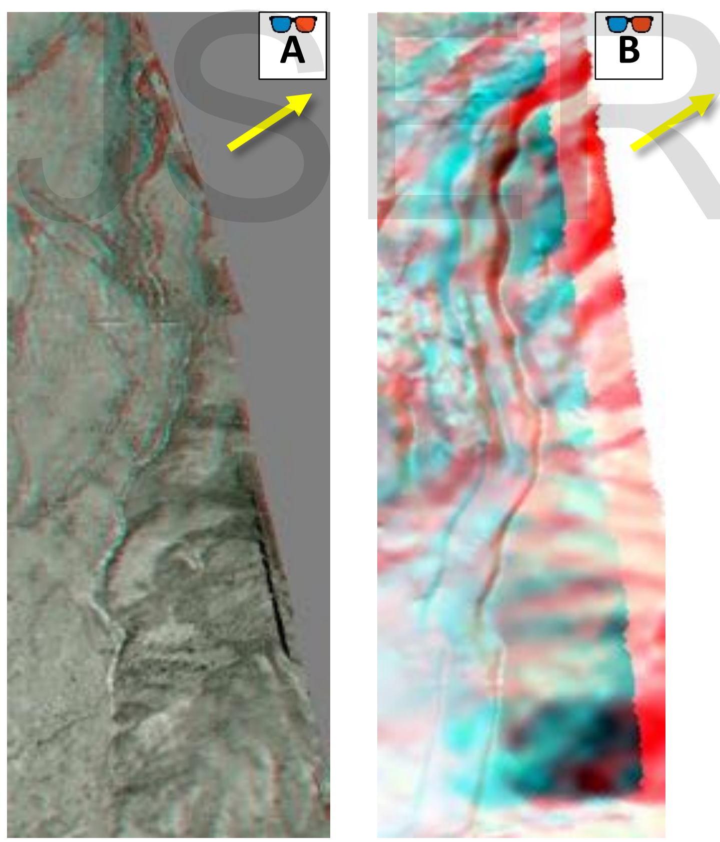

Figure 3.9 Oblique anaglyph stereoscopic views of the deeply incised gully by the foot of the Mingan Mountains east of the study area. (a) Snippet from the aerial photos. (b) Cropped from the DEM. Yellow arrows point north.

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A deeply incised narrow gully by the foot of the MM was quickly identified during the preliminary manual stereoscopic interpretation by virtue of its highly noticeable channel. This deep gully is a segment of the Langawan River and runs NW-SE before shifting to a N-S manner upon juncture with the Pisoh Creek and Davildavilan River. Its characteristic depth can be accounted for by its age and the feeble underlying material composed of the antecedently unconsolidated material of the debris avalanche deposit. It is plausible that the gully developed as a syngenetic feature relative to the said colluvial deposit. Owing to its freeboard, channel migration cannot be expected to transpire for a long period of time, unless precipitation increases and avulsion occurred repeatedly that the bed material reach bank elevations. On the covered area, the gully is about 2.83-km in length, and traverses the barangays Tanawan and Caragsacan. Eccentric lighter tone of the gully in the aerial photo may denote thick accumulations of freshly deposited fine to boulder-sized regolith. Figure 3.9 above shows its form while figure 3.10 below shows the location of the gully and other fluvial features including terraces, confluence point, and bed material composition.

Figure 3.10 View upstream of the Langawan River with facing direction N35°E taken at 15.39° N, 121.39° E showing the dry river bed, location of the gully, and modified river terrace on the river banks.

Debris Avalanche Deposit

The terminology was first used by Rutland (1967) in the description of the massive relict mass movement deposit situated north of the study area. The deposit detached from the MM as a result of quaternary tectonism and slope instability. It formerly spanned far greater than its present form, but because of erosion, mostly due to the riverine action of Dingalan River and Langawan River, a smaller contempo extent is manifested. Chaotic sorting of sediments with sizes ranging from clay to boulder sizes accompanied by inexistent bedding and lamination characterizes the avalanche deposit. On account of the action of gravity, larger materials tend to amass in the toe of the deposit, and finer materials tend to collect near the crest. Figure 3.11 presents a roadside excavation on the deposit depicting its composition. Figure 3.12, on the other hand, displays an anomalous bed on the cutbank of the Dingalan River that gives clues on the presumed greater expanse of the avalanche.

Figure 3.11 Road excavation portraying the lack of bedding and ill-sorted composition of the deposit near its crest. Taken at 15.41°N 121.37°E with a facing direction of N35°E.

Figure 3.12 Cutbank showing a thick matrix-supported breccia layer unconformably overlaying on the defunct riverbank prior to the catastrophic mass movement. Taken at 15.39°N 121.38°E by the floodplain of Dingalan River.

Relative age of the deposit permitted an increase in its overall integrity as time chartered natural compaction processes and consolidation to ensue, hence, porosity diminished. Climatic conditions sanctioned the growth of thick vegetation that provided additional anchorage for the deposit. More recent earthquake events (e.g. magnitude 7.8 July 1990 earthquake) administered further testimony to the heightened stability of the deposit. Multiple fault scarps formed on its west-facing slopes, and with this, the deposit can serve as geologic foundation material for structures. Figure 3.13 indicates the anaglyph images of the deposit.

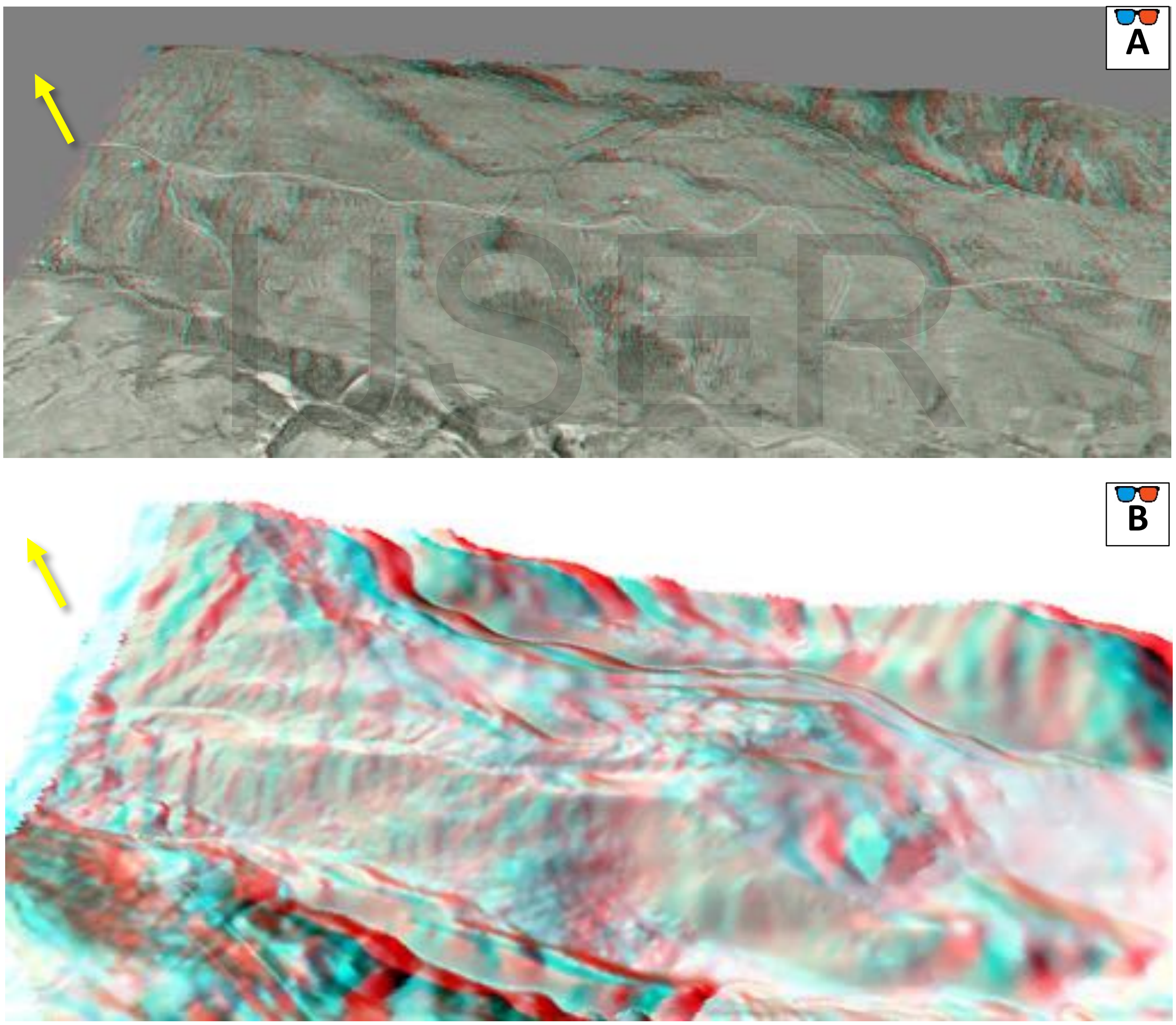

Figure 3.13 Oblique perspective anaglyph imagery of the debris avalanche deposits. (a) Reaped from the aerial photographs. (b) Trimmed from the IfSAR DEM. Arrow points north.

Rotational Landslides

Multiple incipient shallow rotational landslides were observed to prevail in the structurally controlled slopes north of the covered sector. These features are newly formed, so they are absent in the aerial photographs and DEMs. Climate is the foremost instigator in the development of the sliding soil mass. Pronounced scarps, clear to subtle body extents, and widths not exceeding 60 meters are the general descriptive characteristics of the said features. Figure 3.15 shows the land failures atop the east facing structurally-controlled slopes.

Contrary to these recent shallow landslides, a deeper rotational landslide is perceived in the DEM with a southeast slip direction, lodged above the debris avalanche deposit. A large, conspicous scarp is observed, but the extents do not justify the exiled material, so a possible erosion of the landslide body has occurred. The anaglyph image of this feature is displayed in figure 3.14.

Where these mass movements occur, vegetative covers are sparse and thin, generally veneered with short grasses and shrubs. Scarcely any trees on the slopes, coupled with the thick orange-brown colored lateritic soils, and moderate to steep slopes, encouraged the advancement of land failures.

Figure 3.14 Oblique perspective anaglyph image of the relatively deeper rotational landslide with obscured extents due to erosion.

Figure 3.15 Panoramic view of the east facing slopes northwest of the study area showing the structurally controlled slopes, denudational slopes, landslides, pressure ridges, and triangular facet.

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Figure 3.16 View looking north, taken at 15.41°N 121.37°E, showing the perceptible scarp and crest of a landslide but has a concealed body due to thick vegetation.

Figure 3.16 displays another landslide scarp and crest upon the debris avalanche deposits with a secluded body as a result of the dense grasses and shrubs. Lateritic soils comprise the feature with a slip direction of west. Inference regarding the seismic nature of the unit can be argued because of the likelihood of an existing fault scarp, but undetected during the delineation due to the overprinting nascent smaller debris slide over the debris avalanche deposit.

Denudational Slopes

Three kinds of denudational slopes were recognized in the study area which are differentiated from one another based on comprehensive relief, ambiguous controlling factor, and active mass wasting mechanism. They are designated as denudational slopes, denudational slopes with structural control, and highly eroded denudational slopes with minor structural control.

From the nomenclature itself, the denudational slopes do not possess discernible fault-related feaures. This slope class is recognized on a section of the MM northeast of the study area closest to Dingalan Bay. GIS measurements revealed that this area is located approximately 2-km away from the fault trace, with its form being principally governed by the NE-SW trending Subsob River. Figure 3.17 illustrates the said slope classification.

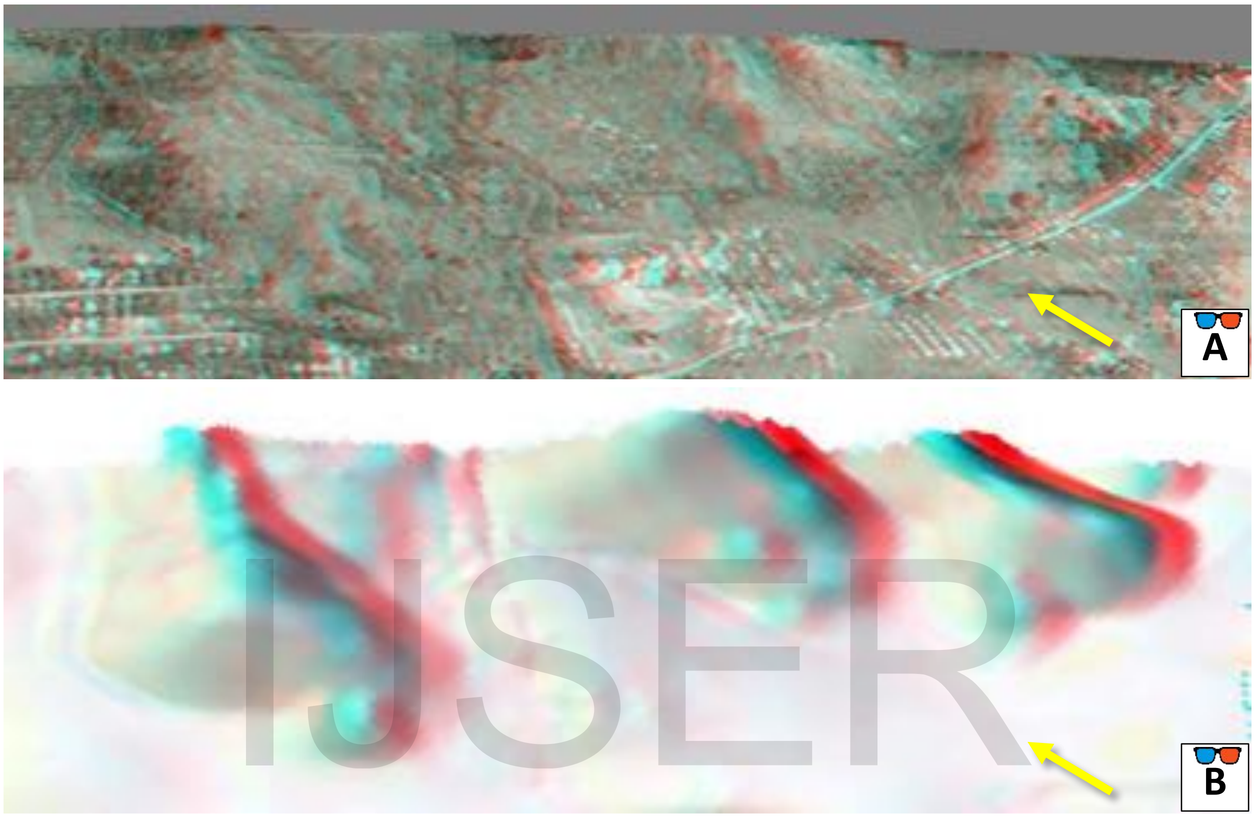

Figure 3.17 Oblique anaglyph perspective views of the denudational slopes and the sole alluvial fan located at the northeastern corner of the study area. (a) Cropped from the aerial images. (b) Trimmed from the IfSAR DEM. Yellow arrows denote north.

The highly eroded denudational slopes with structural control are located on the opposite side of the floodplain in front of the aforesaid class. The PF map of Tsutsumi and Perez (2013), shows that the fault does not stretch to this sector, in consequence, structural control on these slopes pale in comparison to the adjoined slopes where tectonic influence is sharply established. Seismic indicators include pressure ridges and a well-defined triangular facet. However, erosion overwhelms seismic impact as copious stream networks dominate the slopes. Furthermore, peculiar tones of the aerial photos showing the lack of trees and eroded ridges assert the imperative denudational control. The leftmost part of figure 3.15, and figure 3.18 illustrates this slope form.

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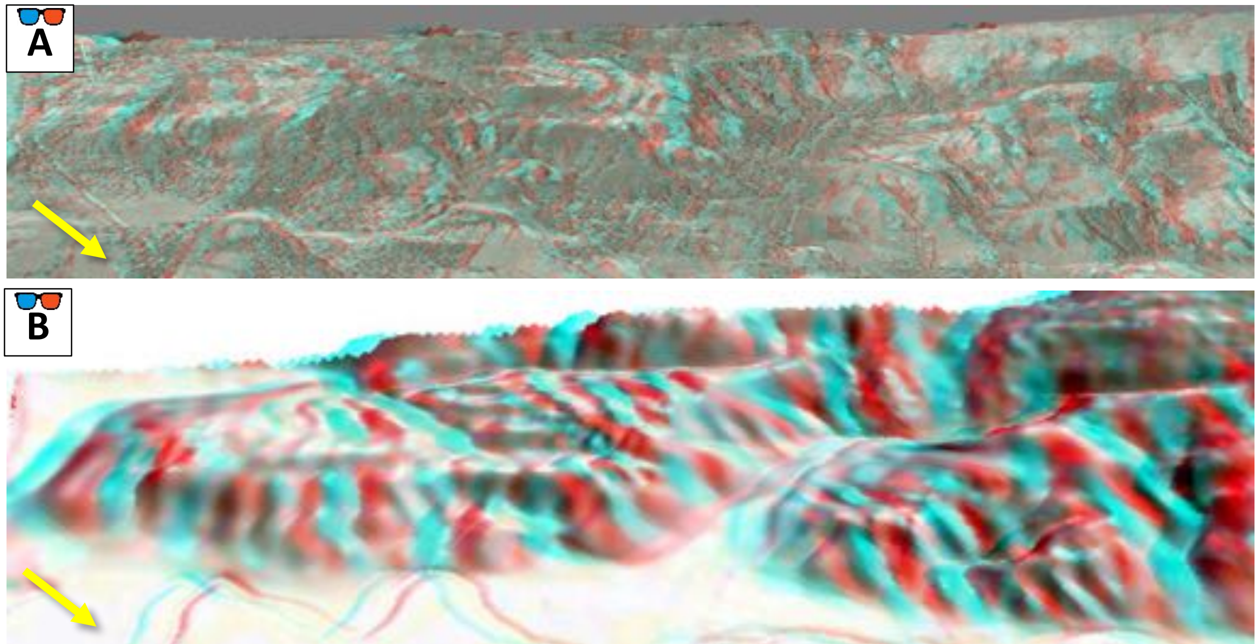

Figure 3.18 Oblique anaglyphic 3D views of the highly eroded denudational slopes with structural control located at barangay Butas na Bato southeast of the study area. (a) Taken from the aerial image stereo pairs. (b) Snippet from the DEM. Arrows denote north.

The presence of the Gabaldon segment of the PF stimulated the progression of fault-related morphological units in the area of study. The resemblance of this major tectonic feature with the San Andreas Fault in California corroborated the presence of similar landforms in its throughgoing trace. Nakata (1977) partially enumerated the tectonic landforms spanning Dingalan Bay to Gabaldon involving left-handed offset streams and depressions. On closer inspection accomplished in this study, several geomorphic units due to seismicity were distinguished, providing thorough characterization relative to preceding studies.

On the field of interest, structural control is seen to predominate the slopes and valleys northwest of the study area. The sinistral strike-slip nature of the fault, however, did not exactly manifest in Dingalan. Most are normal faults, but upon examining in a wider scale, the left-handed aspect is still perceptible. The normal fault traces are segmented, occurring on the valley floors, footslopes, and along the banks of Dingalan River. Adjacent to the valley, two normal fault traces appeared, having opposite plunge and parallel trends. This fault configuration epitomized an array of geomorphologic units with striking characteristics.

Fault Scarps

Several fault scarps are readily detectable on the aerial photographs and DEMs. Existing dense flora, however, obliterated and hindered the field observation of some of these features. Contrarily, east facing scarps positioned by the valley floor were seen in the field, but not in the remotely sensed data. This scarp was observed cutting the earlier formed river terrace of the Dingalan River. An example of which is displayed in figure 3.19.

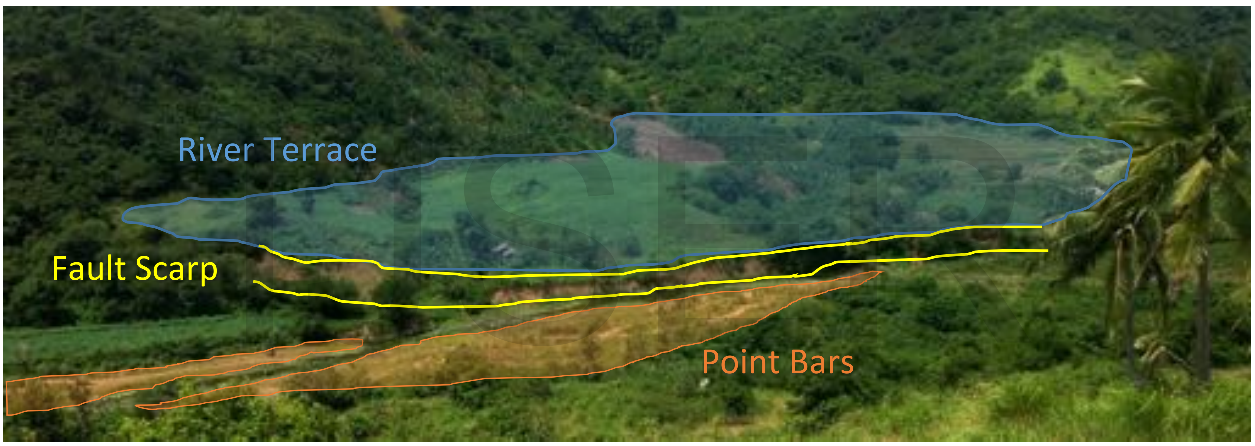

Figure 3.19 View looking southeast taken at 15.41°N 121.38°E showing the valley bottom illustrating the elongated east-dipping fault scarp on the river terrace as well as the point bar deposits of the Dingalan River.

As previously mentioned, west-dipping fault scarps were observed to overlap the whole western expanse of the debris avalanche deposits. Though presently concealed, these landforms are highly distinguishable on the aerial photos and DEM. Among the existing fault scarps, this particular feature is the most extensive and has an immensive span. Despite attesting to the stability of debris avalanche as foundation material, the presence of the fault scarp denotes the fault trace itself, providing additional constrictions towards property development because seismic risks are tremendous. This morphologic feature is displayed in figure 3.20.

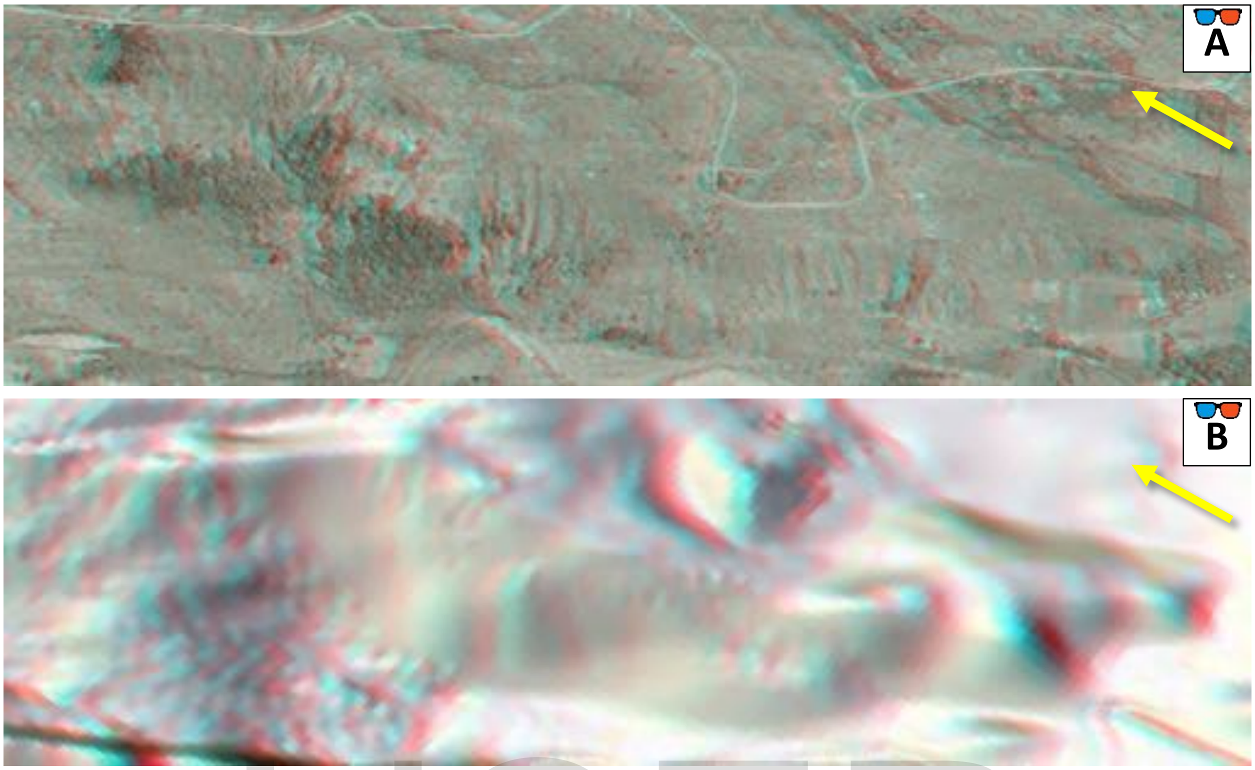

Figure 3.20 Oblique perspective views of the anaglyph images showing the west-dipping fault scarps on the western slopes of the debris avalanche deposit, including the noticeable younger landslide deposits on the leftmost portion of both images that obscured the entirety of the scarp. (a) Sourced from the aerial photos. (b) Taken from the DEM.

Offset Ridges

Two NW-SE trending offset ridges were recognized from the remotely sensed data. Lithologically, both are composed of igneous rocks of the Caraballo Formation. Subdued edges denote that these isolated bodies have undergone subsequent erosion following its detachment. At present, the two are surrounded with alluvial deposits, confirming the ubiquitous fluviatile control on the morphology. Regardless of the abrasive forces, the features still have pronounced west-dipping fault scarps, signifying the intrinsic resistive strength of its constituent materials. Upon the field visit, glaring evidences of the anthropogenic disturbance on these ridges are present. Residents built homes and tilled the soil cover for crops on top of the ridges. Figure 3.21 depicts the scarp as well as the modified state of these units and figure 3.22 illustrates their overview form.

Figure 3.21 View looking northwest taken at 15.40°N 121.8°E illustrating the fault scarp and visible extent of the offset ridge situated near the active channel of the Dingalan River.

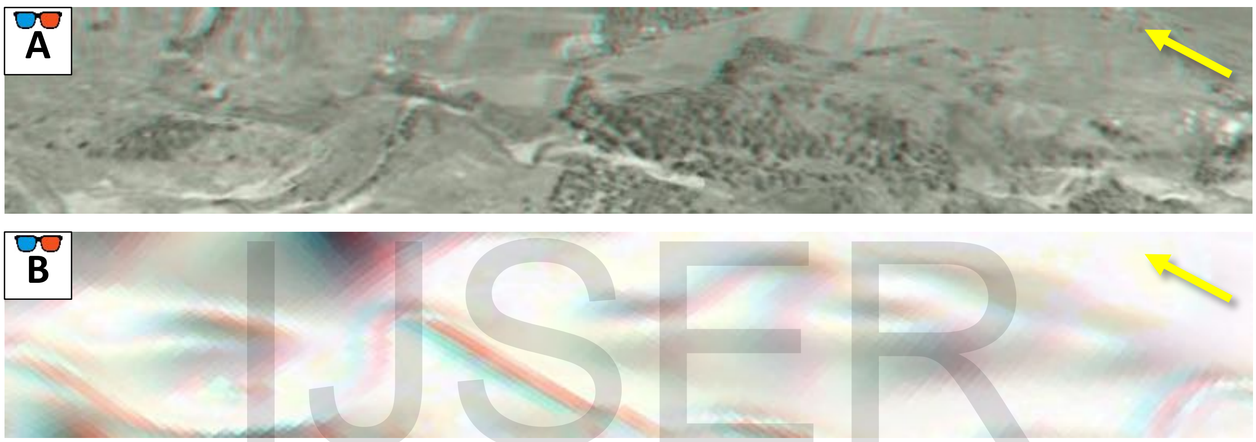

Figure 3.22 Oblique perspective views showing anaglyphic images of the two collinear offset ridges and an offset stream along the slender valley. (a) Snapped from the aerial photos. (b) Cropped from the DEM.

Offset Streams

Three offset streams were readily identified in the preliminary interpretation of the two datasets. The first one, situated near the valley, has a marked left-handed offset as consequence of the sudden change in the dip of the normal fault. Field observation of this feature proved to be challenging due to the vegetative veneer that impedes the field of view. The second offset stream, located near the toe of the debris avalanche, has a distinct sharp curve on an otherwise straight channel. Lastly, the third offset stream positioned near an offset ridge, was detected from the aerial photos. Bizarrely, its channel disappeared, but reappeared less than 10 meters away from the offset point. As multiple migrations had undeniably occurred on the streams and rivers, this third offset was not extant in the DEM. The disconnected stream had already reassociated considering the difference in dataset age. Figure 3.23 shows the remarkable sinistral first offset stream, figure 3.22 above displayed the second offset stream, while figure 3.24 illustrates the third offset stream from the anaglyph aerial photos.

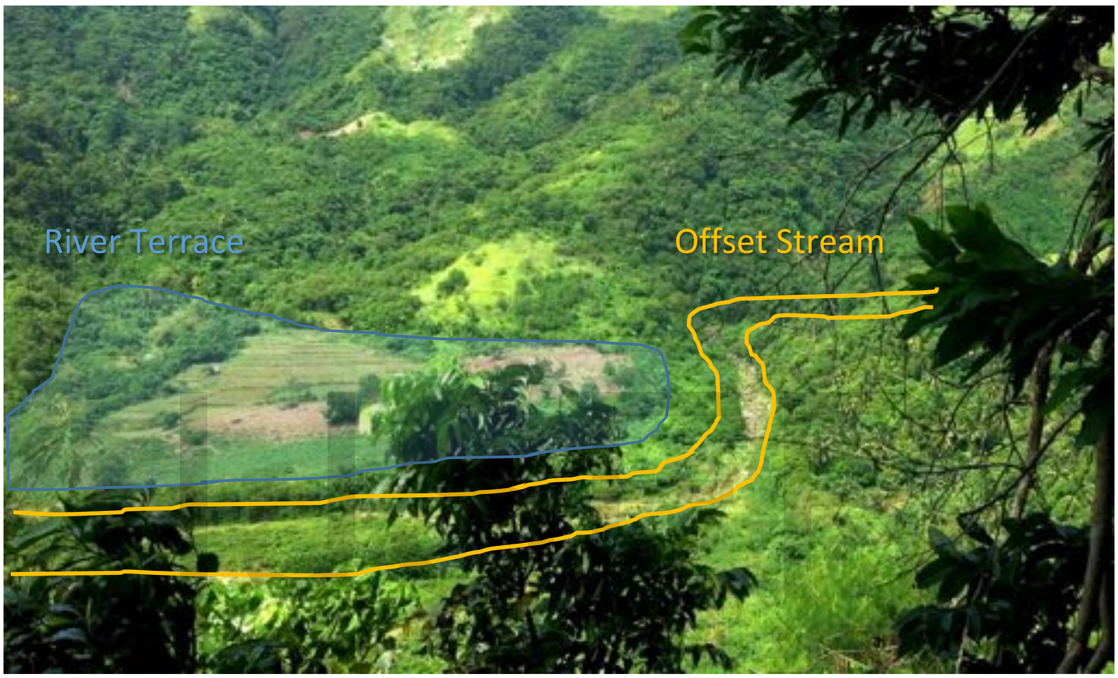

Figure 3.23 First offset stream and a river terrace situated by the footslopes northwest of the study area looking S62°W taken at 15.40°N 121.38°E.

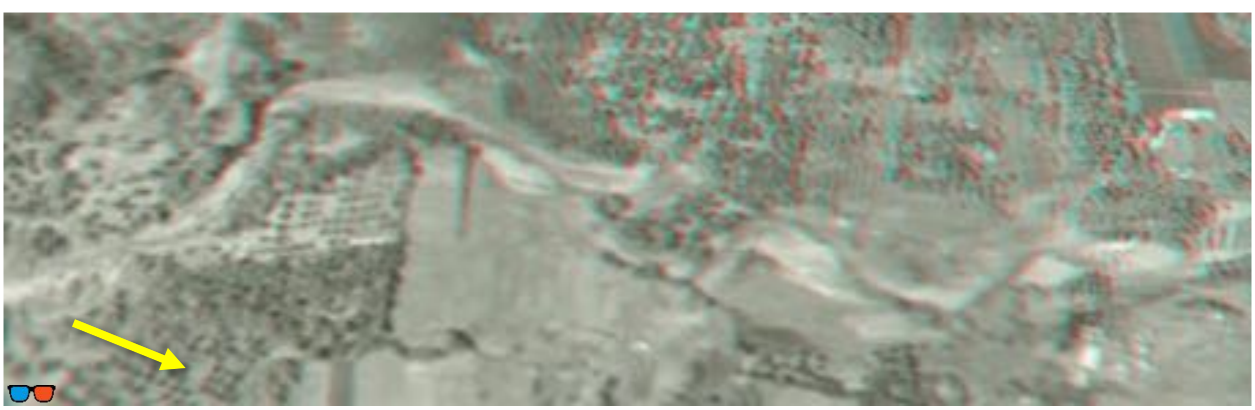

Figure 3.24 Oblique viewpoint taken from the anaglyph aerial imagery depicting the bizarre offset stream nearest to the coastline, which have reconnected by the time of production of the IfSAR DEM. Yellow pointer denotes north direction.

Eroded Linear Escarpment

The eroded N-S trending linear escarpment is prominently exposed adjacent to the headstream of the Dingalan River. An east-dipping normal fault produced the escarpment, hence, a pronounced east-directed scarp manifested on this landform. Accompanying this is a protruding linear ridge, the exposure of which was enhanced by the erosive capability of the said river furrowing its western flank. The southern tip of the escarpment is curved in comparison to its northern apex due to the presence of an offset stream. It also acted as the confinement structure of the nascent debris slide deposits which overprinted the rather wide fault scarp on the debris avalanche slope. Figure 3.25 below shows the escarpment on the utilized datasets.

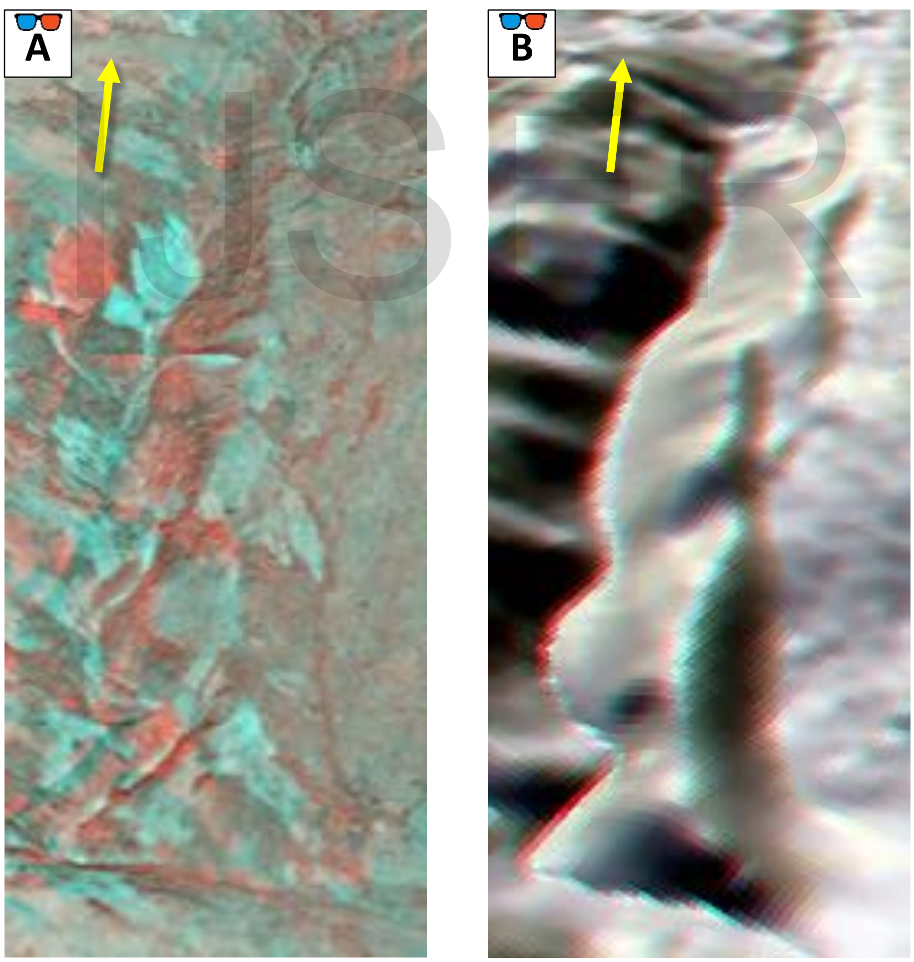

Figure 3.25 Oblique anaglyphic standpoint showing the linear escarpment, ridge, fault scarp, and deep rivers. (a) Taken from the aerial photos. (b) Cropped from the DEM.

Sag Pond

A single sag pond was seen atop the undulating tectonically-influenced slope bordered by two pressure ridges. It trends NW-SE parallel the fault line and is approximately 1.2-km in length and 200-meters in width. The ridge on its eastern flank is comparatively less protruded, almost impairing the detection of this landform. Aerial images barely showed its presence, for this reason, the feature was only distinguished on the elevation model. Figure 3.26 depicts an overhead view of the DEM showing the linear sag pond.

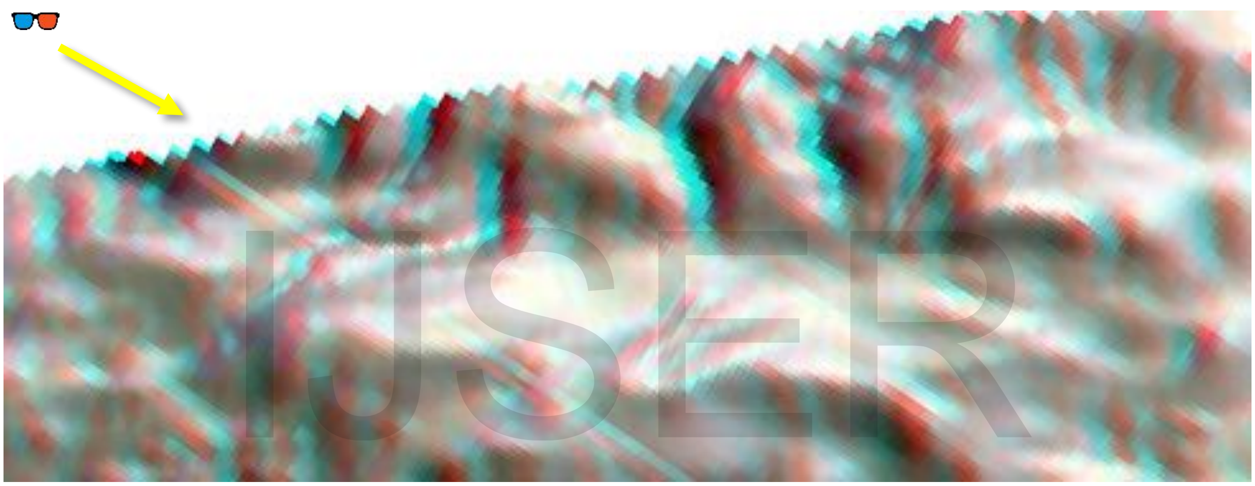

Figure 3.26 Overhead anaglyph view of the sag pond enclosed by two pressure ridges taken from the DEM. Arrow points to the north.

Pressure Ridges

Prevalent structural control of the Gabaldon Fault is exemplified by numerous pressure ridges on the elevated areas northwest of the field of study. Though most are eroded, the striking linearity of these features remained perceptible. These ridges collectively influenced the sag ponds and replacement seismic attributes to the larger terraces in the slopes, as well as the drainage pattern of the sloping region. The ridges trend NW-SE parallel to the fault trace was seen during the aerial photo interpretation. These features are present in figure 3.15 above, while another example was presented in figure 3.26 above.

Triangular Facets

A number of triangular facets are also existent along the footslopes of the elevated areas adjacent to the floodplain. The largest of which has an approximately 300-meters of width characterized by a rounded crest as a consequence of the active erosion and weathering. The facets are arranged collinearly parallel to the fault trace. Multisized flora, including trees down to grasses constitute the proliferate vegetative cover of the facets, effectively cloaking the presence of the two smaller facets. As a result, only the largest facet was seen on the field visit as shown in figure 3.15. Presented below is figure 3.27 illustrating the triangular facets as seen in the aerial photos and DEM.

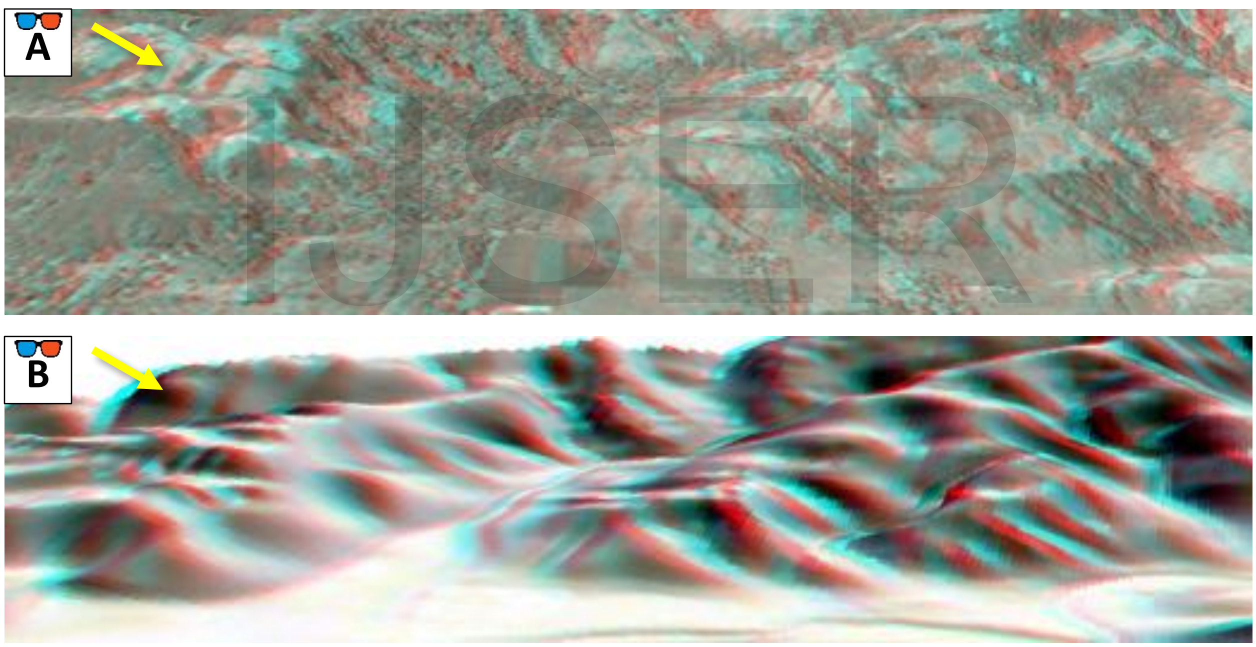

Figure 3.27 Obliquely oriented anaglyph photos picturing the triangular facets, eroded ridges, and a segment of the floodplain. (a) Aerial photo snippet. (b) DEM sourced.

Fault-controlled terraces, benches, and slopes

Structural prominence is most apparent in the slopes northwest of the study area where the active faulting and tectonics reworked the terraces and benched structures which are primarily attributed to the fluvial and erosional environment. Ridges and scarps overprinted the antecedent morphology albeit maintaining substantial information on its predecessor. Similarly, the entire slope exhibited structural features and landforms. The relief shift from undulating to rugged, occurring by the sag pond, further exemplifies the significant tectonic alteration in this slope. Based on its rolling and undulating topography, it can be presumpted that the soil cover have higher porosity and less consolidation in comparison to the adjacent slopes with minor structural influence. The number of land failures alone, promote the inferior pedology in the area. This can be viewed in the rightmost area of figure 3.15 above, while figure 3.28 below presents the three dimensional appearance of this morphologic feature.

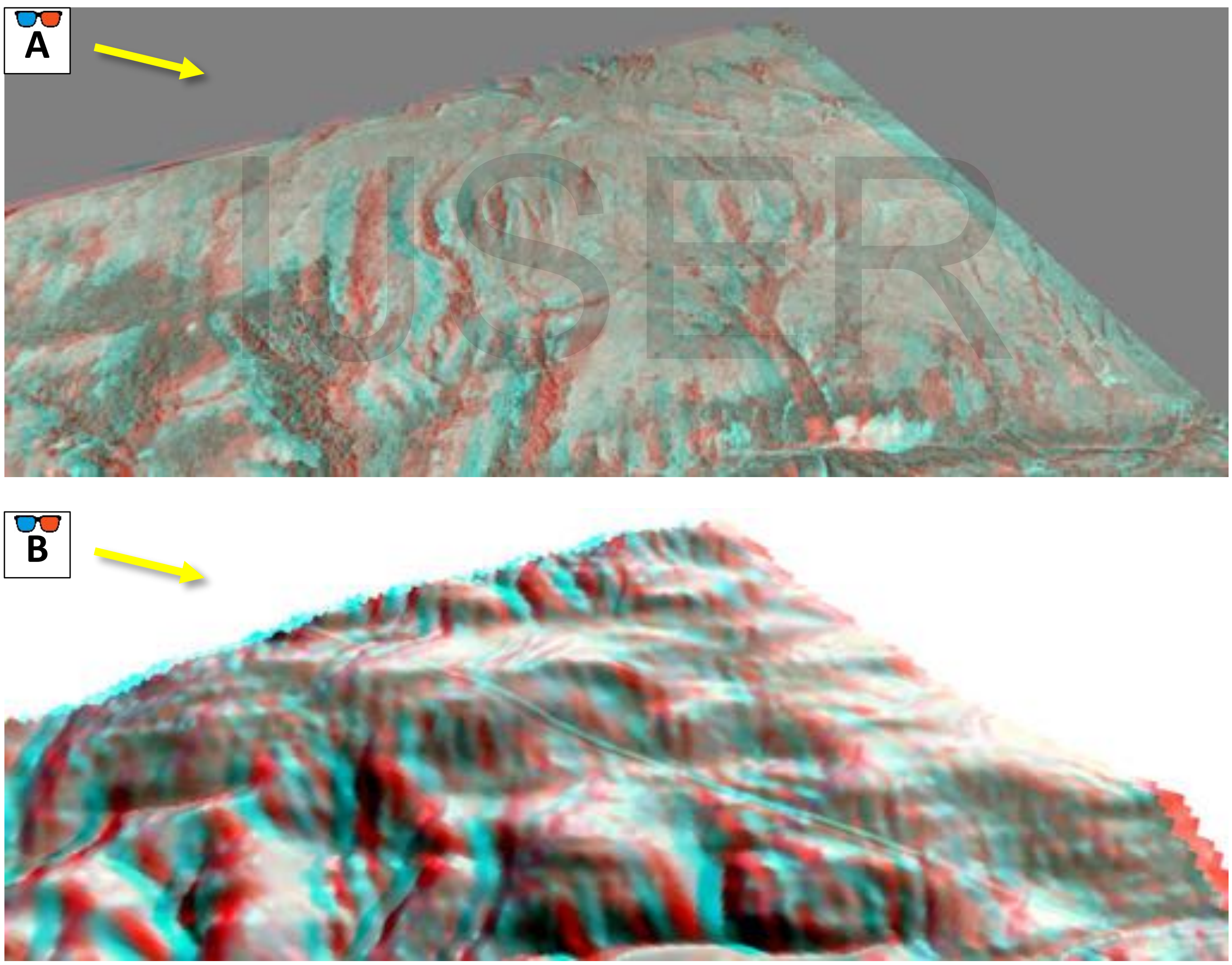

Figure 3.28 Obliquely oriented anaglyph images depicting the structurally-dominated slopes and landform units including benches/terraces, fault scarps, pressure ridges, and the shift in relief from undulating to rugged. (a) Taken from the aerial photos. (b) IfSAR-DEM crop.

As previously mentioned, seven rivers, Dingalan River, Langawan River, Davildavilan River, Pisoh Creek, Subsob River, Amil Creek, and Sapinit Creek comprise the hydrological network of the field of study. Due to topographic relief, lithology, and structures, generally five drainage patterns including, parallel, dendritic, sub-radial, sub-rectangular, and trellis manifested in the study area. Dingalan River is the sole perennial stream, although the efflux is extremely slow to stagnant with abundant moss and algae build up in its active course. The other rivers and streams are dry and are ephemeral in nature, handling flow only during the rainy season. Though this is the case, riverine action is still considerable given the conspicuous cutbanks, deep river beds, bar deposits, and other river-borne geomorphologic features.

Alluvial Fan

One alluvial fan was delineated on the terrain model during the preliminary interpretation. It was deposited by the Subsob River along a young valley of the MM, and the said river dissected the fan along the middle due to it being the prime feeder channel that supplies sediments in the form. Measurements using GIS have shown that this N-S trending feature spans 330-meters of width at most. It is evident that this feature is newly-formed because intensive erosion in the area prohibits growth and development of similar aggradational features. Field inspection of the unit was unaccomplished due to ongoing local legal proceedings prevented entry to selected areas in the municipality. This morphologic unit is presented in figure 3.17 above.

Alluvial Islands

Several alluvial islands were delineated during the preliminary interpretation and investigations. Evidently, the features were formed due to the recurrent channel migration, mostly by the Dingalan River and its confluent streams. As two streams initiated deposition along their inner bends, the islands expanded and widened until plant growth commenced, providing organic anchorage to the deposited islands. However, the biologic veneer was sparse and limited to grasses. In relation to engineering, this does not improve the intrinsic strength of the islands since they are composed of fundamentally cohesionless sediments, allowing for larger settlements to occur and increasing the susceptibility to liquefaction. These landforms are distributed on the barangays Butas na Bato, Aplaya, Poblacion, and Caragsacan. Figure 3.29 below displays the largest of these islands situated nearest the coastline while figure 3.30 shows the anaglyphic overview of all the delineated alluvial islands in the study area.

Figure 3.29 View looking S18°W taken at 15.28°N, 121.39°E showing the alluvial islands, active course of Dingalan River, and non-engineered earth dam composed of clay to fine sand materials.

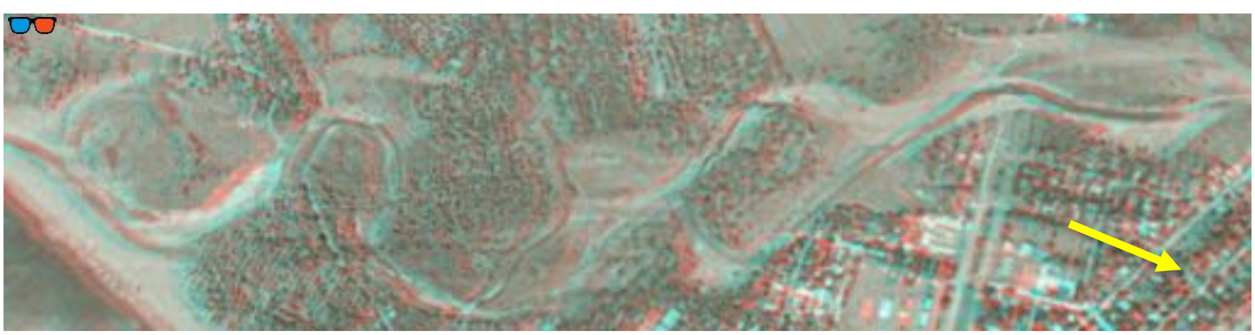

Figure 3.30 Anaglyph overhead view of the delineated alluvial islands and meandering channels.

Floodplain

Included in the delineated floodplain are the basinal lowlands, a majority of the fluvial regime, zones of high, medium, and low flood susceptibilities, and the relatively flat areas by the valley floors. It covers most of Caragsacan, southern portion of Butas na Bato, bulk of Poblacion, whole Aplaya, and a fraction of Davildavilan and Paltic. The domain is entirely overlain by recently deposited unconsolidated alluvium, while previous geotechnical drillings conducted by Llarena (2015) unearthed the underlying highly fractured andesite. Three-dimensional overview of the floodplain including the other fluvial landforms is presented in figure 3.32.

Fluvial Terraces

Most river terraces in the area are reworked either tectonically or anthropogenically. Only those sculpted by the Langawan River and Amil Creek exhibits pure riverine control due to their relatively recent formation. These features exhibit linearity and a narrow width, the longest of which is about 250 meters in length. Terrace of the Langawan River is situated on both sides of the gully, carved on the debris avalanche deposit and the flanks of the MM. It has another perceptible terrace (figure 3.31) from the dataset located in its leeward side after merging with Davildavilan River, however, the terrace is undergoing modification for the construction of the Langawan bridge by the time of field visit. This was displayed above in figure 3.10.

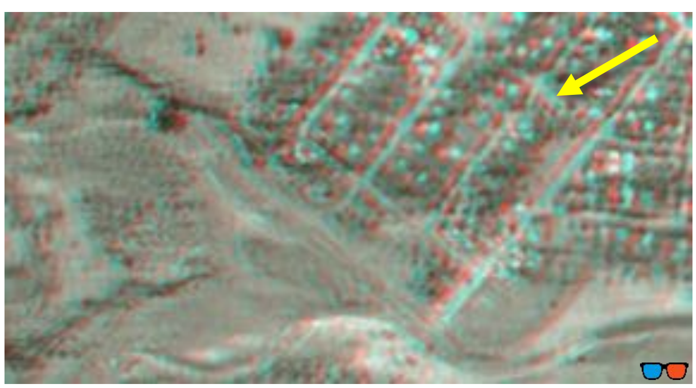

Figure 3.31 Top view of the downsteam terrace of the Langawan River where existing residential structures are concentrated.

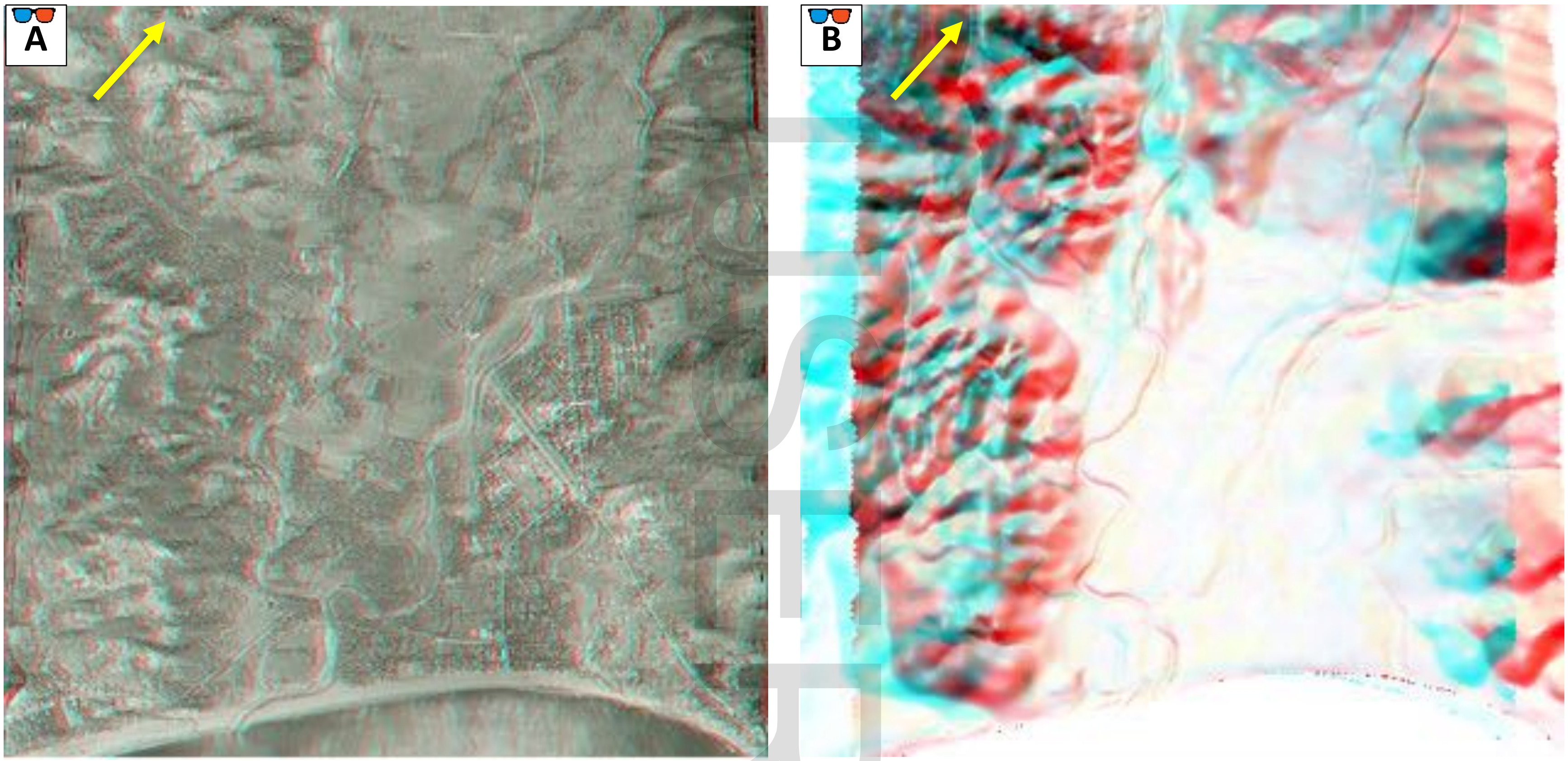

Figure 3.32 Three-dimensional overviews of the floodplain showing other fluvial landforms such as the active channel, migrated channels, valley floors, alluvial islands, point bars, overbank deposits, fluvial terraces, and abandoned channels. Displayed also are some structural and denudational landforms and the coastal region. (a) Taken from aerial stereo pairs. (b) Cropped from the IfSAR DEM.

Stream Channels

Dingalan River solely has active river flow, though the velocity is very slow to practically stagnant. Abundant botanical overgrowth subsisted where water is present, indicating the relative duration of inactivity of the water flow and probable eutrophication. These characteristics effectively classify the river as a bayou. However, abutting deeply incised banks and meanders exemplifies the stream capacity and strong erosive capability of the river during the Quaternary and/or at times of excessive runoff during the wet season. Large sediments of pebble to boulder sizes present in the river bed depicts the high competence of the river when it has considerable flow. Neotectonic influence is indicated by the channel where offset streams persist.

Other streams present in the coverage area were observed to be dry, and have high freeboards. These streams can geomorphologically be called wadis. Similar to Dingalan River, this gives a qualitative estimation of the flow parameters. Riverine flooding has little to no chance of occurring, though heightened susceptibility to flash flooding is to be anticipated. Figures 3.33, 3.34, and 3.35 show the cutbanks, point bars, and the channel of Dingalan River and Amil Creek, respectively. Langawan River was already displayed in figure 3.10 above.

Point Bar Deposits

Several point bars were delineated in the stereographic observation. These deposits are more apprehensible in the aerial photos compared with the field for the reason that most rivers do not have an ongoing flow by that instance. The bars were deposited in the inner bends of the meanders of the Dingalan, Langawan, and Subsob Rivers by the floodplain realm. The deposits are slender, measuring approximately 60 meters wide at most, the longest of which is approximately 282 meters in length. An anaglyph example of these deposits is illustrated above in figure 3.30.

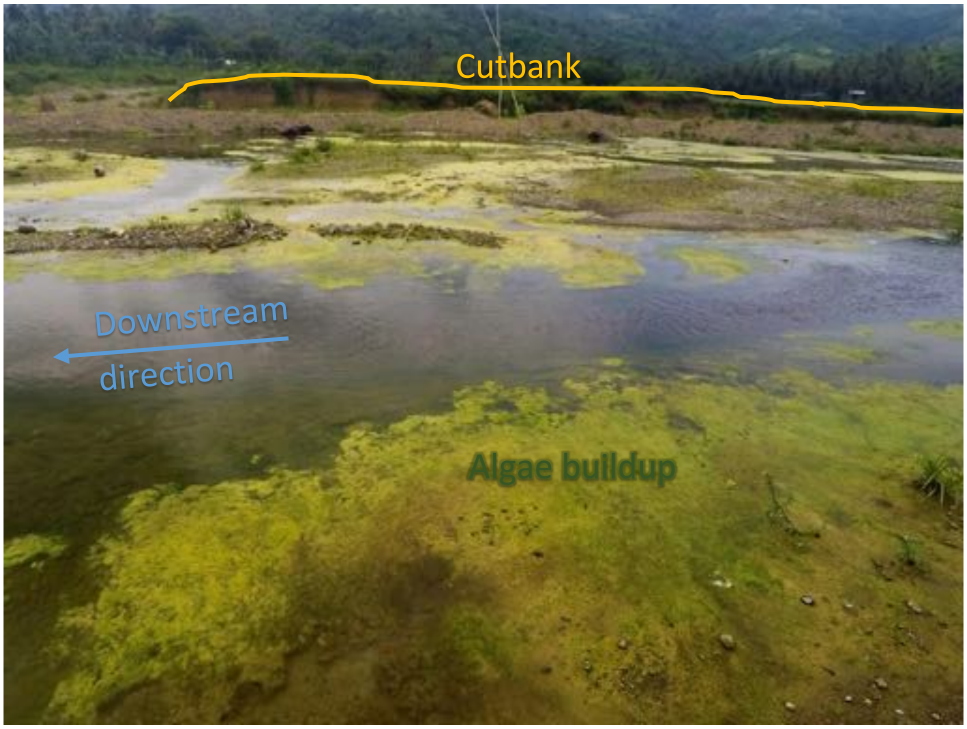

Figure 3.33 View looking N62°E taken at 15.39°N, 121.38°E showing the excessive biologic overgrowth in the active channel and deeply incised banks of Dingalan River.

Figure 3.34 View looking S43°E taken at 15.39°N, 121.38°E illustrating the dry portions of the Dingalan River, unsorted coarse bed material, and boulders by its cutbanks.

Figure 3.35 View looking N43°W taken at approx. 15.39°N, 121.38°E denoting the cutbanks, isolated puddle, coarse bed material, and presently inactive channel of the Amil Creek.

The geographic position of Dingalan allows for high wave energy to transpire as consequence of the Coriolis effect. This primarily controls the morphodynamics and morphology of the transitional and coastal environment. The strategic emplacement of the alluvial lowland between two igneous mountains directly impinges the morphogenetic processes that will occur. Dingalan bay is the adjoined water body, which is typified by its vicious waves and currents. Correspondingly, the development of aggradational landforms is immediately thwarted.

River Delta

Aerial images showed the existence of two deltas in the study area produced by the Langawan River and its confluent streams, and the other, created by Subsob River. Waves instantaneously wash away the sediments deposited by the river, and for this reason, the deltas do not have a specialized structure, albeit they simply followed the concavity of the coast. Upon the field visit, the presence of a non-engineered earthfill dam built to deter the flow of the Dingalan River was duly noted (see figures 3.29 and 3.36). The obfuscated water flow, by virtue of gravity, probed for alternate routes. Further investigation showed that the water infiltrated the underlying strata, and resurfaced at about 75 meters away from the dam before withdrawing to the sea. Figures 3.36 and 3.37 demonstrate the existing status of the delta.

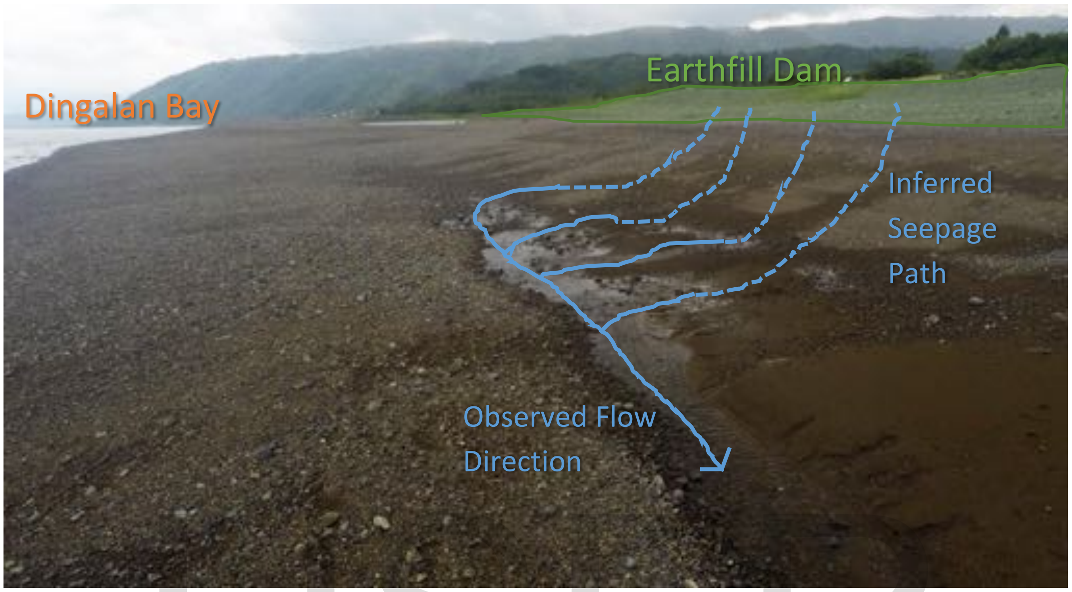

Figure 3.36 View looking W taken at 15.38°N, 121.39°E showing the earthfill dam, inferred underground flow vector, and surficial flow vectors of the riverine waters.

Figure 3.37 View looking E taken at 15.38°N, 121.39°E illustrating the point where fluviatile water concatenates with the marine environment, including the flow path, and the difference in beach materials.

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Coast

The beach is in direct contact with the ocean, thus, it receives and accommodates most of the wave energy. The rigorous waves prohibit the development of substantial landforms beyond the terrestrial region. The difference in beach composition is distinct (see figure 3.37 above), with the coarser fraction tend to remain in the beach face and swash zone nearest to the coastline. Finer portions accrue farther away to the berm, at about 3 meters away from the coastline. This phenomenon can be attributed to the waves eroding and washing away the fine material.

Looking at a much larger scale, a greater curvature and narrower coast can be observed in the northeastern side in comparison to the southwestern end of the beach. It is argued that wave and longshore current erosion is more potent in the northeastern side analogous to the latter where deposition is favored. Figure 3.38 below demonstrates this flexural contrast.

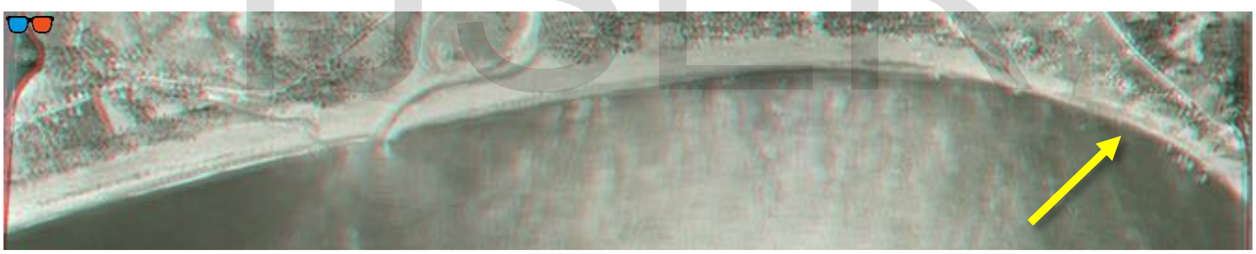


Figure 3.38 Overhead view of a snippet from the anaglyph stereo pairs showing the overall form and profile of the beach and coastline.

A database of the field and preliminary interpretations and investigations were then assembled into a geomorphologic map depicting the four geomorphologic provinces grouped by color. To simulate relief, a hillshaded elevation model was purposefully placed underneath the semi-transparent layer containing the geomorphologic features. The completed map is then cartographically presented in figure 3.39.

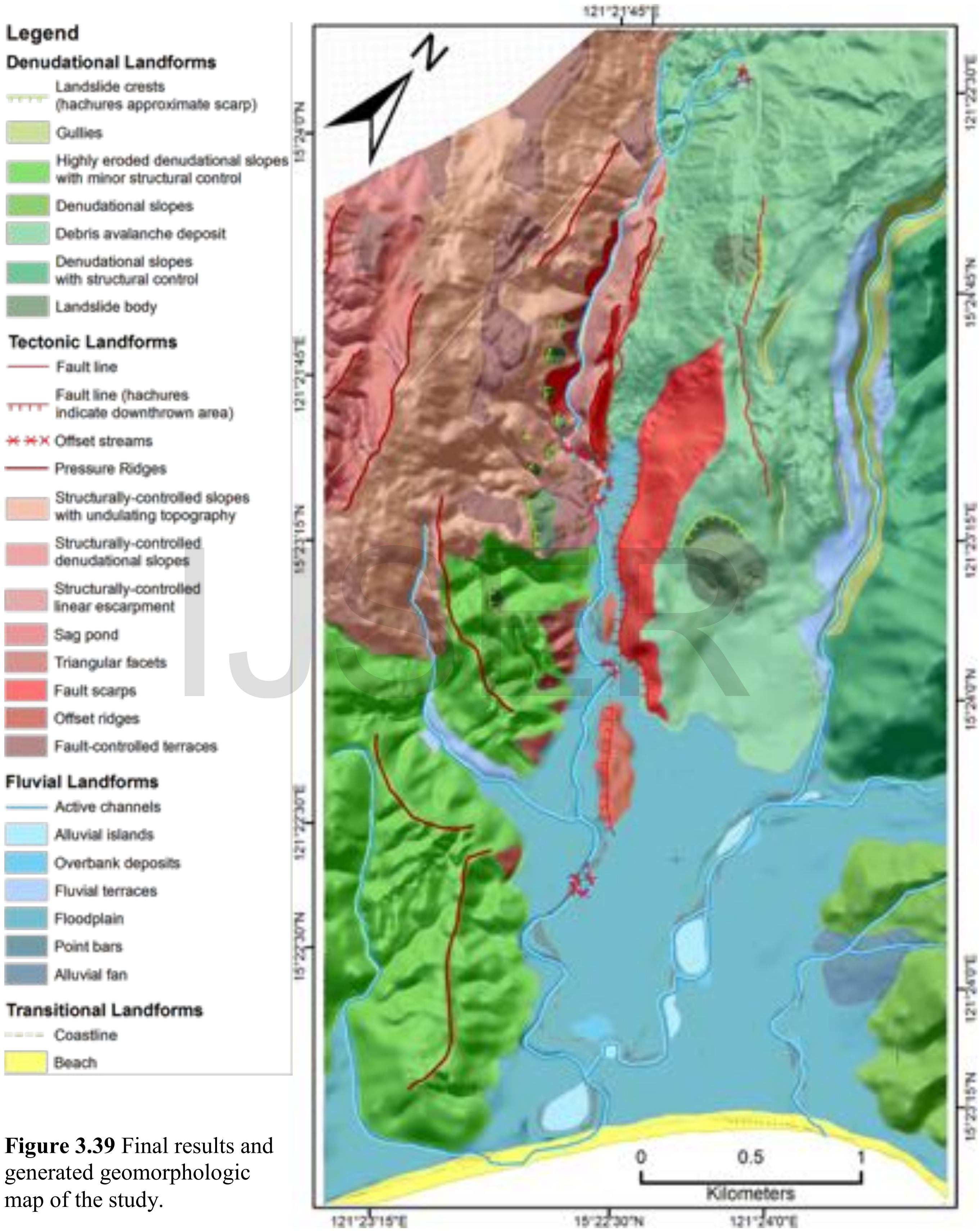
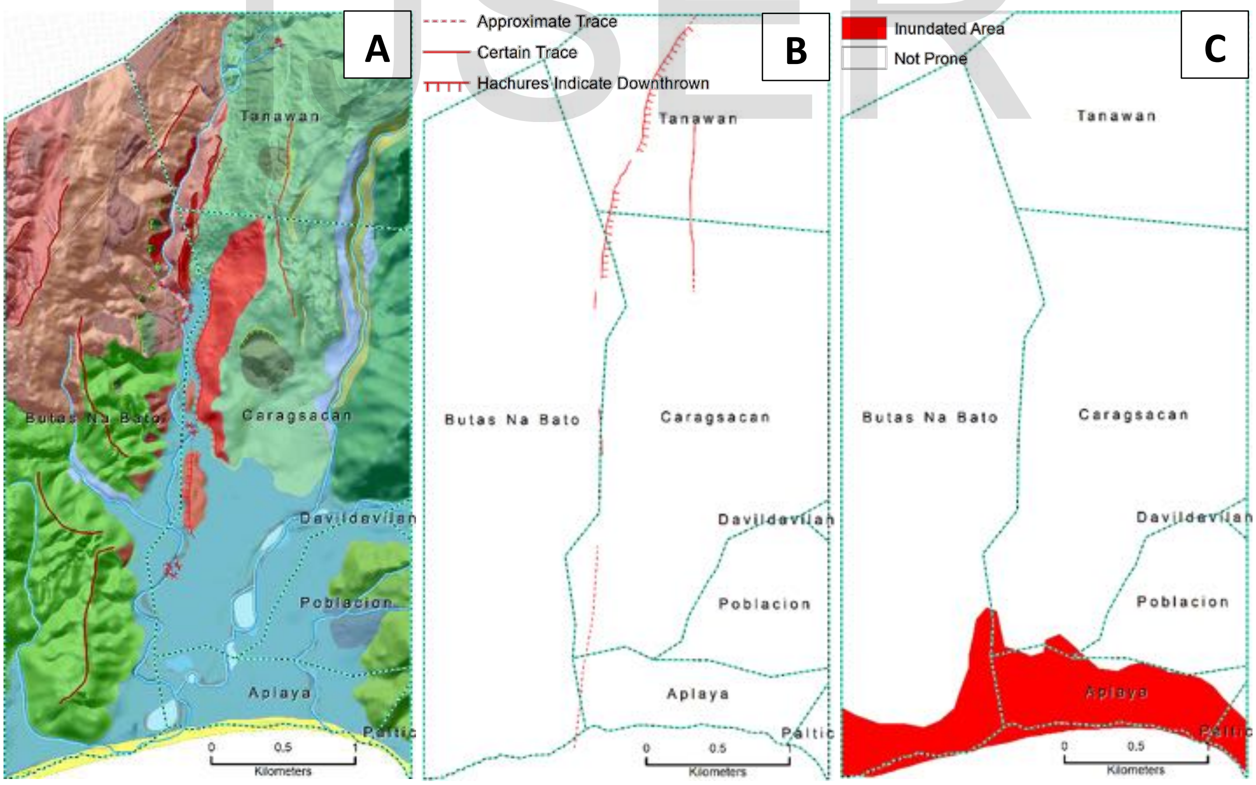


Figure 3.39 Final results and generated geomorphologic map of the study.

Interdependence between Geomorphology, Hazards, and Land Use for Sustainable Engineering Development

Project READY hazard maps for the study area are already published and are available for public use. Maps for the covered location includes ground rupture, tsunami, storm surge, rain-induced landslide, liquefaction, ground shaking, flood, and earthquake-induced landslide. Most maps were published in a 1:600,000 scale covering the whole Province of Aurora, with the exception of earthquake related hazards which were mapped at a 1:50,000 scale spanning the whole Dingalan municipality. The map scale governed the amount of details that each snippet was able to display. Figure 3.40 below displays the juxtaposed hazard maps, including the barangays transected by this research to show the spatial coverage and probable extent of influence of each hazard susceptibility zone.



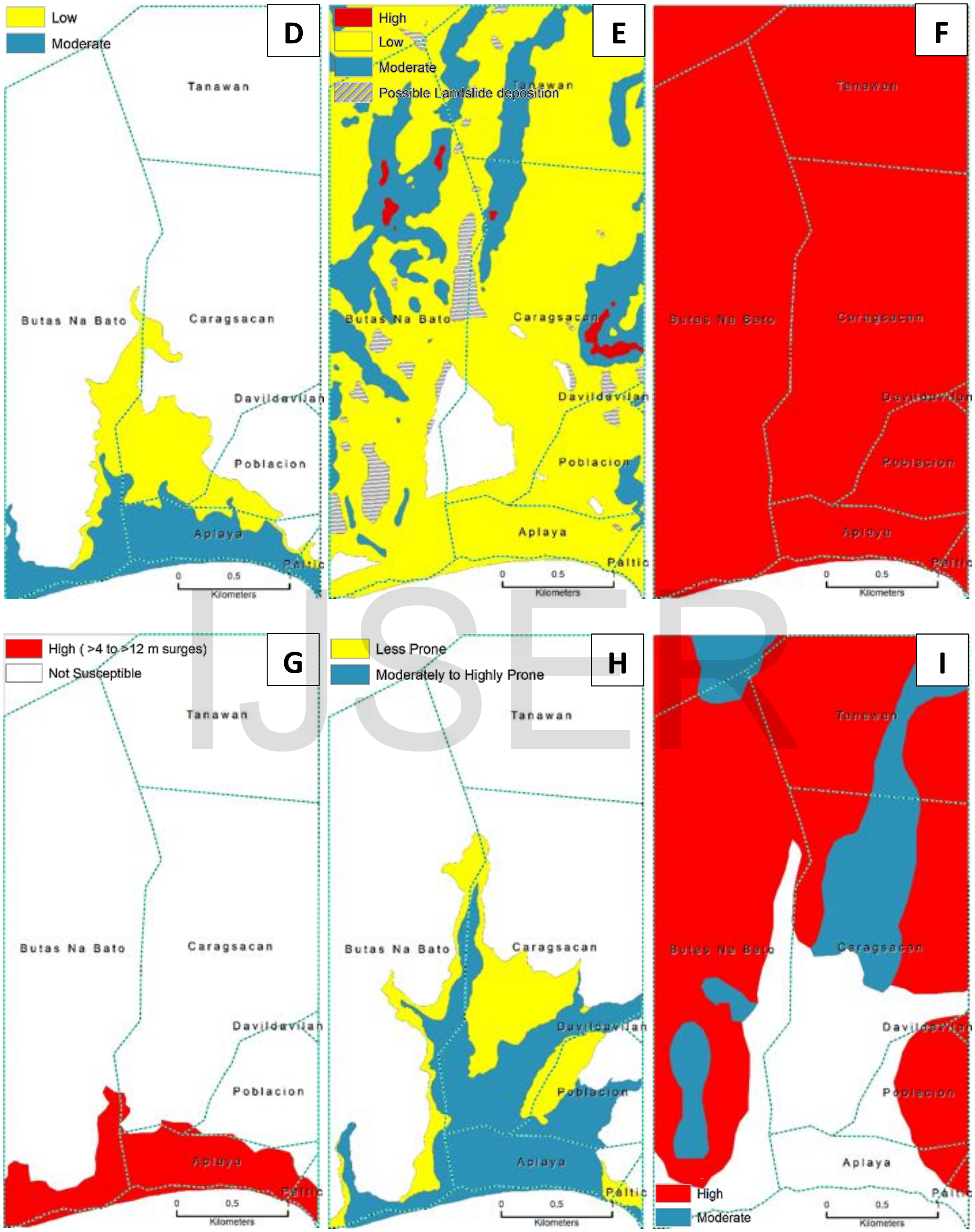


Figure 3.40 (a) Geomorphologic map with barangays. (b) Ground rupture hazards. (c) Tsunami hazards. (d) Liquefaction hazards. (e) Earthquake-induced landslides. (f) Ground shaking hazard. (g) Storm surge hazards. (h) Flood hazards. (i) Rain-induced landslide susceptibilities. (Source: Project READY)

Qualitative ocular correlations between the geomorphology and the geologic hazards precisely complemented one another. Morphodynamics, morphostructures, and morphologic units controlled the hazards that will ensue.

Though no evident trace of the Gabaldon Fault is present adjacent to the shore, an earthquake event produced by the fault is anticipated to cut through the alluvial realm alongside the Dingalan River. It is possible that the fault trace persists on the subsurface and was buried by fluvial sediments and alluvium. The affected areas conformed to the floodplain and fluvial domain extending to the coastal zone. Even though both are comprised of generally unconsolidated and cohesionless materials, the fluvial zone will harbor less liquefaction compared with the latter, for the reason that the groundwater, as denoted by the hydraulics of the area, is much closer to the surface in the coastal area. Earthquake-induced landslide hazard zones are widespread. High and moderate susceptibilities coincided with the very steep slopes in the sector. The whole province is subjected to an Intensity VIII shaking and above when an earthquake is to occur. Most, if not all, of the planned structures should incorporate seismic loading and earthquake resistant design regardless of the structures' relative importance. On similar lines, this limits the planner's available area for urbanization proposals because developing risky and ambitious properties will require premium costs.

The tsunami hazard map portrays that the region is also vulnerable to tsunamis, but such events are the results of seismic activity along the Philippine Trench, and not the PF. Barangay Aplaya, being the most adjacent to the ocean, receives most of the backlash of tsunami waves. Observing the storm surge hazard map denotes minimal differences to the tsunami hazard map, in fact, the two are virtually identical. An advantage regarding wave protection structures can be established such that a single structure type will be able to withstand both surge waves and tsunami waves because of their similar heights and expanse of inundation.

Flooding and rain-induced landslide hazards are largely relief and weather related. Flood waters will accumulate in the catchment basin of the floodplain with the bulk of the surface runoff flowing through the Dingalan, Langawan, and Subsob Rivers. The majority of floodwater will come from the MM, hence, mitigation efforts should be focused on the northeastern side of the study area. Shallow rooted flora along the slopes indorses greater risk due to weather-induced landslide, as illustrated in the map. This factor, coupled with the thick soil cover, and steep gradients aggravates landslide occurrence possibility. Widespread landslides, however, inhibit maximum utilization of the land surface for it will be costly to repeatedly mend the effects of the slip and creep events. The sliding mass will inevitably deposit on the lowlands if the slopes are left unmitigated.

The proposed land use map for the municipality displays information on both the prearranged engineering developments for the years 2014 to 2024 and the land cover of the untapped lands. Figure 3.41 on the following page presents the land use map/urban plan of the area of interest, while figure 3.42 displays the overlay between the geomorphologic map and land use for the identification of structures at risk and how they will affect the natural environment together with its corresponding overlay chart.

Most of the planned infrastructures are centralized on the floodplain and debris avalanche deposits. The road network is tremendously expanded all throughout, a couple of structures are to be built atop the slopes, and the coastal area hardly accommodated any project. A majority of the slopes will serve as croplands and/or forest reservations. Population growth seems to be the largest problem that the engineer considered in the plan because because residential zones are the most

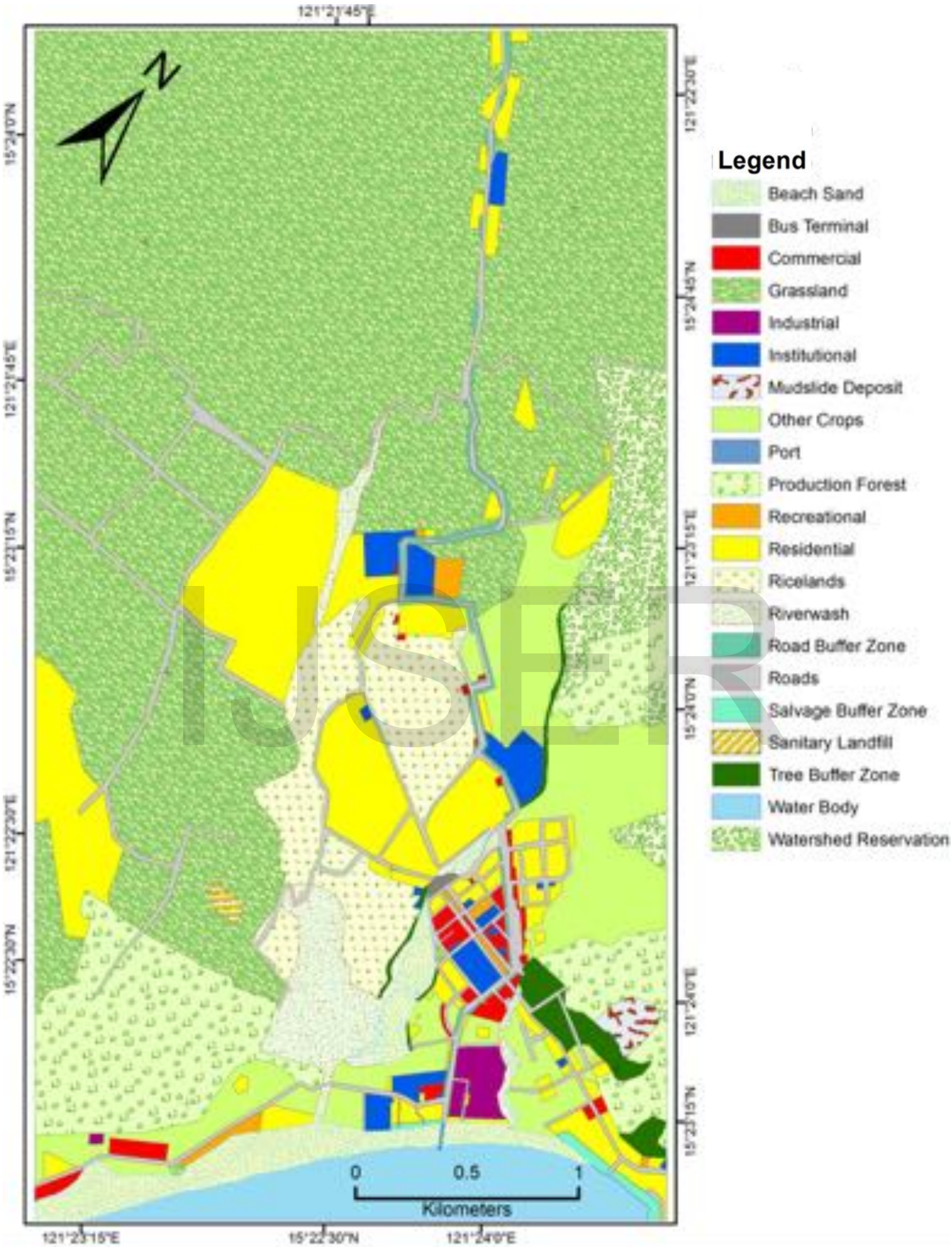


Figure 3.41 Projected land use map for the municipality of Dingalan for the years 2014 to 2024. (Source: Municipal Planning Division)

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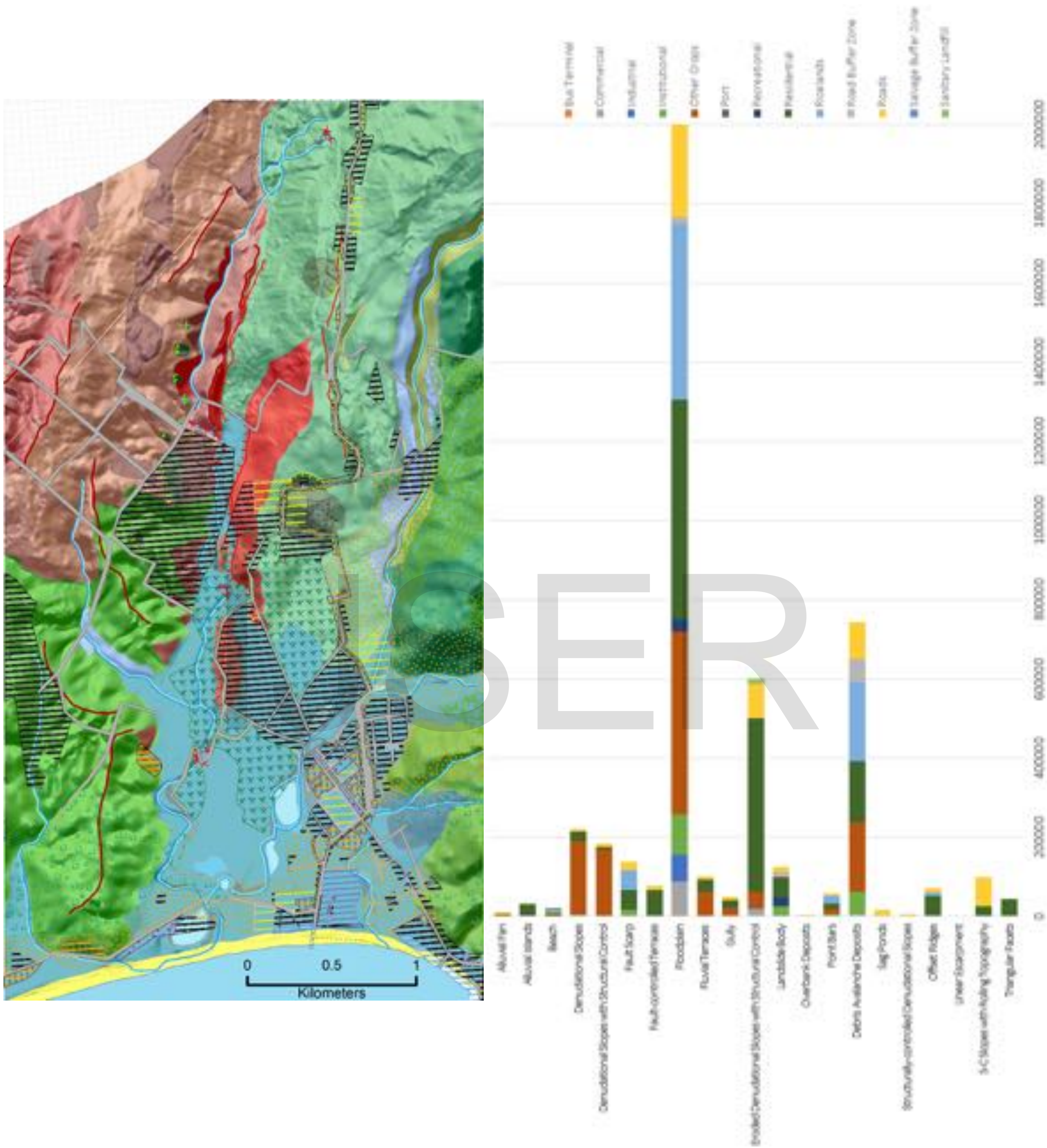

Figure 3.42 Cross-correlation map and chart generated from ArcMap after overlaying the land use map with geomorphologic map.

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numerous among the concrete facilities in the plan. Industrial zones, as expected, will be minimal due to the risky setting.

Upon a critical analysis of the correlated land use map and geomorphological map, several precarious zones were noted to occur on the geomorphologic environments. Firstly, several residential sectors and roads to be built on barangays Butas na Bato, Tanawan, and Caragsacan are situated immediately above the fault line. Numerous planned roads cut through the fault trace itself, while an institutional area and the landfill are located very close to the said geologic structure. This configuration calls for multiple casualties and millions in property damage during an earthquake event. Houses, schools, and roads will be devastated and the transportation system will be compromised. The DPWH standardized a 5-meter buffer zone for structures that will be built parallel to an active fault, and it must be adhered to at all times. The houses and schools must be also designed to endure seismic loading, be equipped with shock absorbers, and constructed using reinforced materials. Abundant structures equate to more residual waste, obliging the need for an effective waste disposal system. As learned, the proposed sanitary landfill will be placed near the fault trace. It can be inferred that the underlying materials are highly fractured, therefore, permeability is high. Bell (2007) described several measures to combat the permeable material. Suggestions regarding the use of a double liner system to contain the leachate are widely accepted, though the proposed disposal being located adjacent to the floodplain dictates that choosing another location will be wiser. It is therefore suggested that the landfill be placed on an area of higher elevation, specifically, on the eroded hillslopes with minor structural control. This way, environmental consequences regarding leachate seepage can be minimized, and the landfill itself will not be affected by flooding.

Secondly, several zones, including residential, road, bus terminal, riceland and other crops, commercial, and institutional zones are stationed directly beside the main river channel and footslopes. Some roads, houses, and croplands perpendicularly cross the deep gully of the Langawan River. The location of the river and slopes in connection with these functions, subjects them to riverine and flash flooding, to being the accretional domains of the products of sliding earth masses from the hillslopes, and scouring during times of fluvial activity. The ephemeral nature of the streams, however, gives these structures certainty during the dry season. Infrastructures will incontrovertibly reduce the natural soil cover and onlaid it with concrete. The impervious surface reduces the seepage and infiltration capacity of runoff, and results in a shorter lag time and longer recession time. The deliberate use of the hillside of the MM as watershed and forest is well esteemed. Not only will the trees serve as organic support to the soil horizons, it will also aid in controlling surface runoff by reducing the peak discharge. Kenny (1990) discussed the flood hazard zones and management strategies for each. This, however, can not be applied to the area because the dense stream network effectively groups all sectors under the first zone in his classification. If followed, no structure will be permitted construction. The main flood path is already straight, instigating the deposition of materials on the downstream direction. Artificial bank heightening by excavating and removing the bed material is suggested to increase the capacity of the river. Diversion can be done in the gully and other straight channels to decelerate the flood velocity. This measure must be designed without increasing deposition in the leeward side because if so, the problem will simply recur again. Levee armoring structures are also necessary to abate channel widening due to scour and bank erosion. The most economical measure that the local government can do is to devise a flood warning system and employ a well-planned evacuation zones during times of emergency. This is not preferable, but can be resorted to when physical mitigation measures cannot be executed due to budgetary constraints. Along related lines, the currently being constructed Langawan Bridge made use of bank heightening to abide by the flood height clearance requirement of the DPWH. Gabions, on the other hand, are applied as cheap and flexible revetment. Figure 3.10 above showcases the gabions, while figure 3.43 demonstrates the bank heightening for the bridge's construction.

Figure 3.43 View looking S35°W taken at 15.39° N, 121.39° E showing the artificial bed excavation for bank heightening purposes in the Langawan River.

Thirdly, numerous residential, commercial, and transportation structures are planned to be constructed on the rugged slopes. Erecting such will not only be costly, but also requires periodic monitoring to track and observe the changes that are possibly occurring. The rugged areas consist of the landslide prone slopes, inflicting overburden hazards upon the low-lying central areas which will act as the deposition zones upon major land failure instances. Vegetative measures are the most favorable preventive actions, for they will mollify multiple hazard types as opposed to structural mitigations which commonly serve a single function. Vetiver grasses are suggested to be planted on the structurally controlled slopes northeast of the area. The slopes with minor structural influence are advised to receive gradient reduction to allow easier access to the sanitary landfill which was recommended to be relocated. This will also reduce the chances of land failure to occur in this sector. Drainage pipes are advocated for utilization in all slopes since oversaturation due to rainwater acts as the principal driver of slope failures in the region. This was also described by Bell (2007) as the only economic way of dealing with landslides that can treat any slide regardless of the type.

Marine action indicates the fourth land use issue that needs to be addressed. Hardly any structures were and are to be built in the coastal region aside from the port and the salvage buffer zone. Reclamation was done to accommodate the two, and knowing the persisting high energy surge waves, the reclaimed areas are bound to be quickly eroded. Simple rockfill breakwaters are recommended to be constructed for shielding the structures against wave erosion. They should be designed in such a way that the gap allows entry of marine vehicles to the port and salvage zone, while positioned strategically so that deposition will take place and a salient tombolo will eventually form. Mangroves can also be cultivated to serve as organic wave breakers against marine impact.

A few projects are also placed atop the non-rigid areas of the floodplain. This includes houses, commercial structures, and roads. Larger settlement and subsidence risk must be duly noted by the structural engineer, as well as the raised liquefaction susceptibilities. Controlling such are achieved by grouting and vibratory compaction techniques. Some structures are planned to be founded on unstable forms, including alluvial fans and islands composed of unconsolidated materials. Such materials are not ideal to serve as geological foundation, thus, improvement by adding cohesive soils are recommended to achieve the design foundation soil properties.

Conclusion

This study fundamentally explored the interconnection between geomorphology, land forms, geologic hazards, conservative sustainability, and engineering via land usage explicitly intended for the municipality of Dingalan. A pragmatic geomorphologic map was employed as the vital decision matrix for structural feasibility and environmental sustainability purposes. The map was created with the use of GIS and remotely-sensed data, following a standard geomorphologic survey and mapping methodology designed by ITC. Upon completion, analyses and insights on the urban development plan of the municipality were concretized.

Four geomorphic provinces subsist in the study area, namely, denudational, fluvial, tectonic, and transitional landforms. Degradational processes predominate, thus, erosion is a significant factor to be considered. Mass wasting reworked some older forms, exemplifying its ubiquitous influence. Notable landforms under this classification include landslides, gullies, debris avalanche, and various slope types. The forms subject the structures to land failures, subsidence, creep, settlement, and scour. This research suggested the use of drainage pipes, gradient reduction, vegetative measures, and bank armor to prevent or decrease the subversive effects the hazards.

Tectonic landforms were produced as a consequence of the seismic activity of Gabaldon Segment of the PF which is demonstrated by oppositely dipping normal faults in the field of interest. Forms including fault scarps, offset ridges and streams, sags and troughs, triangular facets, pressure ridges, and structurally dominated slopes accentuates this geomorphic classification. The fault, being active, exposes the area to a multitude of earthquake related geologic hazards such as ground rupture, ground shaking with a magnitude of approximately M=7.8 and Intensity VII or greater, liquefaction, and landslides. Building high risk infrastructures are not advisable as it will be expensive to maintain and construct. Necessary and crucial structures were prompted to have earthquake resistant designs, irrespective of its importance.

Fluviatile influence is at a bare minimum in the area. Most rivers only administer flow during the last quarter of the year during the wet season. This gives sufficient time for planning the flooding and rain-induced landslide countermeasures. Proposed maneuvers included bank heightening, diversion, and implementation of flood warning systems. Minute river activity in the district, however, did not inhibit the development of fluvial landforms. The mapping activity revealed the alluvial islands, bar deposits, alluvial fan, terraces, and widespread floodplain of the municipality. The fluvial zone sustains most of the planned and existing engineering developments, therefore, settlement, subsidence, and liquefaction vulnerabilities must be properly distinguished. Along similar lines, the Langwan Bridge is already being constructed and the proper countermeasures are being applied that will ensure the longevity of the structure.

The transitional and coastal region is a high energy environment epitomized by the surging waves of the Dingalan Bay. This inhibits aggradational landforms to develop. Plans on reclaiming the segment of the beach to function as port and salvage zone for nautical emergencies are portrayed on the land use map. The zones are vulnerable to wave erosion, hence, recommendations on the use of breakwaters, both vegetative and structural, are made. The breakwaters must be designed in such a way that deposition will ensue without restricting ship passage.

Subsequent environmental consequences of each engineering structure were also duly noted. Infrastructural and anthropogenic impacts towards the groundwater, soil, and ecologic environment were epitomized. Deliberately, the study effectively interlinked geomorphology and land use zoning with sustainability and environmental conservation in mind, proving the direct practical relevance between the two.

Chapter IV

CONCLUSION

This study fundamentally explored the interconnection between geomorphology, land forms, geologic hazards, conservative sustainability, and engineering via land usage explicitly intended for the municipality of Dingalan. A pragmatic geomorphologic map was employed as the vital decision matrix for structural feasibility and environmental sustainability purposes. The map was created with the use of GIS and remotely-sensed data, following a standard geomorphologic survey and mapping methodology designed by ITC. Upon completion, analyses and insights on the urban development plan of the municipality were concretized.

Four geomorphic provinces subsist in the study area, namely, denudational, fluvial, tectonic, and transitional landforms. Degradational processes predominate, thus, erosion is a significant factor to be considered. Mass wasting reworked some older forms, exemplifying its ubiquitous influence. Notable landforms under this classification include landslides, gullies, debris avalanche, and various slope types. The forms subject the structures to land failures, subsidence, creep, settlement, and scour. This research suggested the use of drainage pipes, gradient reduction, vegetative measures, and bank armor to prevent or decrease the subversive effects the hazards.

Tectonic landforms were produced as a consequence of the seismic activity of Gabaldon Segment of the PF which is demonstrated by oppositely dipping normal faults in the field of interest. Forms including fault scarps, offset ridges and streams, sags and troughs, triangular facets, pressure ridges, and structurally dominated slopes accentuates this geomorphic classification. The fault, being active, exposes the area to a multitude of earthquake related geologic hazards such as ground rupture, ground shaking with a magnitude of approximately M=7.8 and Intensity VII or greater, liquefaction, and landslides. Building high risk infrastructures are not advisable as it will be expensive to maintain and construct. Necessary and crucial structures were prompted to have earthquake resistant designs, irrespective of its importance.

Fluviatile influence is at a bare minimum in the area. Most rivers only administer flow during the last quarter of the year during the wet season. This gives sufficient time for planning the flooding and rain-induced landslide countermeasures. Proposed maneuvers included bank heightening, diversion, and implementation of flood warning systems. Minute river activity in the district, however, did not inhibit the development of fluvial landforms. The mapping activity revealed the alluvial islands, bar deposits, alluvial fan, terraces, and widespread floodplain of the municipality. The fluvial zone sustains most of the planned and existing engineering developments, therefore, settlement, subsidence, and liquefaction vulnerabilities must be properly distinguished. Along similar lines, the Langwan Bridge is already being constructed and the proper countermeasures are being applied that will ensure the longevity of the structure.

The transitional and coastal region is a high energy environment epitomized by the surging waves of the Dingalan Bay. This inhibits aggradational landforms to develop. Plans on reclaiming the segment of the beach to function as port and salvage zone for nautical emergencies are portrayed on the land use map. The zones are vulnerable to wave erosion, hence, recommendations on the use of breakwaters, both vegetative and structural, are made. The breakwaters must be designed in such a way that deposition will ensue without restricting ship passage.

Subsequent environmental consequences of each engineering structure were also duly noted. Infrastructural and anthropogenic impacts towards the groundwater, soil, and ecologic environment were epitomized. Deliberately, the study effectively interlinked geomorphology and land use zoning with sustainability and environmental conservation in mind, proving the direct practical relevance between the two.

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Chapter V

RECOMMENDATION

This study produced a correlation between the geomorphology and engineering aspect which is specifically intended for utilization in the covered transect in the municipality of Dingalan, Aurora. Clearly, further research will be needed to adapt to the ever changing dynamic surface of the planet. Whenever possible, it is best to use multiple aerial images and elevation models that are taken simultaneously at different points in time (multitemporal) to clearly see the changes and metamorphology as they occur. Colored aerial photographs are preferred such that more information will be gathered because of the added context. Extremely high resolutions of the dataset are also recommended to detect miniscule scientific details and information.

Further quantitative laboratory modelling and experiments will grant definite figures on the rates of the dynamic processes. Recommended close range field inspections are ideal if the risks and biological hindrance are minimal.

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Appendix

Appendix A

Correlation Table

Landform	Bus Terminal	Commercial	Industrial	Institutional	Other Crops	Port	Recreational	Residential	Ricelands	Road Buffer Zone	Roads	Salvage Buffer Zone	Sanitary Landfill
Alluvial Fan					6428.466426			109.6163239			3943.440638		
Alluvial Islands					5295.246411		299.5510333	24689.39694	2893.616025	156.5369065	1134.339844		
Beach				148.14007	257.6211412	1585.764274		7669.589829			3482.02924	8820.109681	
Denudational Slopes		3304.494363		378.1798974	187809.6432			22154.19893			7987.75891		
Denudational Slopes with Structural Control				113.4694043	169665.7498			6659.299052			8152.071844		
Fault Scarp				16633.17627				49562.45849	50320.0199		22593.50181		
Fault-controlled Terraces								66109.95464			12794.28326		
Floodplain	5147.747153	83768.34683	66563.69803	101669.2706	463557.5309	250.6996163	28704.69649	555030.7187	445296.8458	16899.54152	278567.8411	11420.80306	2029.860395
Fluvial Terraces					61774.69554			31043.47042			8889.751337		
Gully					21263.39781			19718.44825		990.5649813	8635.948691		
Eroded Denudational Slopes with Structural Control		19095.92708	3041.280673		39855.64739			439385.3109	428.9647803		85781.26856		13950.99598
Landslide Body				26208.84627			22201.46671	50641.91738		14605.68086	11171.37727		
Overbank Deposits					721.7429408			2375.363742			714.5050341		
Point Bars	1712.609038	122.0544981	9.93832776	3905.523286	12670.13139		1349.446491	13648.30945	18725.77742	0.36603012	6196.422821		
Debris Avalanche Deposits		5763.211648		56083.34861	175785.0868			154848.4242	199543.5346	57618.77192	94200.15746		
Sag Ponds											18236.36583		
Structurally-controlled Denudational Slopes											5796.621855		
Offset Ridges								51386.32207	10335.98434		9303.929238		
Linear Escarpment											908.6774434		
S-C Slopes with Rolling Topography								26424.36616			73671.17843		
Triangular Facets								42482.06215			1566.681664		532.9503896