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Assessing Future Flooding Risk in a Coastal Lagoon Using Hydrogeological Approaches and Analysis of the 2021 Flood Event: A Case Study of Tasi-Tolu Lagoon, Dili, Timor-Leste

Mafaldo José Faria, Marçal Ximenes, Oktoviano Viegas Tilman de Jesus

Instituto do Petróleo e Geologia—Instituto Publico (IPG-IP), Division of Hydrogeology & Mineral Resources, Hydrogeology Team, Dili, Timor-Leste
Email: mfaria@ipg.tl, mximenes@ipg.tl, otilman@ipg.tl

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Abstract

This study aims to apply a hydrogeological approaches and analysis of the 2021 flood event of Tasi-Tolu Lagoon to achieve four specific goals. Firstly, the study seeks to determine the natural characteristics of the lagoon, which include factors such as size, depth, water quality, and ecosystem composition. Secondly, the influence of precipitation on the water volume in the lagoon will be examined. This analysis involves assessing historical rainfall patterns in the region, as well as the amount and frequency of precipitation during the 2021 flood event. Thirdly, the hydrogeologic and geologic conditions of the lagoon will be evaluated. This involves examining factors such as the type and structure of the soil and bedrock, the presence of aquifers or other underground water sources, and the movement of water through the surrounding landscape. Finally, the study seeks to assess the risk of future flooding in Tasi-Tolu Lagoon, based on the insights gained from the previous analyses. Overall, this study's goal is to provide a comprehensive understanding of the hydrogeological factors that contribute to flooding in Tasi-Tolu Lagoon. This knowledge could be used to inform flood mitigation strategies or to improve our ability to predict and respond to future flooding events in the region.

Keywords

Lagoon Characteristics, Flooding Event, Precipitation, Shoreline Flooding Volume, Hydrogeologic and Geologic Condition, Assessing Future Flooding Risk of Tasi-Tolu Lagoon, Dili, Timor-Leste

1. Introduction

Laguna Tasi-Tolu which means “Three Sea Lagoon” in the Tetum language of Timor-Leste, is situated in the western corner of capital city of Dili, Dom Aleixo Administrative Post, where this area is known for the formation of three separate saline lakes of Santa Maria (east), Klaran (middle), and Joao Paulo (west). Tasi-Tolu became known to the people of Timor-Leste because of its social and historical importance. Pope John Paul II visited the country, formerly Timor-Timur as the 27th province of Indonesia, and held a religious ceremony in the Tasi-Tolu area on October 12, 1989. It was also at Tasi-Tolu that on May 20, 2002, Timor-Leste declared its independence and was recognized as a new member of the United Nations (UN) after centuries of military occupation. The place has since become a site for historic events such as presidential inaugurations, celebrations of independence, and proclamation days, etc.

The Tasi-Tolu lagoon is located along the coast and is not directly connected to the open Savu Sea due to a natural barrier. This coastal lagoon serves as a modern analogue of lagoon formation that is controlled by factors such as barrier formation and progradation, uplifting, and evaporation [1]. The Tasi-Tolu Lagoon is also identified as one of the potential geotourism object and it is considered a protected area based on its ecology and geological characteristics [2], and it has been designated a wetland of national significance since 2002 for an important bird area. Despite being a valuable place in Timor-Leste, it is forbidden for the community to occupy the area of Tasi-Tolu Lagoon. However, over the years, the area has become increasingly dense with human settlement.

From April 2 to 4, 2021, Timor-Leste experienced extreme climate conditions caused by a tropical low depression that emerged along the southern coast of western Timor-Leste. The depression moved gradually towards the sea of Nusa Tenggara Timor (NTT) and eventually evolved into the Seroja tropical cyclone in the area [3]. These intense weather conditions caused heavy rainfalls and strong winds, leading to significant flooding in almost all areas with low-lying topography across Timor-Leste, including the capital city of Dili. Based on the Ministry of State Administration (MSA) data, the families affected by the inundation event in entire Timor-Leste region were 28,734 households including the Dili city with a total of 25,881 [4]. After the flooding disaster, apart from damaging public infrastructures such as roads, bridges, schools, offices, etc., it also killed 45 people all over the country [5].

The flooding event in Tasi-Tolu Lagoon was a natural occurrence, which directly inundated the local resident houses in the lagoon area, which the government previously prohibited for the habitants to occupy it. According to a satellite image analysis conducted by UNITAR-UNOSAT on April 09, 2021 [6], the shoreline of Tasi-Tolu Lagoon was found to have moved forward up to 220 m maximum and inundated the surrounding area, affecting more than 800 households (**Figure 1**). The increased water volume in Tasi-Tolu Lagoon after the event, resulted in the flooding of many home habitants, with water levels reaching

Figure 1. The satellite image analysis of Tasi-Tolu Lagoon [6].

hundreds of centimeters for around three (3) months. The water levels have since returned to normal due to the efforts of local volunteer teams who began removing water from the lagoon on April 9, 2021 (**Figure 2**).

In light of the flooding event, this study applies a hydrogeological approaches and analyzes the 2021 flood event in Tasi-Tolu Lagoon to accomplish the following goals: 1) to determine the natural characteristics of the lagoon, 2) to examine the influence of precipitation on the water volume in the lagoon, 3) to evaluate the hydrogeologic and geologic conditions of the lagoon, and 4) to assess the risk of future flooding in Tasi-Tolu Lagoon.

2. Theoretical Framework

According to the dictionary definition of geography [8], lagoon is a salt lake situated near the coast where previously it was a part of the ocean with shallow depths and has been separated by the ocean due to the geographic events. Lagoon means an isolated pool on the coast and bounded by a barrier.

In general, the formation of lagoon systems is caused by coastal process systems such as sand deposits transport from ocean wave activity and plate tectonic dynamics that later form beaches and barrier gaps, which eventually made the lagoon is separated from the ocean (**Figure 3**; [9]).

Figure 2. Photography: (A) satellite image of the study area (Google Earth, 2022), (C) the efforts of local volunteer teams to pump out the water from Tasi-Tolu Lagoon (Photo: [7]), ((B), (D), and (E)) the houses of residents were submerged under hundreds of centimeters of water (Photos: Machel Silveira, April 08, 2021).

Naturally, lagoons are characterized by their isolated form and their salt content, which can vary from very high to fresh depending on the hydrogeological and climatic conditions of the area. Lagoons formed in arid areas usually have higher salinity levels (hypersaline) compared to those formed in semi-arid areas that often receive rain (wet) resulting in brackish water.

Based on the salt content (salinity) in the water [10], laterally the lagoon is divided into four (4) parts: freshwater dominated zone is an area near the incoming freshwater flow where the water is dominated by freshwater, brackish zone is an area where freshwater mixes with seawater that enters through the gaps in the barrier, sea-water dominated zone is an area close to the barrier gaps where seawater can flow in, and hypersaline zone is an area that has high salinity because no freshwater flows in through the barrier gaps

Moreover, according to Forch *et al.* (1902) in [11], salinity refers to the level of salt content in water, which can be calculated in ppt/part per thousand (‰) units meaning that every 1 liter of water gets salt material dissolved in it. Piranti, A. S. [12] also classified water types based on their salinity levels into three categories: "Fresh-Water" (salinity 0 - 3‰), "Brackish-Water" (salinity 4‰ - 20‰), and also "Sea-Water" (salinity > 20‰).

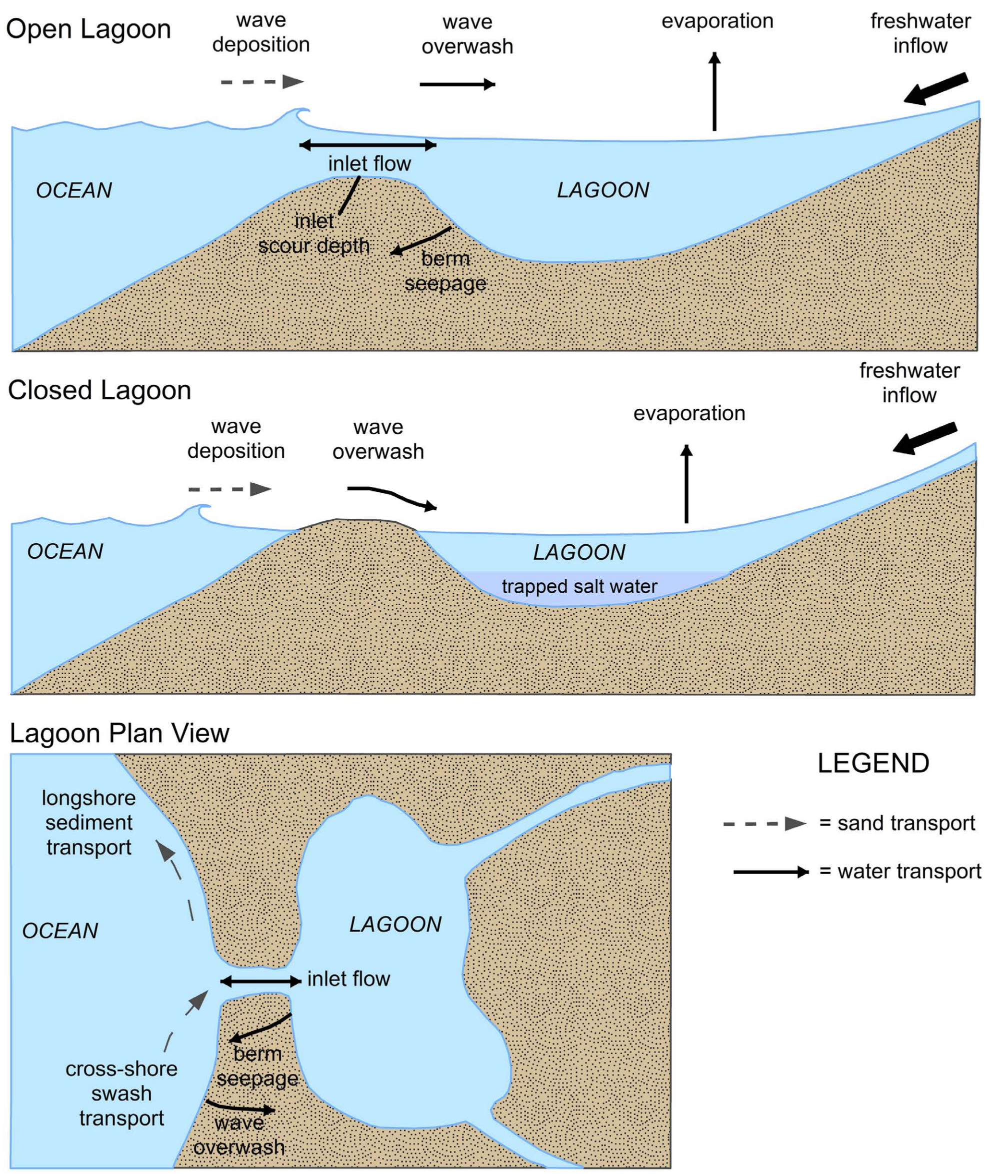

Figure 3. Schematic influences of important factors in lagoon system [9].

Generally, the salt concentration in water can be determined by measuring physical water parameters such as EC (electrical conductivity) and TDS (total dissolved solid). TDS provides an aesthetic indication and determines water salinity. According to *Lehr et al.*, (1980) in [11], the relationship between TDS and EC can be formulated as; TDS = 0.65 × EC. Based on the TDS value, water can be categorized into four types [13]: "Fresh-Water" (TDS < 1000 mg/L), "Brackish-Water" (TDS 1000 - 10,000 mg/L), "Saline-Water" (TDS 10,000 - 100,000 mg/L), and "Hypersaline-Water" (TDS > 100,000 mg/L). Moreover, water acidity (pH) also affects fish life, with a pH value above 9.2 or below 4.8 leading to fish death. The optimal pH range for fish in water is between 6.5 and 8.5 [12]. The normal pH value for seawater is 7.9 - 9.0. The physical parameters of pH, EC, TDS, and salinity are influenced by water temperature.

This study defines the lagoon as a bay shore, where water flowing in derived from the land area in a limited quantity and also has a circulation system with the ocean with a limited model as well. Sedimentologically, the lagoon environment is unique and different from both estuary and marine environments and its presence can be identified via stratigraphic records. This environment generally has a dissimilar salinity from the ocean and gets limited detrital sediment supply, chemical precipitation also frequently forms in this area.

In particular, the lagoon environment has low energy because it is isolated and bounded by a barrier, therefore the lagoon deposits consist of sediments with finer grain-sized [14]. Lagoons without estuaries, the deposited material within came from marine material and is dominated by clay. The sedimentary structures usually occurred are ripple marks, laminations, and cross bedding with small dimensions caused by tidal seas. Fossils present in lagoon environments depend on salinity conditions where brackish water fossils found are an indication as a part of an estuary [10]. Lagoons with normal salinity conditions (equal to seawater) have similar fossils as marine and sometimes contain mud-carbonate associated with shell-fragment. This is interpreted as a part of the lagoon that has experienced re-forming due to tectonics and mollusk fossils presence indicating the environment is located close to the marine environment [15].

Climate is an important factor that affects the formation and evolution of lagoons. When there is high rainfall in coastal areas, it can lead to the formation of canals that carry rainwater directly to the sea, which can prevent or even stops the formation of lagoons. Therefore, it is important to study the precipitation patterns in the area. The classification of rainfall used in this study is based on the standards set by [16] (**Table 1**).

3. Materials and Methods

This research utilizes data from a previous survey conducted by IPG-TL in the Tasi-Tolu Lagoon area in 2017, combined with newly collected data to assess the risk of future flooding in the lagoon by applying a hydrogeological approaches and analyzes the 2021 flood event of the lagoon.

Geoelectric survey conducted in 2017 was using the Resistivity Meter Type ABEM Terrameter SAS 300B with the dipole-dipole configuration method.

Table 1. The rainfall classification [16].

Classify	Rain per hour	Daily Rainfall	Monthly Rainfall
Very Light	<1 mm/hour	<5 mm/24 hours	0 - 50 mm
Light	1 - 5 mm/hour	5 - 20 mm/24 hours	50 - 100 mm
Moderate	5 - 10 mm/hour	21 - 50 mm/24 hours	100 - 300 mm
Heavy	10 - 20 mm/hour	50 - 100 mm/24 hours	300 - 500 mm
Very Heavy	>20 mm/hour	>100 mm/24 hours	>500 mm

*BMKG: Badan Meteorologi, Klimatologi, dan Geofisika, Indonesia.

Additionally, primary data was collected, which included measuring the physical water parameters of Tasi-Tolu Lagoon (EC, TDS, pH, temperature, and salinity) by applying Hanna Instrument H19811-5 Portable; pH-EC-TDS Meter and the depth with a tape meter when Santa Maria Lagoon turned pink in early October, 2017. Also measured the newly groundwater level after the flooding event in Tasi-Tolu Lagoon area utilizing Solins Water Level Meter Model 101. The shoreline volume of water estimation before and after inundation event in Tasi-Tolu Lagoon was interpreted by using Surface Volume Analyst tools based on the LIDAR-5 m Digital Elevation Model (DEM) data in ArcScene 10.4. The flood susceptibility level in Tasi-Tolu Lagoon area was also assessed applying overlay + scoring method in ArcMap 10.4 utilizing five (5) combination parameters between; slope, precipitation, elevation, land cover and soil type. The rainfall data from the capital city of Dili [17] during the period time of 2010 to 2018 was computed to confirm the rainfall intensity and the maximum rate of runoff based on the following equation by (Mononobe & Hudson [18]):

$$I = R_{24} \Big/ 24\left(24/t\right)^{2/3}$$

where:

I = rainfall intensity (mm/hour);

t = duration of rain (hour);

R_{24} = the maximum rainfall for 24 hours (mm).

$$Q = c/360\left(I \times A\right)$$

where:

Q = maximum rate of runoff (m^3/s);

I = rainfall intensity (mm/hour);

A = catchment area (Km^2);

c = coefficient values of surface runoff [19].

All the piezometric data are interpolated in Golden Software's Surfer 16 then exported to geoTiff and displayed in ArcGIS 10.4 along with other relevant data. The physical parameter values of EC, TDS, pH, temperature, and salinity were utilized to determine the characteristic type of Tasi-Tolu Lagoon. The rainfall data, rainfall intensity and maximum rate of runoff are applied to examine the influence of precipitation on the volume of water in Tasi-Tolu Lagoon. The lithologic outcrop observation in the Tasi-Tolu Lagoon area was also utilized to identify the sedimentological characteristics of lagoon. The resistivity sections were used to interpret the interconnection between Tasi-Tolu Lagoon and ocean beneath the surface. Lastly, creating flood susceptibility level map of Tasi-Tolu Lagoon and its surroundings to assess the areas prone and risk to flooding in the future.

4. Result and Interpretation

The Natural Characteristics of Tasi-Tolu Lagoon

The physical water parameters (pH, temperature, EC, TDS, and salinity) were measured vertically in October 2017 at different depths of Tasi-Tolu Lagoon when the water in the Santa Maria Lagoon turned pink. The measurements showed varying values depending on the depth of the lagoon (Table 2 & Figure 4).

The physical water parameter values, particularly pH, temperature, and EC vertically have varying levels based on the depth of lagoon. When the water depth increased, the values of temperature, pH, and EC decreased, and conversely, when the water depth decreased, these values increased. Normal temperature for sub-tropical regions is 26˚C - 32˚C [12]. The water temperature changes can impact various physical parameters, including pH, EC, dissolved gas concentrations, and chemical reaction processes in water.

Water temperature above 32˚C can lead to evaporation and chemical precipitation, impacting the salinity level in water. This process causes a decrease in the volume of water and an increase in the salinity value. During the time when the water in Santa Maria Lagoon turned pink and resulted in chemical precipitation, the salinity and TDS values in that lagoon significantly increased, particularly compared to the Klaran Lagoon and João Paulo Lagoon. This was the first assessment of such an occurrence in the area, with salt deposits being formed due to the chemical precipitation (Figure 5). The differences in salinity values observed in Tasi-Tolu Lagoon indicate variations in water volume and evaporation rates among the separate lagoons.

Normal salinity and TDS values (referring to the Klaran and João Paulo Lagoon in Table 2) signifying the Tasi-Tolu Lagoon belongs to the "Brackish-Water" category, also known as the brackish zone, with moderate salt content. Based on its definition, the Tasi-Tolu Lagoon naturally emerges as an isolated lagoon without any surface water supply from rivers or seawater via a barrier gap. This suggests that the lagoon possibly has an interconnection with the

Table 2. The pH, temperature, EC, TDS, and salinity levels of Tasi-Tolu Lagoon are based on the depths [20].

Area	Distance to Shoreline (m)	Depth (± cm)	pH [potential hydrogen	TDS [total dissolved solid] (ppm)	EC [electrical conductivity] (mS/cm)	Temperature (˚C)	Salinity (‰)
Santa Maria Lagoon (East)	5	15	9.4	11,214	18.61	45	71.5
	20	70	9.3		17.49	43	
	60	100	9.3		15.66	38.4	
Klaran Lagoon [Middle]	5	60	8.3	7531	12.26	32.3	15
	50	200	8.5		11.25	31.1	
	110	1200	8.1		10.95	30.5	
João Paulo Lagoon (West)	2	55	8.7	7732	12.53	35	15
	20	110	8.8		11.84	33.6	
	70	600	8.6		11.32	32.1	

1 ppm = 1 mg/L; 1 millisiemens = 1000 microsiemens.

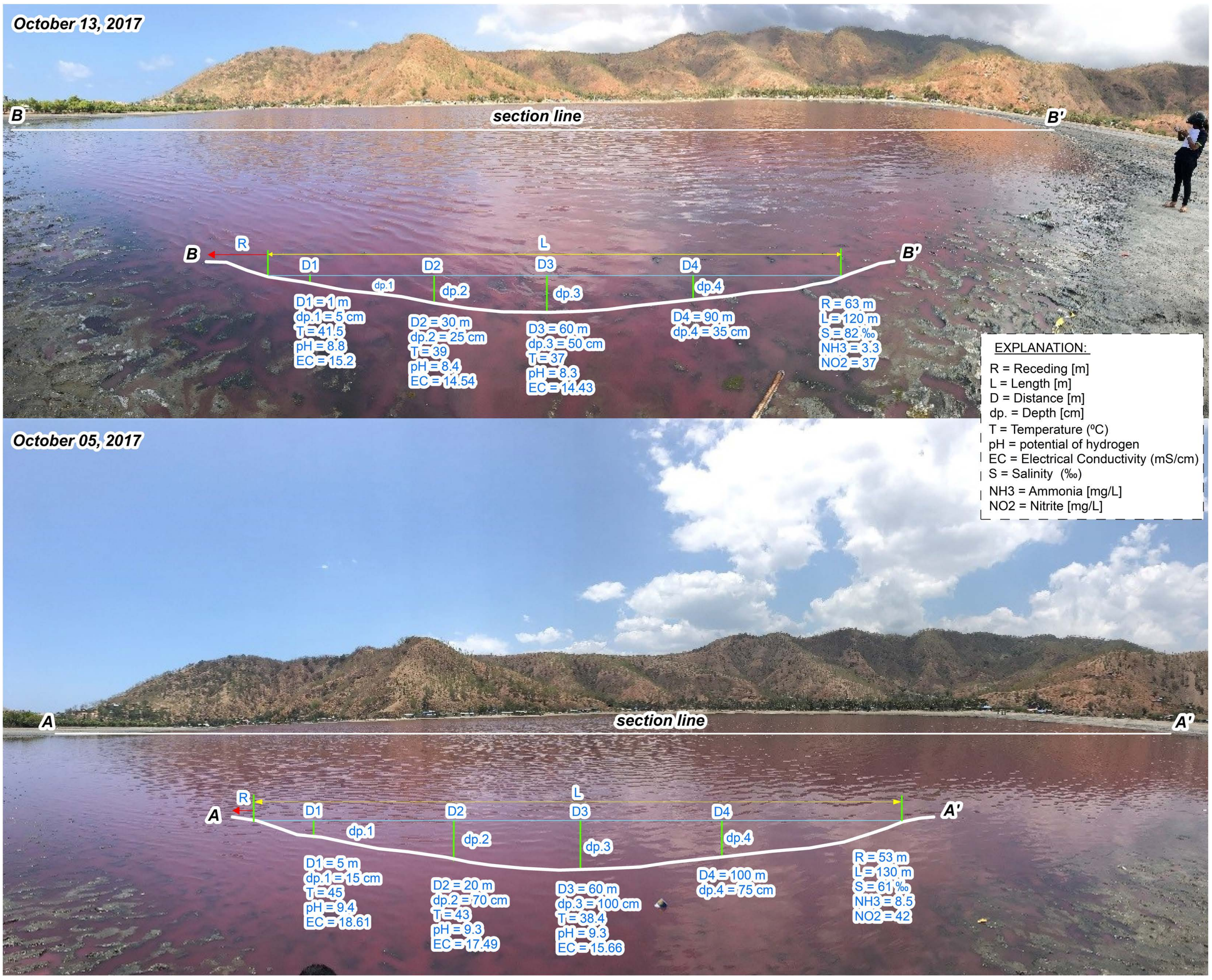

Figure 4. The values of physical and chemical water parameters in Santa Maria Lagoon were recorded on October 5th and 13th, 2017 at various depths and distances along two section lines labeled (A) and (B).

ocean beneath the surface and typically as a basin to accumulate rainwater and surface runoff through watersheds. These water supplies will neutralize the water volume and salt contents in the lagoon, which will help the Tasi-Tolu Lagoon retain its brackish-water characteristic over time. It is likely that the reason for the pink color of Santa Maria Lagoon in October 2017 was due to a prolonged dry season and tidal seas, which resulted in a lack of seawater supply under the subsurface into lagoon. As a result, there was a significant increase in temperature, pH, EC, TDS, and salinity levels. This drastic change in water conditions led to an algal bloom of red pigment (*Phycoerythrin*), which turned the water pink [20]. The same could be true for Joao Paulo Lagoon when its water also turned pink in 2006.

Table 2 presents the physical water parameters of Santa Maria Lagoon, particularly the temperature, pH, and salinity values which are not suitable for aquatic organisms such as fishes to survive. An experiment was conducted in the field by capturing fishes from Klaran Lagoon and releasing into Santa Maria

Figure 5. Photography (IPG-TL, 2017); (A) measured physical water parameters and depths of Santa Maria Lagoon; (B) Chemical precipitation of salt deposits (evaporation) in Santa Maria Lagoon area; (C) the physical water parameters and depths of Klaran and João Paulo Lagoons were measured; (D) the experiment of taking fishes from Klaran Lagoon and releasing into Santa Maria Lagoon to monitor the fishes resistances in water conditions with high temperature, pH, EC, TDS, and salinity values (>normal).

Lagoon in order to observe the fishes resistances, where typically the Tasi-Tolu Lagoon is considered as one ecology with brackish water characteristics. However, the fishes were unable to survive in such conditions. During the experiment, the fishes were hard to breathe and became increasingly sluggish, eventually dying within eight (8) minutes as their movements became uncontrolled and lethargic. Salts found in the fishes gills may affect the fish's breathing (Figure 5(D)).

The Influence of Precipitation on the Water Volume of Tasi-Tolu Lagoon

Tasi-Tolu Lagoon is an isolated basin that naturally accumulates surface water particularly rainfall and surface runoff through the watersheds from high-laying topography. Owing to the increasing volume of water in Tasi-Tolu Lagoon, it is necessary to estimate the effect of precipitation on the inundation event.

The average monthly rainfall in the Tasi-Tolu Lagoon area between 2010 and 2018 was 86.91 mm with a median daily rainfall intensity of 17.17 mm/hour (Figure 6). Referring to the rainfall classification from [16], the monthly precipitation and daily rainfall intensity were classified as light-raining.

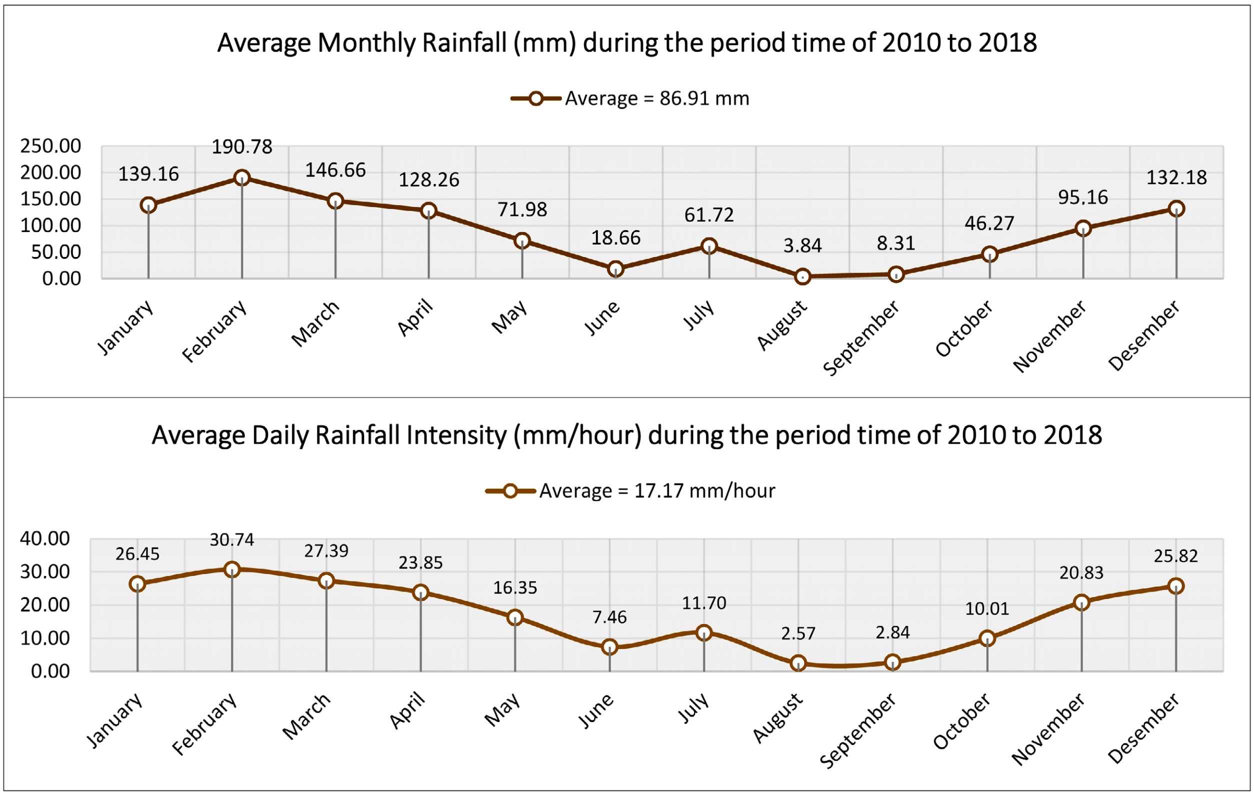

Figure 6. The graphic lines of average monthly precipitation (above) and daily rainfall intensity (below) in Tasi-Tolu Lagoon area during the period time of 2010 to 2018.

Furthermore, with the rainfall catchment area of 6.28 Km^2, the coefficient surface runoff value of 0.12 for sandy soil lawn—2% - 7% slope [19] and also the median rainfall intensity of 17.17 mm/hour thus, the maximum rate of runoff (Q) found in Tasi-Tolu Lagoon area was 0.036 m^3/s or 129.6 m^3/hour. According to [16], the precipitation of 100 mm in a catchment area of 1 Km^2 is equivalent to 100,000 m^3 of rainwater it means, in Tasi-Tolu Lagoon area the average rainfall of 86.91 mm with the catchment area of 6.28 Km^2 obtained 545,794.8 m^3 of rainwater and the amount of rainwater experienced surface runoff was 129.6 m^3/hour.

In addition, the precipitation obtained from the Dili International Airport rainfall station, which is approximately 700 meters away from the study area, was 341 mm in ten hours or 34.1 mm per hour on April 4, 2021. This extreme weather event caused major flooding in the capital city of Dili [21], where this daily rainfall or rain per hour is classified as very heavy-raining (**Table 1**). An area may experience flooding and landslides if the rain precipitation is categorized from heavy to very heavy-raining in a day or 24 hours [16]. Pointing that the daily precipitation of 341 mm in the catchment area of 6.28 Km^2 obtained rainwater fell by 2,141,480 m^3 and rainwater went through surface runoff was 2573.46 m^3/hour or 25,734.6 m^3 for ten (10) hours.

The estimation analysis of water volume on the shoreline of Tasi-Tolu Lagoon before and after the flooding event revealed a significant effect of the amount of rainwater that fell and underwent surface runoff on the increased water volume in the area. The results found that before the flooding on April 23, 2020, the water volume on the shoreline of João Paulo Lagoon was 339,435.72 m^3 and in Klaran - Santa Maria Lagoon was 3,406,099.81 m^3 (**Figure 7**). However, after the flooding event on April 09, 2021, the water volume increased to 645,725.22 m^3 in João Paulo Lagoon and 5,026,302.26 m^3 in Klaran—Santa Maria Lagoon (**Figure 8**). This indicates an increase in water volume of 306,289.5 m^3 in João Paulo Lagoon and 1,620,202.45 m^3 in Klaran—Santa Maria Lagoon after the flooding occurrence (**Table 3**).

The hydrogeologic and geologic conditions of Tasi-Tolu Lagoon

Apart from being an isolated lagoon, the research site is also a catchment area with its own hydrographic system and is separated altogether from the Dili plain by a spur of schist and metamorphosed basalt bedrock [22]. In terms of hydrogeology, the Tasi-Tolu Lagoon area is composed of localized aquifers with metamorphic rock materials controlled by fracture system in high topographic areas and intergranular aquifers with unconsolidated alluvial deposit materials in low-lying areas [23] [24].

Groundwater table measurements from dug wells in the lagoon area indicating the average groundwater level after flooding increased to 2.35 m from median groundwater level of 3.53 m before the flooding event and rose to 1.18 m after the inundation event (**Table 4**), with groundwater flow direction into the Tasi-Tolu Lagoon (**Figure 9**). Groundwater in the lagoon area is identified as saline groundwater [23], which is possibly caused by a natural effect between intensive surface evaporation and seawater intrusion beneath the surface [22].

The Tasi-Tolu Lagoon area is geologically composed of unconsolidated alluvial deposits in low-lying areas and metamorphic rock units of meta peridotite, metasandstone, greenish and blackish phyllitic schist in high topographic area (**Figure 10**, [25]). The alluvial materials derived from detrital sediment transport of metamorphic rocks in the foothills and unconsolidated marine terrace sediment lying in the coastal area, with sand-gravels grain-sized, composed of schist, calcite, and quartzite fragments displaying a parallel bedding structure with the coast (**Figure 11**). Within the lagoon, found finer-grained alluvial deposits, with a majority of the fragments being composed of metamorphic rocks.

The unconsolidated sediment with finer grain-sized within the lagoon displays a lamination structure and contains a lot of mollusks shells such as pelecypods and gastropods, as well as anthozoa like corals (**Figure 11**). These conditions representing the Tasi-Tolu Lagoon environment is normally controlled by low energy with brackish water characteristic. The pelecypods and gastropods shells found in Tasi-Tolu Lagoon, which typically has brackish water, have thinner shells with smaller dimensions compared to those living in marine environments meanwhile, based on the habitation, corals have two (2) ways of living; the tentacle corals often live in the ocean at depth of approximately 3300 m, whereas the unicellular photosynthetic dinoflagellate corals live in shallow marine at

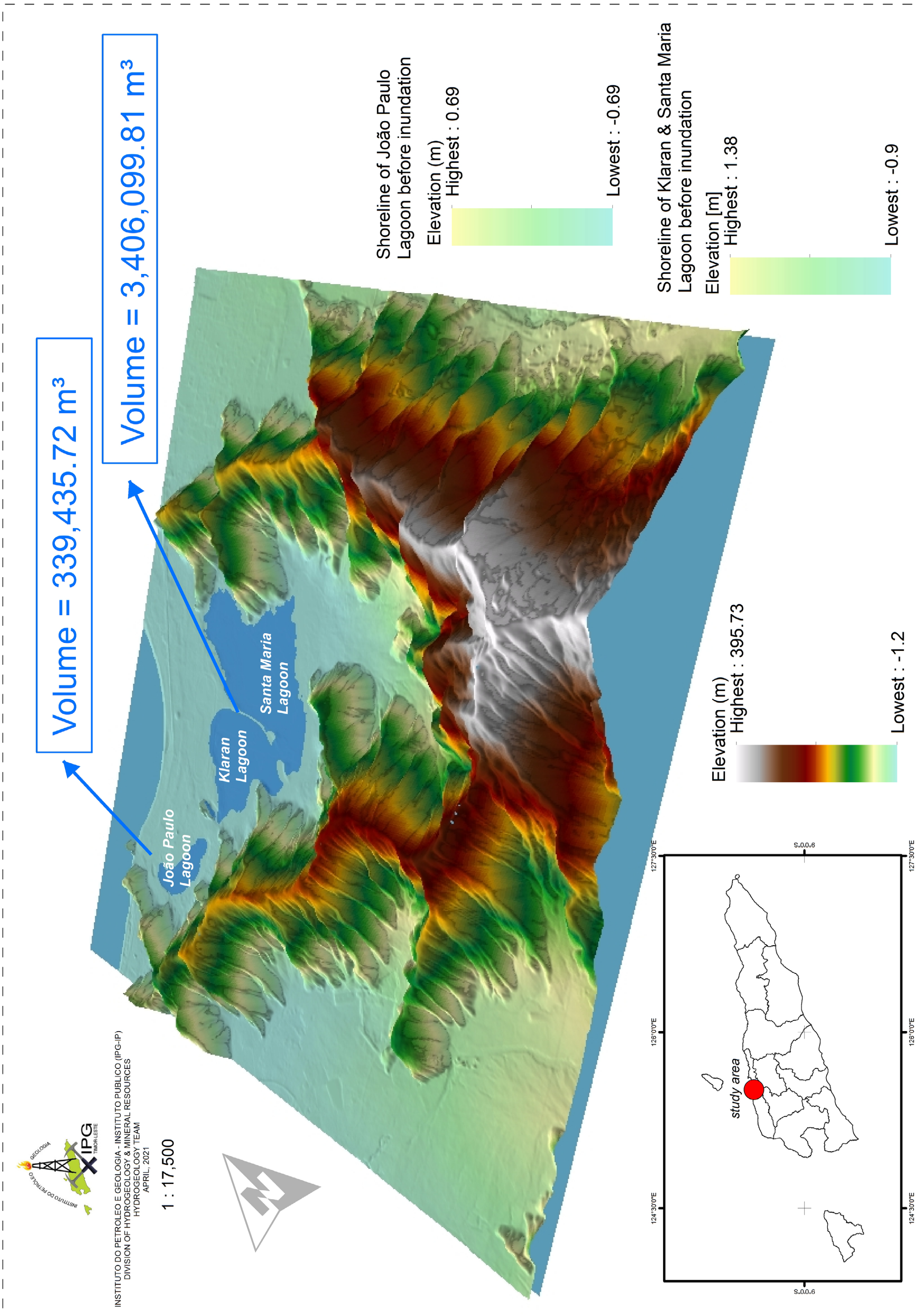

Figure 7. The water volume on the shoreline before the inundation (April 23, 2020) in Tasi-Tolu Lagoon.

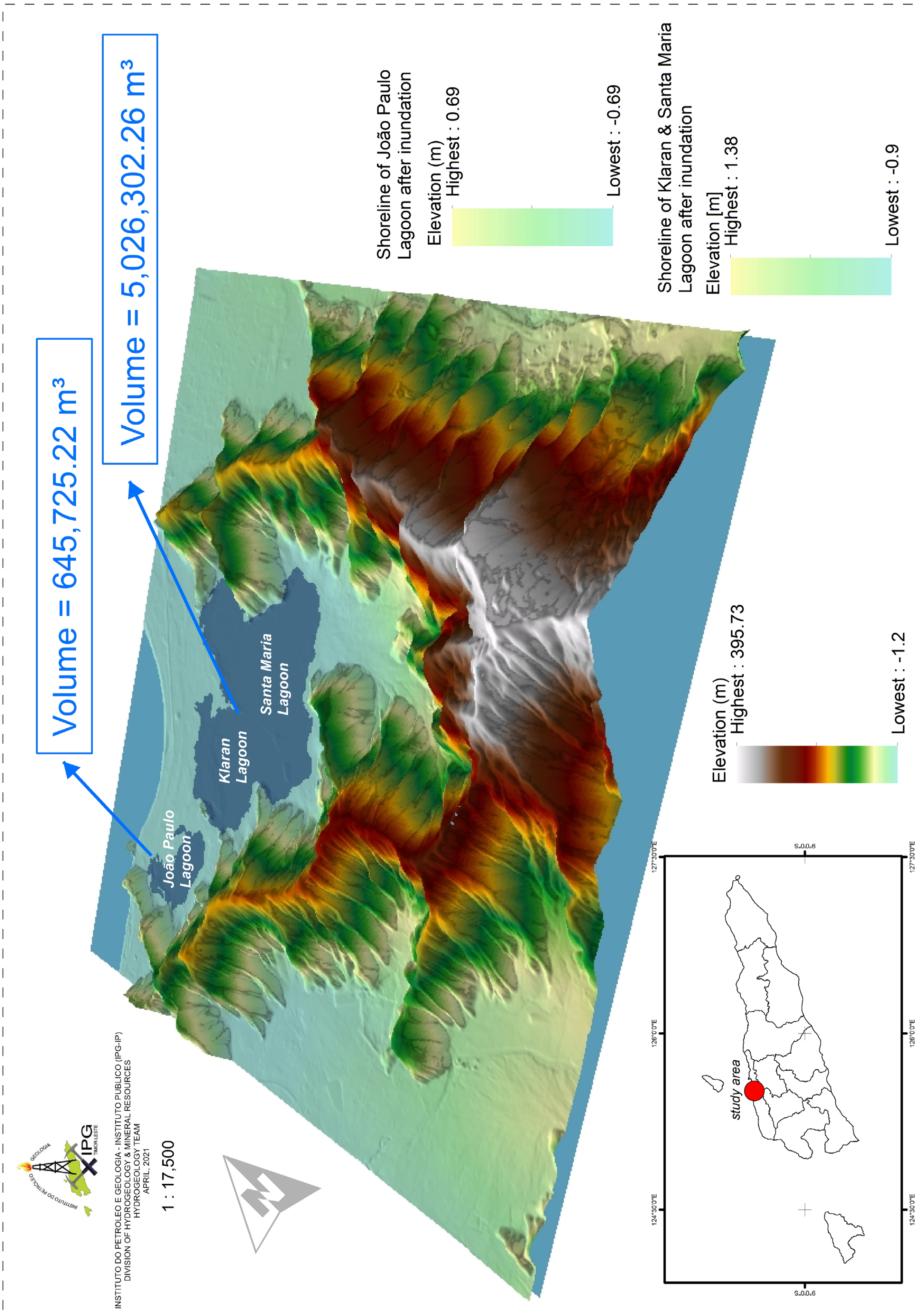

Figure 8. The water volume on the shoreline after the inundation (April 09, 2021) in Tasi-Tolu Lagoon.

Table 3. The water volume and area of Tasi-Tolu Lagoon before and after the inundation event.

Dataset	Plain Height [m]	References	Factor Z	Area-2D [m²]	Area-3D [m²]	Volume [m³]
Shoreline of 5 m DEM LIDAR Tasi-Tolu Lagoon [Santa Maria & Klaran]: after inundation [April 09, 2021]	5 meter above sea level [masl]	Below	0.00000898	1,005,259.85	1,005,259.85	5,026,302.26
Shoreline of 5 m DEM LIDAR Tasi-Tolu Lagoon [Santa Maria & Klaran]: before inundation [April 23, 2020]	5 meter above sea level [masl]	Below	0.00000898	681,219.28	681,219.28	3,406,099.81
Total Difference				**324,040.57**	**324,040.57**	**1,620,202.45**
Dataset	**Plain Height [m]**	**References**	**Factor Z**	**Area-2D [m²]**	**Area-3D [m²]**	**Volume [m³]**
Shoreline of 5 m DEM LIDAR Tasi-Tolu Lagoon [João Paulo]: after inundation [April 09, 2021]	5 meter above sea level [masl]	Below	0.00000898	129,145.01	129,145.01	645,725.22
Shoreline of 5 m DEM LIDAR Tasi-Tolu Lagoon [João Paulo]: before inundation [April 23, 2020]	5 meter above sea level [masl]	Below	0.00000898	67,887.08	67,887.08	339,435.72
Total Difference				**61,257.93**	**61,257.93**	**306,289.5**

Table 4. The groundwater table data from dug wells in Tasi-Tolu Lagoon area.

No.	Elevaation [m]	Well Depth Before Inundation [m]	Well Depth After Inundation [m]	Height of Well lips [m]	Groundwater Level Before Inundation [m]	Groundwater Level After Inundation [m]
BP 1	13	4	1.46	0.67	8.33	10.87
BP 2	5	4.19	1.59	0.52	0.29	2.89
BP 3	7	3.85	1.38	0.42	2.73	5.2
BP 4	7	4.6	0.81	0.45	1.95	5.74
BP 5	4	1	0.65	0.64	2.36	2.71

depth of 60 m with clean seawater conditions, calm sea waves, and accessible to sunlight. The anthozoa found in Tasi-Tolu Lagoon are unicellular photosynthetic dinoflagellate coral. Furthermore, the abundant fragment of metamorphic rocks found within the lagoon possibly come from bedrocks or detrital sediment transport through watersheds and surface runoff.

In addition, the geoelectric survey conducted on five (5) resistivity lines in the study area displayed resistivity values that varied from 0.06 - 3660 Ω·m and reached out to a depth of 39 m. Based on this information, three (3) different geological zones can be identified, including the seawater saturated zone (<5 Ω·m), saturated alluvium zone (5 - 150 Ω·m), and dry alluvium zone (>150 Ω·m) (**Figure 12**), [26] [1]. It means the Tasi-Tolu Lagoon has an interconnection with the ocean under the surface via the seawater saturated zone at depth of 2 to 10 m

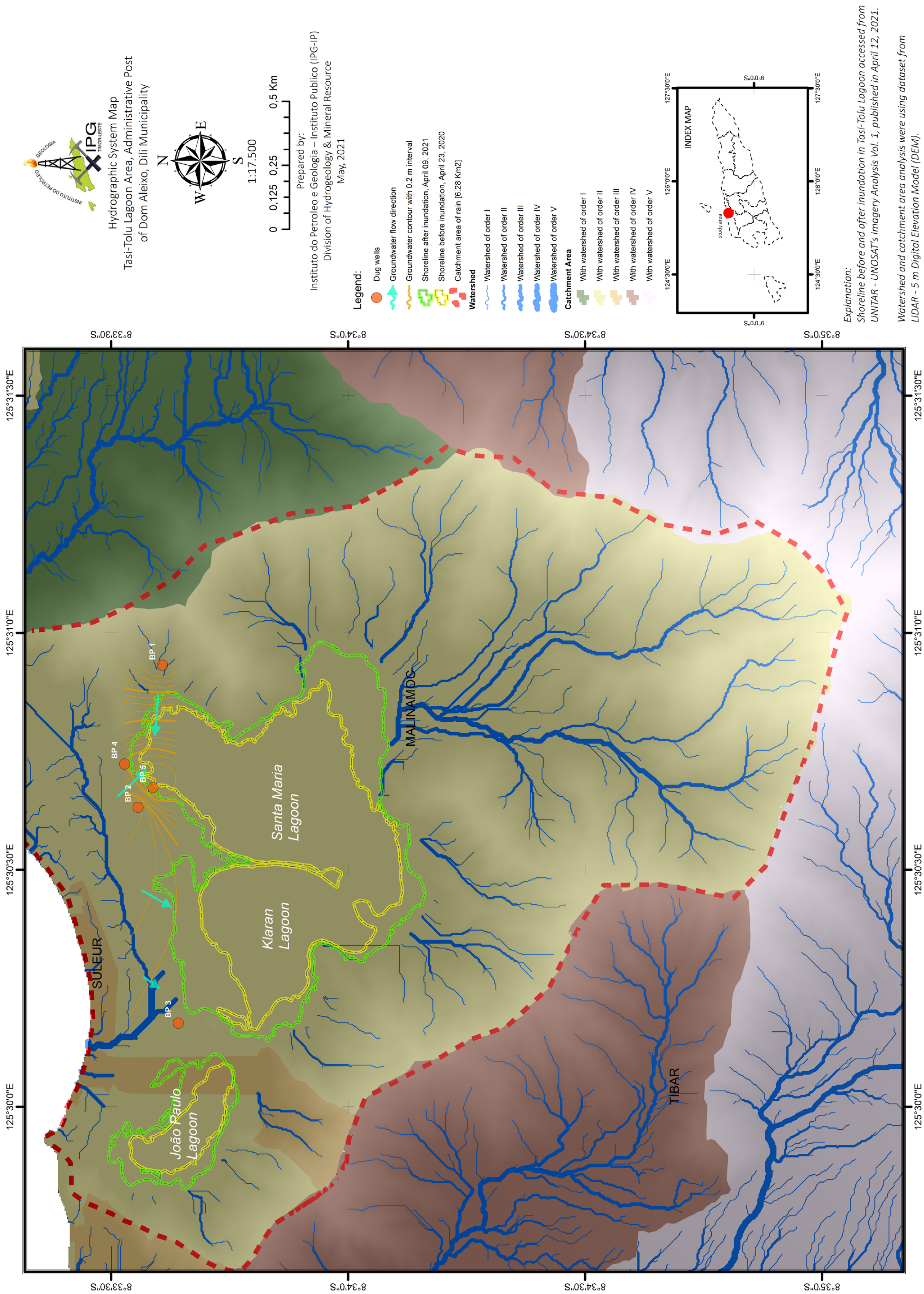

Figure 9. The hydrographic system map of Tasi-Tolu Lagoon area.

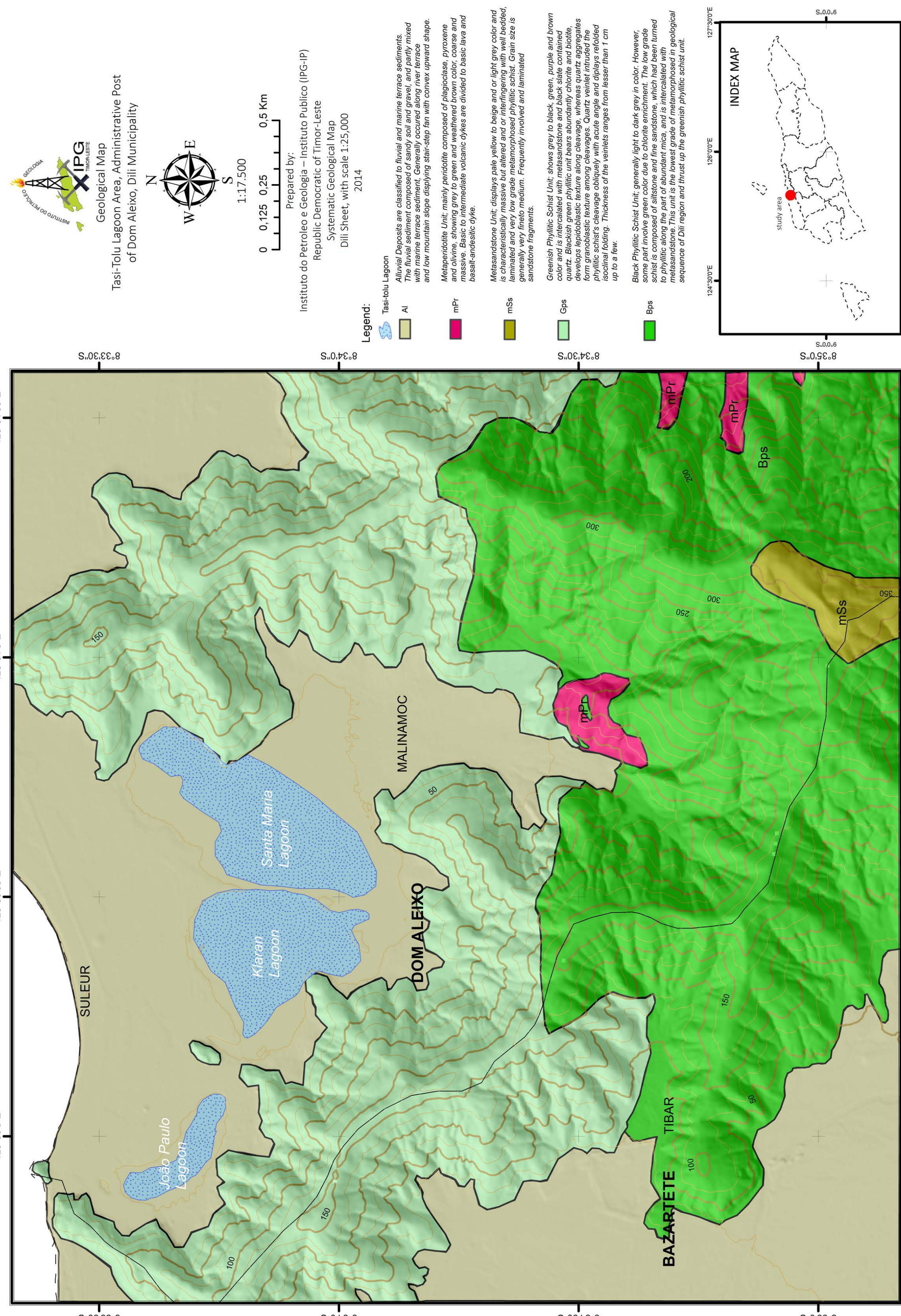

Figure 10. The geological map of Tasi-Tolu Lagoon area (Al: alluvial deposit, mPr: metaperidotite unit, mSs: metasandstone unit, Gps and Bps: phyllitic schist unit) [25].

Figure 11. (A) the unconsolidated material of sand marine terrace bedding with metamorphic fragments, (B) finer grain-sized lagoon deposit, uncompact lamination structure, and contains abundant mollusk shells (pelecypods gastropods) and anthozoa (coral), (C) and (D) abundant metamorphic rocks fragment in Tasi-Tolu Lagoon with finer grain-sized of matrix sediment (Photos: USJTL, 2016)

as a result, the lagoon always maintains its brackish water characteristic. The interconnection between the lagoon and the ocean through the saturated alluvium zone is limited to a certain extent by the circulation system, which is controlled by tidal activity that will affect the characteristics and volume of water in the lagoon.

Assessing future flooding risk in Tasi-Tolu Lagoon

By combining the hydrogeological approaches and analysis of the 2021 flood event, it may be possible to develop a more comprehensive understanding of the flooding risk in the Tasi-Tolu Lagoon and to identify a few strategies and management for reducing that risk. A flood susceptibility map was developed to assess the flooding risk using an overlay and scoring method, which considers parameters such as slope, precipitation, elevation, land cover and soil type (in [27] [28] [29] [30] [31]). The map (**Figure 13**) displayed the Tasi-Tolu Lagoon is a catchment area with a high flood susceptibility level. These parameter factors of slope (25%), soil type (25%), precipitation (20%) and land cover (20%) are considered to have a major influence on flood susceptibility level compared to elevation or topography factor (10%).

The Tasi-Tolu Lagoon area is prone to flooding due to its nature as both an

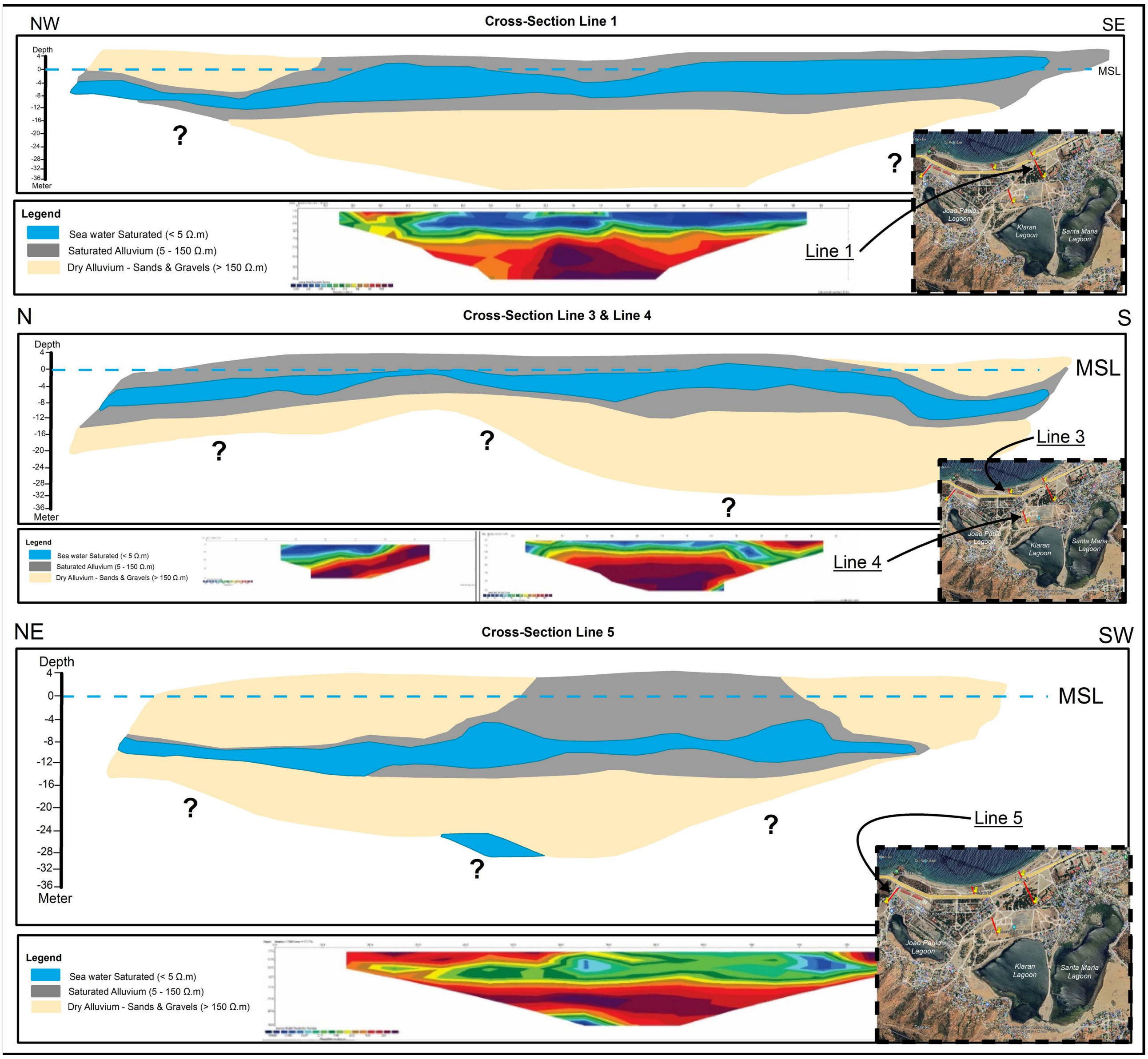

Figure 12. The resistivity cross section lines in Tasi-Tolu Lagoon area [26].

isolated lagoon and a discharge area. This means that rainwater and surface runoff can accumulate in the area without being drained away. During the 2021 flood event, with the precipitation of 341 mm which lasted ten (10) hours, caused major flooding by the increasing water volume in Tasi-Tolu Lagoon and an expansion of shoreline to move forward. We assume that a future flooding in Tasi-Tolu Lagoon could potentially happen again if there is more than 250 mm of precipitation within a day (10 hours), where it would generate 1,570,000 m^3 of fallen rainwater and 1884 m^3/hour or 18,840 m^3 of surface runoff over a ten (10) hours period. As a result, the flooding could cause an expansion of the Joao Paulo Lagoon area by over 30,000 m^2 and Klaran-Santa Maria Lagoon area by more than 150,000 m^2, which affects around 400 households with current human settlements.

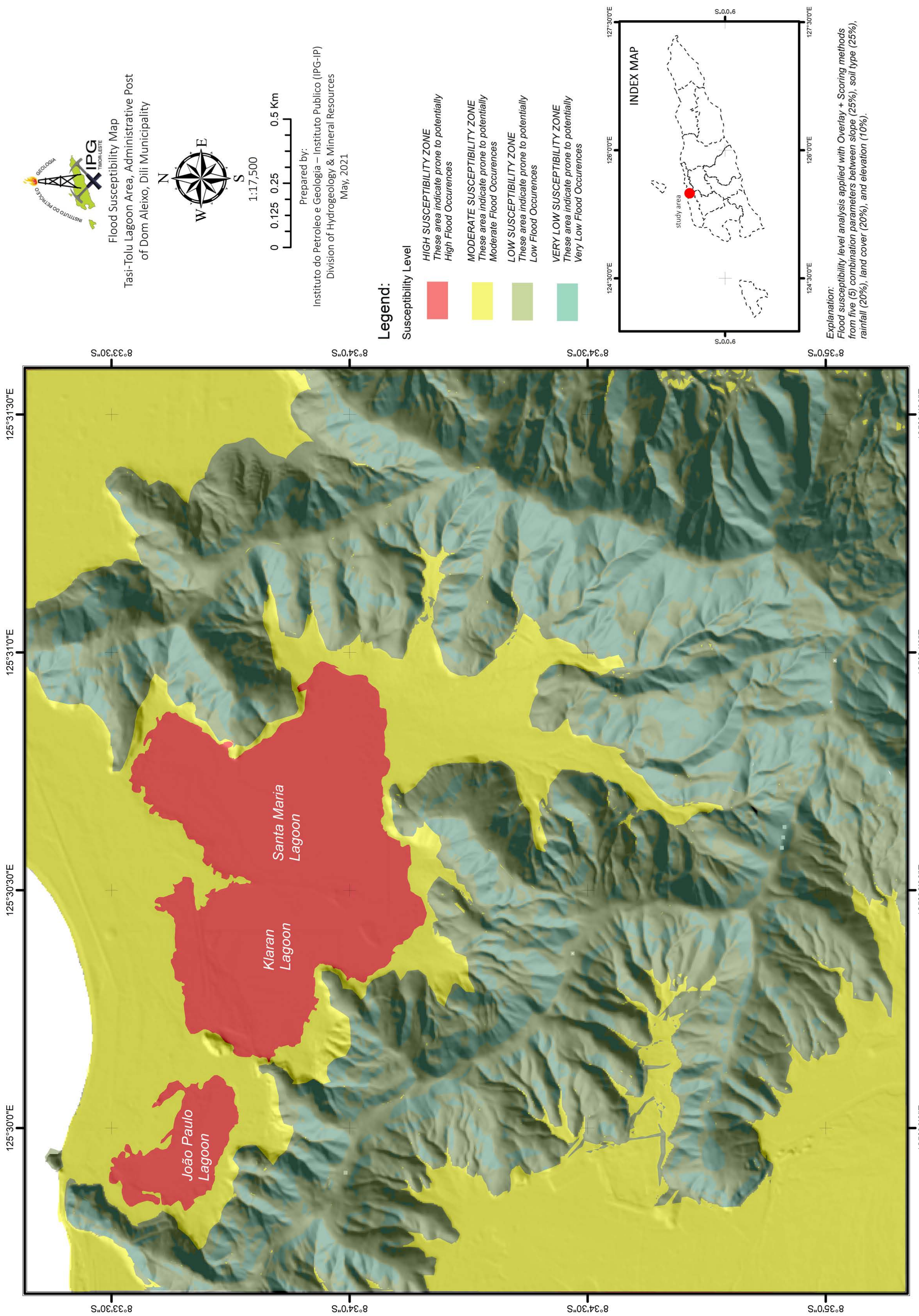

Figure 13. The flood susceptibility level map of Tasi-Tolu Lagoon area.

5. Conclusions and Recommendations

The Tasi-Tolu Lagoon is identified as a catchment area and an isolated lagoon with brackish-water characteristics. It accumulates rainwater and surface runoff through its watersheds and has an interconnection with the ocean beneath the surface. After a heavy rain event that lasted for ten (10) hours on April 04, 2021, the water volume in the lagoon increased and did not return to its normal level for over three months due to three (3) factors: 1) the thickening of water volume due to the heavy rainfall and the evaporation from the water surface did not have any impact on it, 2) vertically, the impermeable finer grain-sized of unconsolidated alluvial deposit material in the lagoon preventing water infiltration downwards, and 3) horizontally, the lagoon is connected to the sea, which keeps the water saturation level constant below the surface, where this interconnection prevented any significant change in the water volume of the lagoon despite the high rate of surface evaporation.

The study suggests that future flooding in the Tasi-Tolu Lagoon is prone to occur again if there is more than 250 mm of precipitation within a day (10 hours). Some possible options of strategies and management that could be considered to address future flooding risk in the Tasi-Tolu Lagoon area such as: developing early warning system, implementing flood control measures, land use planning and zoning, restoration and management of wetlands, establishing evacuation centers, and improving the drainage systems.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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