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File size:	4.14M
Page count:	14
Word count:	7,369
Character count:	54,484
Submission date:	02-Jul-2021 07:46AM (UTC-0500)
Submission ID:	1614930334

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Mechanism of the Rapid Shrinkage of Limboto Lake in Gorontalo, Indonesia

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Received: 11 October 2020; Accepted: 16 November 2020; Published: 18 November 2020

Abstract: This study explores the mechanisms behind the rapid shrinkage of Limboto Lake, Gorontalo, Indonesia, using remotely sensed imagery and river outcrop investigation data. The results show that more than 70% of the sedimentation resulting in shrinkage is contributed by riverbank erosion causing rivers to drain into the lake during the period 2003–2017. From geological investigation, it is found that the lowland area to the west of Limboto Lake comprises 1 m of flood sediments, followed by at least 5 m of fine-grained inner bay sediments. Severe riverbank erosion is also observed at many points. Hence, it is concluded that the shrinkage of Limboto Lake resulted from rapid-induced rapid erosion of inner bay sediments formed during plate collision which readily flowed into and were deposited in Limboto Lake; this created a delta, especially on the west side of the lake. Accelerated sedimentation caused by river erosion has led to rapid lake shrinkage. This phenomenon could be typical of the transformation of enclosed seas into lakes by the rapid uplifting movement of land in collision zones.

Keywords: Indonesia; lake shrinkage; lake sedimentation; Limboto Lake; remote sensing; riverbank erosion; rural sustainability

1. Introduction

The combination of rapid environmental changes induced by socioeconomic transformation and meteorological changes has a significant impact on local communities and their sustainability. These changes lead to environmental degradation, increased vulnerability to natural disasters, and the restructuring of rural livelihoods. Thus, understanding the driving factors and mechanisms behind accelerating environmental changes provides significant insight into appropriate sociotechnical interventions for their mitigation, and can create opportunities involving various stakeholders for sustainable development.

The impact of environmental change together with human activities has been also considered the most significant driving factor influencing the current rapid changes of lake systems [1–6] at a global scale. Environmental changes and human activities are diverse at the local level. Furthermore, local characteristics, such as the type of human activities and nature of the soil system, influence the rapid disappearance of lakes [1].

Indonesia is a contact point between a vast continent and the Eurasian–Australian plates, forming an accretionary prism in which the collision and accretion of microcontinents occurs due to subsidence of the oceanic plate from the east over the last 100 million years [7]. Sulawesi island has an especially

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Indonesia is a contact point between a vast continent and the Eurasian–Australian plates, forming an accretionary prism in which the collision and accretion of microcontinents occurs due to subsidence of the oceanic plate from the east over the last 100 million years [7]. Sulawesi island has an especially extensive coverage of sands, gravels, and coral reefs coupled with continuous earthquakes and volcanic activity [7]; hence, it is considered that the island continues to undergo uplift, resulting in various unusual geological phenomena.

Among the results of the pre-Pleistocene uplifting of land by plate tectonics in Indonesia are inner seas, including the Tempe, Sidenreng, Buaya, and Limboto Lakes in Sulawesi Island. All of these lakes are undergoing rapid shrinkage [7–9], which can be caused by large-scale sedimentation, erosion, and the discharge of a variety of sludges including chemical, fecal, and activated and solid waste [10]. Erosion is defined as the processes of removal of soil, sediment, and rock particles under natural forces such as water, wind, glaciers, and gravity. Increased sedimentation and erosion have a negative influence on the lake's condition in terms of its size and quality. Furthermore, the overgrowth of water hyacinth, an invasive floating plant forming thick layers over the water surface, accelerates siltation of the lake [11] by shading other aquatic plants, forming organic deposits after decay, trapping smaller particles, and contributing to lake shrinkage. Additionally, human activity catchment disturbance, including deforestation, land clearance for agriculture, mining, mineral exploitation, construction, and infrastructure development, increases the sediment load in rivers [12]. This is further accelerated by rapid population growth and urbanization.

Recent research has focused on lake degradation problems from geographical and geological perspectives. For example, quantitative analysis of lake size in terms of time-series and the factors accelerating lake disappearance have been studied at the global scale [1–6,8,13]. Furthermore, geological ages [2,14–16], particulate material [3,4,17–19], and the volume of annual average sedimentation [7,14,20,21] have been investigated. However, these studies have lacked qualitative time-series analyses. Furthermore, no studies have qualitatively addressed the mechanism of lake shrinkage from a geological perspective, particularly the vulnerability of geological components to erosion. Hence, a quantitative assessment of lake shrinkage mechanisms associated with a qualitative geological assessment may help to explain the mechanisms causing rapid sedimentation at Limboto Lake and provide an alternative strategy for future mitigation.

Remote sensing technologies are widely used for the characterization of natural features and physical objects and enable their spatial changes to be monitored in time-series. Remote sensing also provides a variety of continuous temporal, spectral, and spatial resolution data. Freely available satellite remote sensing data, such as Landsat and Sentinel, are extensively used to detect and monitor land cover changes due to the availability of data since the 1970s [22,23]. The use of such long-term satellite datasets helps to form a comprehensive and qualitative understanding of changes in lake conditions, such as lake extent [24–26] and aquatic vegetation [27–31].

In this study, the primary objective was to explore the mechanisms behind the rapid shrinkage of Limboto Lake, Indonesia. Specifically, the objectives were to (1) assess the status of lake environments associated with lake extent, the distribution of water hyacinths, and sedimentation volume using satellite imagery and survey data; (2) assess the volume of sediment derived from riverbank erosion flowing into Limboto Lake using a program map; (3) assess relationships between the volume of riverbank erosion and lake sedimentation; (4) assess the geological components of outcrops and compare these with the lake sedimentary environment. This study is expected to quantitatively and qualitatively assess the mechanisms causing the rapid shrinkage of the lake. Furthermore, the result should contribute to proposing appropriate interventions to mitigate the extent of threat to the lake and facilitates the creation of alternative sustainable economic activities through the involvement of local-level stakeholders.

2. Study Area

Limboto Lake was formed during the pre-Pleistocene uplifting of the inner bay [18] approximately 3 km west of the city of Gorontalo in northern Sulawesi, Indonesia. It receives water from 23 rivers, mainly the Alopohu, Biyonga, Marisa, Meluopo, and Rombongan rivers [7]. The lake provides critical ecological, hydrological, and socioeconomic services to the province [17,32]; however, it is listed as one of 10 critically endangered lakes in the country and its conservation is a priority for the national sustainable management strategy [33]. The surface extent and depth of the lake were reported as 6000 hectares (ha) and 30 m (m), respectively, in 1930; however, this declined to between 1900 and 3000 ha and 2 and 3 m by 1999 [21] following the invasion of the water hyacinth [34].

The study area is located in the Gorontalo flat lowland plain, covering 352 km^2 (16 by 22 km) (Figure 1). The present topography of the study area was formed by the most recent volcanic activities in the early Quaternary [7], demonstrated by coral growths forming limestone rock in high-elevation areas [9]. The basement rocks in the study area are predominantly igneous, volcanic, and sedimentary rocks generated between the middle Tertiary and early Quaternary periods. Crystallized limestones and unconsolidated deposits of gravels and sands are widely distributed throughout the highland and lowland portions, respectively, of the study area.

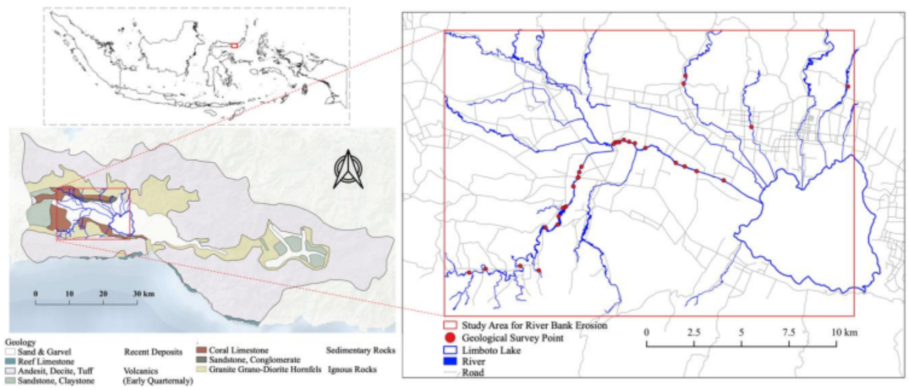


Figure 1. Study area.

The main livelihood in the study area is lowland agriculture, such as crop cultivation and freshwater fisheries. Paddy and corn cultivation in the province has rapidly increased since 2001, as a result of the development of a province-level agricultural strategy [35].

A variety of research studies and projects have recently been conducted at diverse scales ranging from local to watershed levels to mitigate severe lake degradation due to increased sedimentation. These include environmental management strategies, such as sedimentation and sludge management [10,14], aquatic environment management [36], watershed management [37,38], environmental assessments [7,17,32,39], and lake extent monitoring [30,40]. Technical assistance for flood mitigation has been provided in collaboration with international development agencies from, for example, Canada and Japan [7].

Despite various corrective technical interventions in the Limboto Lake watershed [7], the shrinkage of the lake has continually worsened. This extensive shrinkage has further reduced the reservoir capacity volume, resulting in high vulnerability to natural disasters, degradation of the lake environment (e.g., water quality, ecosystems, and biodiversity), eutrophication, and the restructuring of local community livelihoods and economic activities at various scales.

3. Methods

3.1. Overall Methodological Workflow

Figure 2 shows the methodological workflow used in this study. The workflow focused on four significant steps to achieve its primary objective of evaluating the mechanisms of rapid shrinking in Limboto Lake. Firstly, the lake sedimentation volume accumulated in 2003–2017 was estimated using Landsat satellite data and previous studies. Secondly, the magnitude of riverbank erosion between

2003 and 2017 was estimated. Thirdly, the relationship between the volume of riverbank erosion and lake sedimentation was assessed. Fourth, a field survey was conducted to investigate the geological components and characteristics of outcrops along associated rivers and lowland plain areas. Together, this evidence enabled us to determine the mechanisms causing rapid shrinkage of Limboto Lake; we present this discussion based on all the findings described above. The methods utilized in each step are explained in the following sections.

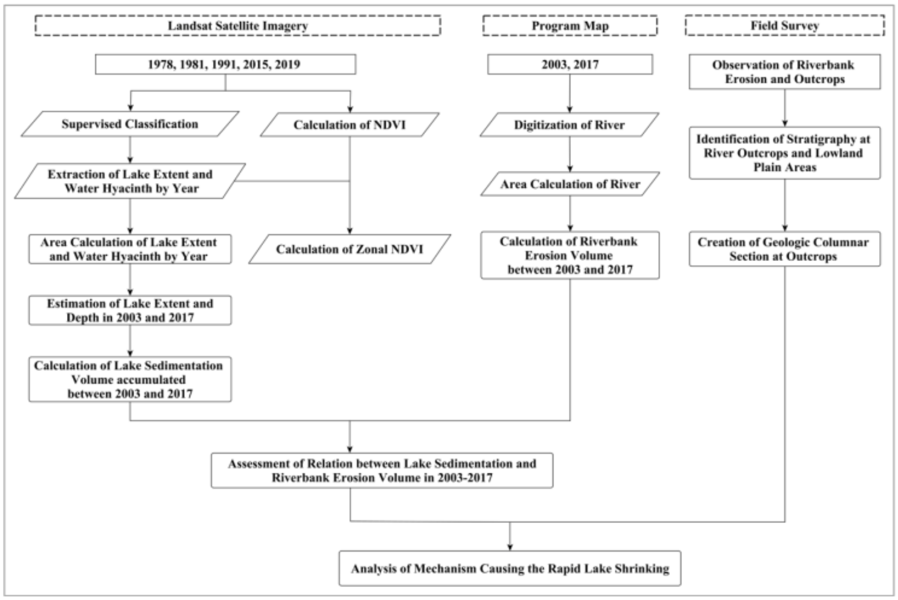


Figure 2. Overall methodological workflow.

3.2. Satellite Imagery

Landsat series provide the long-term datasets of Earth observations. Atmospherically corrected cloud-free Landsat data from the Multispectral Scanner (MSS), Thematic Mapper (TM), and Operational Land Imager (OLI) satellite images, available from the United States Geographic Survey through the Google Earth Engine, were used for analyzing lake extent changes in time-series. Landsat imagery is freely available and commonly used for detecting land cover changes in time-series. Images were chosen based on season, satellite data availability, and cloud coverage to minimize potential influencing factors affecting lake fluctuation. Imagery acquired during the dry season was primarily targeted to minimize meteorological influences, such as rainfall. Furthermore, various factors other than rainfall have been shown to exert an influence on lake size fluctuation. Since a moderate correlation was found between lake size and rainfall amount [24], the influence of other potential factors, such as seasonal agricultural and industrial use, should be standardized. Taking this into account, satellite imagery acquired in 1978, 1981, 1991, 2015, and 2019 with a ground resolution of 60 and 30 m in the World Geodetic System 84 (WGS84) geographic coordinate reference system was utilized for detecting and analyzing lake extent. The MSS datasets were resampled to the resolution of 30 m employing the nearest neighbor resampling method.

In the previous studies, yearly lake water extent was extracted from global water surface data demonstrating a reduction of 12.8 km^2, which is equivalent to 51.9%, from 2001 to 2014 [40]. Similarly, 51% lake coverage by water hyacinth was reported during the dry season of 2012 [17]. Hence, the long-term trend of lake shrinkage and the distribution of water hyacinth can be observed from satellite imagery even with a 30–60 m ground resolution. The main specifications of sensors used in this study are summarized in Table 1. A program map (Google Earth Pro) provided high-resolution imagery acquired on 16 April 2003 and 11 April 2017, and was utilized for digitizing rivers flowing into the lake on the basis of visual interpretation.

Table 1. Main specification of satellite imagery in the study.

Year	Landsat	Acquisition Date	Resolution	NIR (μm)	Red (μm)	Green (μm)
1978	MMS	05/23	60 m	0.70–0.80	0.60–0.70	0.50–0.60
1981		04/28				
1991	TM	05/26	30 m	0.76–0.90	0.63–0.69	0.52–0.60
2015	OLI	05/28	30 m	0.85–0.88	0.64–0.67	0.53–0.59
2019		05/07				

3.3. Extraction of Lake Extent and Water Hyacinth on the Lake Surface and Calculation of Zonal NDVI

Landsat satellite images acquired in 1978, 1981, 1991, 2015, and 2019 were used. Different band combinations help to highlight specific features on the ground, and the application of near-infrared and shortwave infrared color composites can emphasize the contrast between materials [41]. The standard infrared false color composites Red:Green:Blue (R:G:B) = 6:5:4 (MSS), 4:3:2 (TM), 5:4:3 (OLI) were applied for conducting supervised classification to extract the extent of the lake and water hyacinth at the surface. These parameters were extracted in vector format using the Quantum Geographic Information System software. Results from 1978, 1981, 1991, 2015, and 2019 were visualized in time-series. Fifty points for lake extent in 2019 were randomly selected and validated using the high-resolution image obtained on 19 April 2019 from Google Earth Pro to assess accuracy. Since images acquired on the same date of Landsat imagery were not available, images acquired on the closest date were used. This study applied the validated accuracy to all classification results due to unavailability of reference data. Since water hyacinth overgrowth severely influences the environment of the lake, vegetation spread can be a good indicator. A number of spectral indices, such as the Atmospherically Resistant Vegetation Index (ARVI) [42], Enhanced Vegetation Index (EVI) [43], Normalized Difference Vegetation Index (NDVI) [44], Normalized Difference Chlorophyll Index (NDCI), Normalized Difference Aquatic Vegetation Index (NDAVI) [45], and Water Adjusted Vegetation Index (WAVI) [27] have been proposed for detecting aquatic vegetation with formulas consisting of near infrared, red, and blue bands, or a combination thereof. Previous studies found that NDAVI [27,28] and WAVI [29,31] had higher sensitivities for retrieving aquatic vegetation; however, this study applied NDVI containing the infrared and red bands available to all sensors of MSS, TM, and OLI to assess dynamic lake conditions over long timescales. The value of NDVI at the lake boundary was analyzed using Equation (1) to assess the parameter at the zone level.

$$\text{NDVI} = (\text{NIR} - \text{Red})/(\text{NIR} + \text{Red}). \quad (1)$$

3.4. Calculation of Sedimentation Volume Accumulated in the Lake

Regression analysis was performed to interpolate the missing values of lake extent in 2003 and 2017 needed for further analysis. Average lake depths in 2003 and 2017 were calculated using regression based on the combination of field survey data conducted during 1993–2012 [7,17,20]. Accordingly, the total volume of lake sedimentation accumulated during 2003–2017 was calculated based on changes in lake extent and depth, the results of which were utilized for the discussion presented in Section 4.2.

3.5. Extraction of Riverbank Erosion and Estimation of its Volume

A river can be defined as a watercourse comprising a perennial or nonperennial natural channel or artificially improved natural channel or a branch or other watercourses into or from which the waterway flows [46]. Nonperennial rivers are characterized by the existence of a dry phase, lacking surface water [47]. In this study, river is defined as any watercourse area [46], including river-eroded land area.

Rivers associated with Lake Limboto were extracted from the program map, providing high-resolution images both in 2003 and 2017 through digitization based on human visual interpretation. The extracted rivers were categorized into 12 groups based on the main river and its associated tributaries, and changes in area and volume were calculated accordingly. In this study, an average depth of 1.7 m was calculated using the average depth of 13 major rivers, including the Alopohu, Reksongoro, Biyonga, and Meluopo [7]; this depth was applied to all identified rivers to avoid limitations arising from inabilities to identify the actual depth of rivers in 2003 and 2017. Furthermore, the target area of 16×22 km was divided into smaller areas of 1×1 km each, generating a total of 352 tiles to further analyze the diversity of riverbank erosion and its geographical characteristics. This result was utilized for the discussion presented in Section 4.2.

3.6. Field Survey of Outcrops

A field survey using a Garmin Oregon 750 handheld Global Positioning System (GPS) was conducted in early February 2020 to investigate the geology of the Gorontalo lowland plain area. A total of 130 points were investigated in terms of sedimentary structure and facies, grain size, and the presence of organic materials and fossils. A typical geologic columnar section along the Alopohu river (Figure 1) shows that the lowland plain area comprises fine-grained sand and clay, including organic clay.

3.7. Investigation of the Sedimentary Component of River Outcrops and Lowland Plain Areas

Quaternary fine-grained sediments are widely distributed across the Gorontalo plain to the west of Lake Limboto. Previous studies have suggested that this stratum was formed by sediments from Limboto Lake [14]; however, qualitative analyses should be performed to explain the mechanisms causing the magnitude of sedimentation in Limboto Lake. Herein, the stratigraphy of river outcrops and the lowland plain area was explored from a geological perspective. Furthermore, a typical geologic columnar section was produced at thirty outcrops along the Alopohu river by specifying the results of a previous study [16]. The results are compared with the sedimentation components of the lake studied by [17] and are also used to explain the shrinkage mechanism of Limboto Lake in further discussion.

4. Result and Discussion

4.1. Changes in Lake Extent in Time-Series and Estimation of Lake Sedimentation Volume

The extent of the lake extent and changes in the distribution of water plants such as the water hyacinth were extracted as described in Section 3.2, enabling the lake extent to be visualized (Figure 3). The lake extent was identified as 31.50 (1978), 30.25 (1982), 23.02 (1991), 19.65 (2015), and 20.44 km^2 (2019), with an accuracy of 98.0%—i.e., the lake extent declines. Notably, the lake extent in 2019 was only 64.9% of that in 1978. Similarly, the identified areas of water hyacinth at the lake surface were 0.0027 (1991), 4.3 (2015), and 3.31 km^2 (2019). NDVI values calculated using formula 2 were −0.40 (1978), −0.08 (1982), −0.14 (1991), −0.16 (2015), and −0.20 (2019).

The observed shrinkage of the lake occurred largely in its western part in the form of delta growth toward the center of the lake. Possible reasons for this lake shrinkage during the period of 1978–2019 are changes in land-use resulting from increased agricultural activities in the Gorontalo plain area, and population growth around the lake. Lake shrinkage is concentrated in the western part, in which the lake receives water from major rivers, such that the lands nearby are largely used for agricultural activities. On the contrary, the eastern side of the lake is an urban area. The area used for the cultivation of rice and corn showed a 1.7- and 3.5-fold increase, respectively, from 2001 to 2015 at the Gorontalo province level [48]. This production increased by 1.5 and 7.9 times, respectively, during the period 2001–2015 [48] as a result of the agricultural reconstruction policy and programs implemented by the Indonesian central government after the early 2000s, which have prioritized the production of rice, corn, soybean, and meat [49]. Similar rapid increases in area and production can be expected in the Gorontalo flat plain area. This increased agricultural production requires an increased water supply from the nearby rivers and the amount of water usage may affect lake shrinkage. The spatial concentration of lakes that have disappeared due to human activities is in accordance with previous case studies [1]. Furthermore, the population growth of Gorontalo province shows a 2.26- and 1.64-fold increase for 2000–2010 and 2010–2015 [50], respectively. Furthermore, the population is highly concentrated in urban areas, which account for 34.0%, 39.0%, and 44.0% of the total population in 2010, 2015, and 2020 [51], respectively. Thus, the growing population in the Limboto Lake area has resulted in increasing daily water usage, which may contribute to facilitating the shrinkage of the lake. Furthermore, population growth leads to over-cultivation and deforestation, causing erosion and environmental degradation [6].

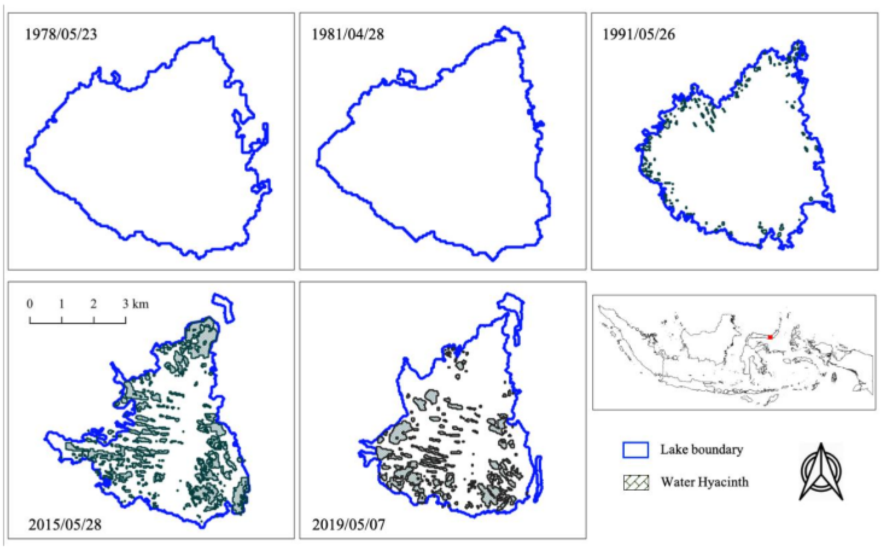


Figure 3. Time-series change in Limboto Lake extent and distribution of water hyacinth at the lake surface.

In terms of the rate of lake shrinkage, Limboto Lake shows a higher speed than other rapidly disappearing lakes, such as Dongting Lake in China, which showed a 58.1% decrease during 1930–2000 [1], and Lake Alaotra in Madagascar, for which the corresponding value is 5 km^2 during 1972–2000 [2].

The extent of water hyacinth was identified from 1991. Lower coverage of water hyacinth in 1991 or before are attributed to the spatial resolution of the sensors: areas less than 30–60 m resolution are not reflected in the earlier datasets. However, these results can nonetheless be consistent with the fact that there has been an overwhelming encroachment of invasive water hyacinth in Limboto Lake over recent decades [36]. This invasion of water hyacinth is predicted to seriously threaten the lake and, in particular, lead to the conversion of lake border areas into land, resulting in further reduction in lake storage capacity. Since the bloom of water hyacinth has accelerated with eutrophication in the lake [39], which itself is caused by urbanization and agricultural development [48–50], lake shrinkage is expected to occur ever more rapidly in the future. Moreover, the notable increase in zonal NDVI values can be interpreted as arising from the blooming of water hyacinth, which likely invaded the lake prior to 1991. Zonal NDVI values decreased together with the area of water hyacinth in 2019, which can imply specific human intervention before the image acquisition period. Indeed, since the rapid increase in water hyacinth can pose a severe threat to the lake environment, its management has been implemented at the provincial government level. As discussed above, the value of NDVI can be a crucial indicator to explain the state of the lake surface environment; vital information can thus be extracted for lake management [30]. Annual changes in lake extent, zonal NDVI, and the distribution of water hyacinth are shown in Figure 4.

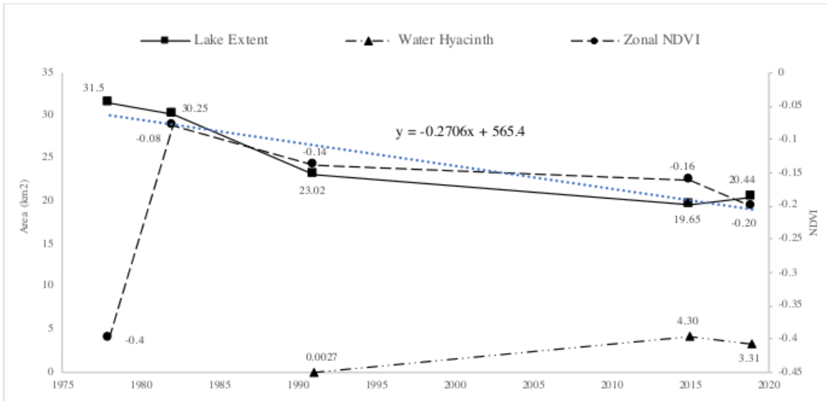


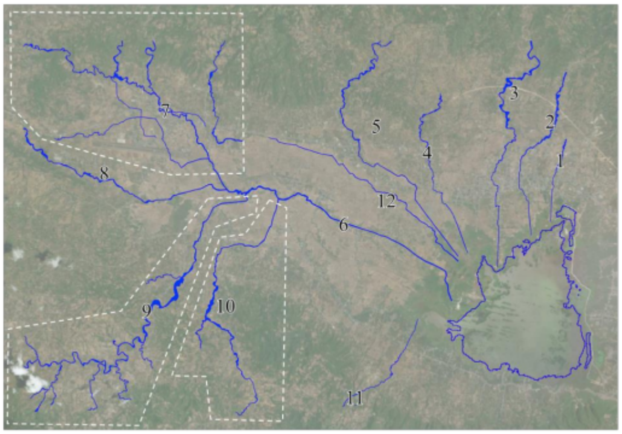
Figure 4. Yearly change of lake extent, water hyacinth, and zonal Normalized Difference Vegetation Index (NDVI).

Furthermore, based on the regression analysis described in Section 3.3, the lake extent and its average depths were 23.39 km^2 and 2.99 m, and 19.60 km^2 and 1.88 m, in 2003 and 2017, respectively. Consequently, the magnitude of sedimentation accumulated between 2003 and 2017 can be estimated as 4,227,096.72 m^3.

4.2. Estimation of Riverbank Erosion Volume and Its Geographical Characteristics

Using the high-resolution imagery provided by the program map, the rivers were digitized on the basis of visual interpretation. Out of 23 possible rivers flowing into the lake, 12 rivers were identified, namely, the Talumeli, Bulota, Biyonga, Melopo, Marisa, Alopohu, Alo, Reksonegoro, Rambongan, Pohu, Hutokiki, and one unknown river (Figure 5). The identified total areas are thus 1,883,054.47 and 3,812,733.14 m^2 for 2003 and 2017, respectively. This demonstrates a 202.5% expansion; indeed, a positive expansion was noted in all rivers. The rivers demonstrating a significant size in 2003 were the Rambongan (488,342.24 km^2), Alo (345,580.00 km^2), Pohu (209,461.67 km^2), Biyonga (195,143.36 km^2), and Reksonegoro (190,607.30 km^2). Similarly, the Rambongan (873,540.31 km^2), Alo (751,299.99 km^2), Pohu (402,057.60 km^2), Alopohu (343,952.08 km^2), and Biyonga (337,403.05 km^2) showed significance in 2017. The rivers indicating a higher rate of riverbank erosion during the period of 2003–2017 were the Buloto (296.3%), Marisa (287.1%), Hutokiki (254.3%), and Alo (217.4%).

To calculate erosion volumes for 2003–2017, an average river depth of 1.7 m was used for all rivers, as described in Section 3.4. The total volume of eroded land area was found to be 3,280,453.74 m^3, of which the Alo river contributed most (21.0%), followed by the Rambongan (20.0%), Pohu (10.0%), Marisa (9.0%), Alopohu (8.3%), and Biyonga (7.4%) rivers. This result is consistent with previous studies [7,21], where it was pointed out that significant sources of lake sediment stem from the Alopohu area (including the Alo and Pohu rivers). The major significant sources of sedimentation identified in 2002 [7], 2009 [21], and 2003/2017 were similar; thus, it can be concluded that the riverbanks are highly vulnerable to erosion, which can be further accelerated, contributing to lake shrinkage. The identified eroded land area, expansion rate, and volume of erosion are summarized in Table 2.



	River
1	Talumeli
2	Bulota
3	Biyonga
4	Meluopo
5	Marisa
6	Alopohu
7	Alo
8	Reksonegoro
9	Rombongan
10	Pohu
11	Hutokiki
12	unknown

Figure 5. Rivers associated with Limboto Lake based on visual interpretation.

Table 2. Eroded area and estimated erosion volume between 2003 and 2017.

Rivers	Eroded Area (m^2)	Expansion (%)	Erosion Volume (m^3)	Ratio (%)
Talumeli	14,144.46	144.8	24,045.58	0.7
Bulota	118,816.33	296.3	201,987.76	6.2
Biyonga	142,259.69	172.9	241,841.47	7.4
Meluopo	62,242.39	187.1	105,812.06	3.2
Marisa	173,053.06	287.5	294,190.20	9.0
Alopohu	160,649.31	187.6	273,103.83	8.3
Alo	405,719.99	217.4	689,723.98	21.0
Reksonegoro	109,339.43	157.4	185,877.03	5.7
Rombongan	385,198.07	178.9	654,836.72	20.0
Pohu	192,595.93	192.0	327,413.08	10.0
Hutokiki	22,824.39	254.3	38,801.46	1.2
unknown	-	-	242,820.55	7.4
Total	1,929,678.67	202.5	3,280,453.74	100.0

The volume of lake sedimentation between 2003 and 2017, as calculated in the previous section, is 4,227,096.72 m^3. Thus, a maximum of 77.6% of lake sedimentation originated in the study area. Various factors contribute to this massive sedimentation [10,12]; however, the sedimentation caused by river erosion is the most significant.

At this point, it should be emphasized again that the results presented are based on the average river depth as calculated from the average river depth of 13 major rivers [7]. Since the actual depth of the rivers in 2003 and 2017 cannot be precisely determined, a qualitatively measured average depth was used in this study.

Changes at various levels and the characteristics of this change can be clearly extracted at the mesh level. Hence, the target areas were visualized using a 1 by 1 km mesh, as described in Section 3.4 (Figures 6 and 7). From Figure 6, rivers with areas greater than 60,000 m^2 were identified as the Biyonga, Pohu, and Rombongan in 2003; however, the Alo, Alopohu, Marisa, and Reksonegoro rivers had expanded in area along with these rivers by 2017. Rivers in the west lowland plain areas of Limboto Lake are particularly significant. Furthermore, major rates of river expansion of 100%–200% (41.1%) and 200%–300% (25.0%) were demonstrated between 2003 and 2017 (Figure 7). Since the meshes termed "NA" are only found in 2017, their rate of change cannot be estimated. Rivers with larger areas or showing a higher rate of expansion in size are found mainly in the lowland plain catchment area of Limboto Lake. Since the magnitude of water flow is assumed to become higher and more aggressive in river catchment areas, these areas could be more sensitive to erosion during heavy rainfall. Furthermore, the lack of adequate dikes also accelerates soil and sludge erosion.

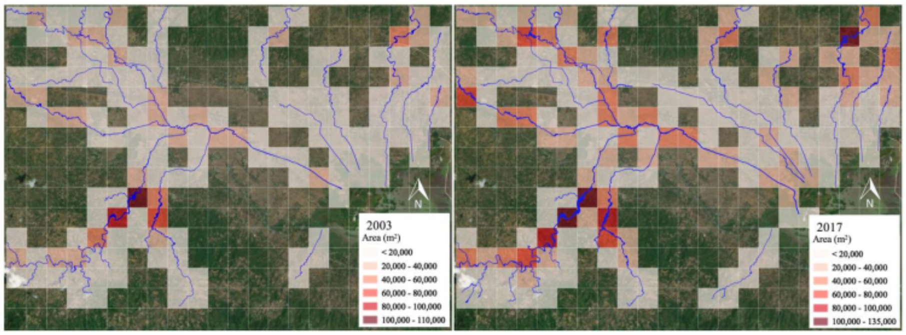
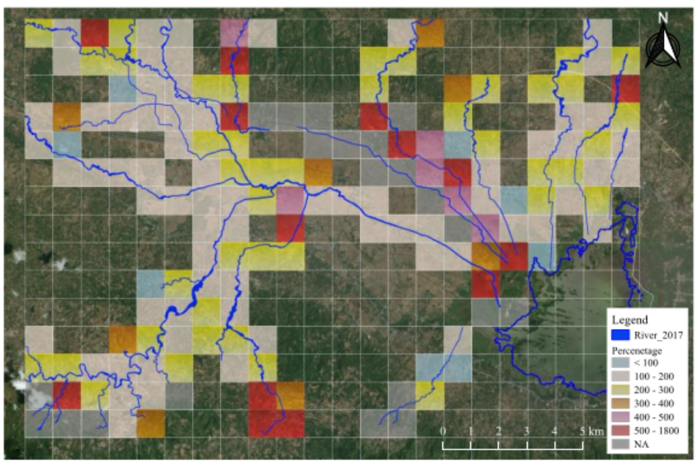


Figure 6. River in 2003 and 2017 by Mesh.



Change (%)	Mesh #	Ratio
< 100	8	4.8
100–200	69	41.1
200–300	42	25.0
300–400	8	4.8
400–500	6	3.6
500 <	14	8.4
NA	21	2.5
Total	168	100.0

Figure 7. Expansion ratio of river by mesh.

4.3. Stratigraphy and Paleoenvironment of the Grontalo Plain Area

Understanding the sedimentary environment of the lowland plain area from the geologial perspective is important for assessing the mechanisms responsible for accelerating the rapid shrinkage of Limboto Lake. Therefore, the sedimentary environments of outcrops along the riverbank and lowland plain areas were investigated. Based on previous research [16], a typical geologic columnar section at thirty outcrops along the Alopohu river was modified in this study as described in Figure 8.

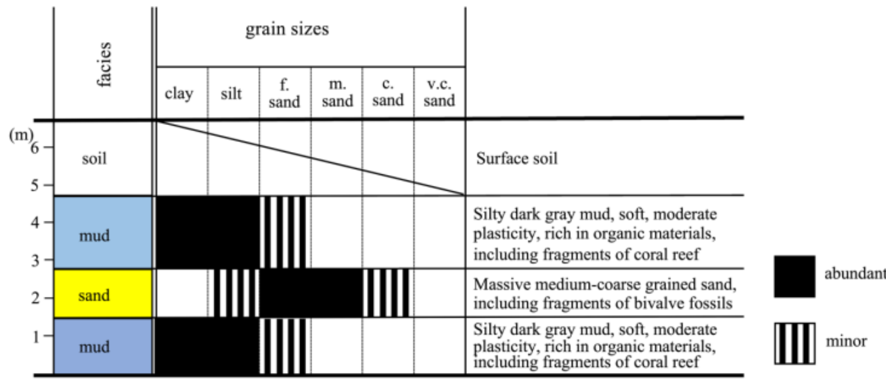


Figure 8. Representative geologic columnar section at an outcrop along the Alopohu river in the west area of Limboto Lake, Gorontalo Province.

Excluding the uppermost surface soil, the lower limit of this formation is unknown, but it is at least 5 m thick. The formation is primarily composed of mud beds, with a fine- and middle-grained sand bed forming a 1 m thick interlayer between them. The mud layer is characterized by fragments of coral reef and organic material. The sand layers contain fragments of fossilized bivalves. Hence, the peleoenvironment of the Gorontalo lowland plain area is determined to have been an innar bay during the Quarternary.

4.4. The Mechanisms of Rapid Shrinkage of Limboto Lake

Regions influenced by substantial tectonic activity able to cause geomorphologic and sedimentological modification of the landscape due to earthquakes are influenced by a complex interrelationship of nature and human-induced activities [4]. Therefore, understanding the rapid shrinkage of the lake at geological scales gives significant insights. At Sulawesi island, where pre-Pleistocene uplift was caused by the Australia-Southeast Asia collision [52], some areas were transformed from seas into lands and from inner bays into inner lakes. As a result of these geological events, the region mainly consists of fine-grained inner bay sediments.

Based on the results shown in the previous sections, it can be concluded that the rapid shrinkage of Limboto Lake is likely due to the deposition of fine-grained inner bay sediments, which represent eroded remnants from the rapid uplift by the Eurasian–Australian plates, widely distributed across the Gorontalo lowland plain areas. This can be confirmed by the low-frequency distribution of larger particles, such as pebbles, in the lowland area [53]. This formation is easily eroded by river water and turbid water. Although several water gates have been built along the associated rivers to control the inflow of sediments to the lake, small sediment particles are still transportable beyond the gates into the lake as turbid water. The identified particulate materials are also found in sediments in the inner lake area [17], demonstrating that the average concentrations of dried mud, fine sand, and gravel are 81.6%, 14.1%, and 4.3%, respectively.

In spite of the fact that environmental change and human-induced activities have largely been considered the most significant driving factors influencing rapid changes in lakes [1–6], tectonic events are also a fundamental factor accelerating such changes. An inner sea in South Sulawesi, generated over 16 centuries, has been further transformed into three smaller lakes, namely Tempe, Sidenreng, and Buaya, owing to filling up by silt together with connecting rivers into the lake [8,54]. This could be a typical phenomenon associated with the transformation of enclosed seas into lakes by rapid uplift of land in the collision zone, as has been observed at Limboto Lake.

5. Conclusions

The combination of rapid environmental changes induced by socioeconomic transformation and meteorological changes has significant impacts on local communities and their sustainability. Understanding factors and mechanisms causing significant accelerations in environmental change enables the development of possible strategies and alternative activities to promote sustainable development at local levels. In this paper, the mechanisms behind the rapid shrinkage of Limboto Lake, Indonesia, created by the rapid uplift of the Eurasian–Australian plate, were explored using remote sensing imagery and river outcrop data. The results presented herein show that the extent of the lake in 2019 was reduced by 64.9% relative to that in 1978. Water hyacinth identified at the lake surface from 1991 onward can further threaten the lake, particularly through converting the lake border area into land, resulting in further reduction in lake storage capacity. More than 70% of lake sedimentation, resulting in shrinkage, is contributed by riverbank erosion caused by river drainage between 2003 and 2017. This study also found that the paleoenvironment of the Gorontalo lowland plain area was an inner bay during the Quaternary. Therefore, it can be concluded that the mechanism causing rapid and severe lake shrinkage was the deposition of fine-grained sediment from the eroded remnants deposited during rapid uplift. Despite environmental changes and human-induced activities, the lake system generated under the transformation of enclosed seas to lakes by rapid uplift in the collision zones is also a fundamental factor in accelerating the rapid disappearance of lakes. These results enable an understanding of the mechanisms causing the rapid shrinkage of Limboto Lake, which can assist in the development of appropriate technical interventions for the mitigation of lake extinction. This creates opportunities to develop alternative sustainable economic activities together with various stakeholders at the local level.

Author Contributions: S.K. contributed to design the research, conduct data collection, data analysis, and data visualization. A.K.M.A.A. conducted the geological investigation in the field with the supervision of Y.I.A., M.S., and M.N. provided conceptual advice and critical comments. All authors have read and agreed to the published version of the manuscript.

Funding: This research was financially supported by Research Institute for Humanity and Nature (RIHN: a constituent member of NIHU).

Acknowledgments: This research was financially supported by Research Institute for Humanity and Nature (RIHN: a constituent member of NIHU) 14200102.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Du, Y.; Xue, H.; Wu, S.; Ling, F.; Xiao, F.; Wei, X. Lake area changes in the middle Yangtze region of China over the 20th century. *J. Environ. Manag.* **2011**, *92*, 1248–1255. [CrossRef]
2. Bakoariniaina, L.N.; Kusky, T.; Raharimahefa, T. Disappearing Lake Alaotra: Monitoring catastrophic erosion, waterway silting, and land degradation hazards in Madagascar using Landsat imagery. *J. Afr. Earth Sci.* **2006**, *44*, 241–252. [CrossRef]
3. Page, M.J.; Trustrum, N.A.; DeRose, R.C. A high resolution record of storm-induced erosion from lake sediments, New Zealand. *J. Paleolimnol.* **1994**, *11*, 333–348. [CrossRef]
4. Ariztegui, D.; Anselmetti, F.S.; Robbiani, J.M.; Bernasconi, S.M.; Brati, E.; Gilli, A.; Lehmann, M.F. Natural and human-induced environmental change in southern Albania for the last 300 years—Constraints from the Lake Butrint sedimentary record. *Glob. Planet. Chang.* **2010**, *71*, 183–192. [CrossRef]
5. United Nation Drying Lake Chad Basin Gives Rise to Crisis. Available online: https://www.un.org/africarenewal/magazine/december-2019-march-2020/drying-lake-chad-basin-gives-rise-crisis (accessed on 3 September 2020).
6. Kiprutto, N.; Munyao, C.; Ngoriarita, J.; Kangogo, M.; Kiage, E. Tracing the possible root causes for fleeing flamingos in Kenya' s Lake Nakuru National Park. *J. Nat. Sci. Res.* **2012**, *2*, 23–31.
7. Japan International Cooperation Agency. *The Study on Flood Control and Water Management Limboto-Bolango-Bone Basin in the Republic of Indonesia Volume-III Supporting Report: Part-A Existing Conditions*; Japan International Cooperation Agency: Tokyo, Japan, 2002.

8. Druce, S.C. *The Lands West of the Lakes*; KITLV Press: Leiden, The Netherlands, 2009; ISBN 9789004253827.
9. Katili, J.A. Past Anr Present Getectonic Indonesia Position of Sulawesi, Indonesia. *Tectonophysics.* **1978**, *45*, 289–322. [CrossRef]
10. Fulazzaky, M.A.; Abdul Gany, A.H. Challenges of soil erosion and sludge management for sustainable development in Indonesia. *J. Environ. Manag.* **2009**, *90*, 2387–2392. [CrossRef]
11. Rostitawati, T.; Wahyuddin, N.I.; Obie, M. The poverty puddles of the cage fishing community at Limboto Lake Coast, Indonesia. *J. Sustain. Dev.* **2019**, *12*, 82. [CrossRef]
12. Walling, D.E. The impact of global change on erosion and sediment transport by rivers: Side publications series The United Nations World Water Development Report 3. *U. N. World Water Assess. Program.* **2009**, *81*, 26.
13. Sharifikia, M. Environmental challenges and drought hazard assessment of Hamoun Desert Lake in Sistan region, Iran, based on the time series of satellite imagery. *Nat. Hazards* **2013**, *65*, 201–217. [CrossRef]
14. Putra, S.S.; Hassan, C.; Suryatmojo, H. Reservoir saboworks solutions in Limboto Lake Sedimentations, Northern Sulawesi, Indonesia. *Procedia Environ. Sci.* **2013**, *17*, 230–239. [CrossRef]
15. Aliaj, S.; Baldassarre, G.; Shkupi, D. Quaternary subsidence zones in Albania: Some case studies. *Bull. Eng. Geol. Environ.* **2001**, *59*, 313–318. [CrossRef]
16. Amin, A.K.M.; Arifin, Y.I.; Akase, N. Studi fasies formasi endapan danau untuk menentukan lingkungan pengendapan danau limboto. *Jambura Geosci. Rev.* **2019**, *1*, 50–67. [CrossRef]
17. Subehi, L.; Wibowo, H.; Jung, K. Characteristics of rainfall-discharge and water quality at Limboto Lake, Gorontalo, Indonesia. *J. Eng. Technol. Sci.* **2016**, *48*, 288–300. [CrossRef]
18. Yunginger, R.; Bijaksana, S.; Dahrin, D.; Zulaikah, S.; Hafidz, A.; Kirana, K.H.; Sudarningsih, S.; Mariyanto, M.; Fajar, S.J. Lithogenic and anthropogenic components in surface sediments from lake limboto as shown by magnetic mineral characteristics, trace metals, and REE geochemistry. *Geoscience* **2018**, *8*, 116. [CrossRef]
19. Siti Aisyah Physical and Chemical Characteristics of Sediment in Lake Tempe Using Multivariate Analysis Approach. In Proceedings of the 16th World Lake Conference, Bali, Indonesia, 7–11 November 2016; pp. 586–592.
20. BPDAS-BB. *Technical Planning for Land Rehabilitation and Soil Conservation for Limboto Watershed (Book 1)*; BPDAS-BB Gorontalo: Gorontalo, Indonesia, 2004.
21. *Sulawesi II River Basin Authority Sediment Management Planning of Limboto Lake Watershed, Final Report*; Indonesian Ministry of Public Works: Gorontalo, Indonesia, 2009.
22. Kimijima, S.; Nagai, M. Study of urbanization corresponding to socio-economic activities in Savannaket, Laos using satellite remote sensing. *Malays. J. Remote Sens. GIS* **2014**, *3*, 71–75. [CrossRef]
23. Alam, A.; Bhat, M.S.; Maheen, M. Using Landsat satellite data for assessing the land use and land cover change in Kashmir valley. *Geo. J.* **2019**. [CrossRef]
24. Eraku, S.; Akase, N.; Koem, S. Analyzing Limboto lake inundation area using landsat 8 OLI imagery and rainfall data. *J. Phys. Conf. Ser.* **2019**, *1317*. [CrossRef]
25. Zhu, W.; Jia, S.; Lv, A. Monitoring the fluctuation of lake Qinghai using multi-source remote sensing data. *Remote Sens.* **2014**, *6*, 10457–10482. [CrossRef]
26. Dörnhöfer, K.; Oppelt, N. Remote sensing for lake research and monitoring—Recent advances. *Ecol. Indic.* **2016**, *64*, 105–122. [CrossRef]
27. Villa, P.; Mousivand, A.; Bresciani, M. Aquatic vegetation indices assessment through radiative transfer modeling and linear mixture simulation. *Int. J. Appl. Earth Obs. Geoinf.* **2014**, *30*, 113–127. [CrossRef]
28. Zhou, G.; Ma, Z.; Sathyendranath, S.; Platt, T.; Jiang, C.; Sun, K. Canopy reflectance modeling of aquatic vegetation for algorithm development: Global sensitivity analysis. *Remote Sens.* **2018**, *10*, 837. [CrossRef]
29. Jaskuła, J.; Sojka, M. Assessing spectral indices for detecting vegetative overgrowth of reservoirs. *Pol. J. Environ. Stud.* **2019**, *28*, 4199–4211. [CrossRef]
30. Szabó, L.; Deák, B.; Bíró, T.; Dyke, G.J.; Szabó, S. NDVI as a proxy for estimating sedimentation and vegetation spread in artificial lakes-monitoring of spatial and temporal changes by using satellite images overarching three decades. *Remote Sens.* **2020**, *12*, 1468. [CrossRef]
31. Villa, P.; Bresciani, M.; Braga, F.; Bolpagni, R. Comparative assessment of broadband vegetation indices over aquatic vegetation. *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.* **2014**, *7*. [CrossRef]
32. Noor, S.Y. Trophic status of Limboto lake in Gorontalo Province. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *567*. [CrossRef]
33. Lamangida, T.; Akib, H.; Malago, J. Management of public assets study management of Lake Limboto Gorontalo District. *IOSR J. Humanit. Soc. Sci.* **2018**, *23*, 92–99. [CrossRef]

34. Trisakti, B.; Suwargana, N.; Cahyono, J.S. Monitoring of lake ecosystem parameter using landsat data (a case study: Lake Rawa Pening). *Int. J. Remote Sens. Earth Sci.* **2017**, *12*, 71. [CrossRef]
35. BPS—Statistics Indonesia STATISTIC INDONESIA. Available online: https://www.bps.go.id/ (accessed on 3 September 2020).
36. Chrismadha, T.; Haryani, M.G.S.; Fakhrudin, P.E.H. Ecohydrological application in lake management. In Proceedings of the National Symposium on Ecohydrolog, Jakarta, Indonesia, 24 March 2011; pp. 23–42.
37. Hidayat, G.G.; Kakizawa, H. Development process of watershed partnership: A case study of Limboto Watershed—Gorontalo, Indonesia. *Indones. J. For. Res.* **2014**, *1*, 9–20. [CrossRef]
38. Soeprobowati, T.R. Integrated lake basin management for save Indonesian Lake movement. *Procedia Environ. Sci.* **2015**, *23*, 368–374. [CrossRef]
39. Rahim, A.; Soeprobowati, T.R. Water pollution index of Batujai reservoir, Central Lombok Regency-Indonesia. *J. Ecol. Eng.* **2019**, *20*, 219–225. [CrossRef]
40. Rossi Hamzah, B.M.; Fukushima, T. Long-term monitoring of lake surface area change in Indonesia from global surface water data. In Proceedings of the 17th World Lake Conference, Ibaraki, Japan, 15–19 October 2018; pp. 600–602.
41. Japan Association on Remote Sensing. *Remote Sensing Note*; Japan Association on Remote Sensing: Tokyo, Japan, 1993.
42. Kaufman, Y.J.; Tanre, D. Atmospherically resistant vegetation index (ARVI) for EOS-MODIS. *IEEE Trans. Geosci. Remote Sens.* **1992**, *30*, 261–270. [CrossRef]
43. Huete, A.; Didan, K.; Miura, T.; Rodriguez, E.P.; Gao, X.; Ferreira, L.G. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sens. Environ.* **2002**, *83*, 195–213. [CrossRef]
44. Rouse, J.W.; Hass, R.H.; Schell, J.A.; Deering, D.W. Monitoring vegetation systems in the great plains with ERTS. *NASA Spec. Publ.* **1974**, *351*, 309.
45. Villa, P.; Laini, A.; Bresciani, M.; Bolpagni, R. A remote sensing approach to monitor the conservation status of lacustrine Phragmites australis beds. *Wetl. Ecol. Manag.* **2013**, *21*, 399–416. [CrossRef]
46. Taylor, M.P.; Stokes, R. When is a River not a River? Consideration of the legal definition of a river for geomorphologists practising in New South Wales, Australia. *Aust. Geogr.* **2005**, *36*, 183–200. [CrossRef]
47. Vidal-Abarca, M.R.; Gómez, R.; Sánchez-Montoya, M.M.; Arce, M.I.; Nicolás, N.; Suárez, M.L. Defining dry rivers as the most extreme type of non-perennial fluvial ecosystems. *Sustainability* **2020**, *12*, 7202. [CrossRef]
48. Badan Pusat Statistik BERITA RESMI STATISTIK. Available online: https://bps.go.id/pressrelease.html (accessed on 3 September 2020).
49. Wardis, G. Food security systems in Indonesia: Challenges and implications to food security in Maluku. *Occas. Pap.* **2014**, *12*, 35–45. [CrossRef]
50. Statistics Indonesia Population Growth by Province (Indonesia). Available online: https://www.neliti.com/publications/51226/population-growth-by-province (accessed on 7 September 2020).
51. Statistics Indonesia Percentage of Urban Population by Province, 2010–2035 (Indonesia). Available online: https://www.neliti.com/publications/51230/percentage-of-urban-population-by-province-2010-2035 (accessed on 7 September 2020).
52. Hall, R. Australia-SE Asia collision: Plate tectonics and crustal flow. *Geol. Soc. Spec. Publ.* **2011**, *355*, 75–109. [CrossRef]
53. Japan International Cooperation Agency. *The Study on Flood Control and Water Management in Limboto-Bolango-Bone Basin in The Republic of Indonesia Final Report Volume-1 Summary*; Japan International Cooperation Agency: Tokyo, Japan, 2002.
54. Pelras, C. *The Bugis*; Blackwell: Oxford, UK, 1996.

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