Endemic and invasive species of Lake Matano and allowable suspended solid load to sustain high species endemism

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Abstract. Lake Matano, an ancient tectonic, is characterized by its high degree of aquatic fauna endemism and richness dwelling the littoral bed. Two main issues threatening the sustainability of those species are 1) high rate of land conversion and 2) the occurrence of invasive fish species. Through this study, we unveiled how sediment load from converted lands may have influenced the habitat of the endemic species. Based on our hydrodynamic simulation, suspended solid loads from the incoming streams have been accumulating in certain littoral areas of the lake, which is the preferable habitat for most endemic species. We computed that the maximum suspended solid loads from those inlets is 25 kg/day in order to minimize the impact of sedimentation in littoral zones. An in-depth analysis of species interaction in the littoral zone was also performed to depict probable threats to endemic fauna dwelling littoral areas of the lake.

1. Introduction
Lake Matano, an ancient tectonic lake, is characterized by relatively steep topography, flat bottom area and high degree of endemic species. Lake Matano has very steep sides, along northern and mid-southern sides reaching 30° with an average of 15°, with soft substrate and often bordered by rock at the bank, a slope or drop off on the lake site [1]. Total catchment area of Lake Matano is relatively small (436 km²) with its highest point at 1,400–1,700 m above sea level (a.s.l). The water surface of Lake Matano is at 382 m a.s.l. while the deepest lake (bottom) is at 238 m below sea level. This crypto depression and a graben structure were due to its tectonic originated back around one to four million year ago [1,2].
Lake Matano is an oligotrophic lake with a high transparency of up to 20 m, however, there was a trend to decrease as in 2017 was 18.8 m [3], while in 2001 and 1992, it were 20 m and 22 m respectively [4, 5]. Euphotic zone of Lake Matano was estimated to reach 130 m [1]. A study has reported that persistent thermocline was found in 100 m depth [6]. Although the thermal stratification was relatively weak compared to seasonally stratified temperate lakes, the similarity of the density profiles between the wet and dry seasons as well as the accumulation of TDS in the hypolimnion, suggests that Lake Matano has not been vertically mixed [1]. The soluble reactive phosphate (SRP) and total P in Lake Matano were still below the detection limit (0.05 µmol.L⁻¹) [1]. P concentration in the epilimnion is likely limited by sorption to particulate or colloidal Fe (hydr)oxides. The large particulate Fe flux to Lake Matano may help buffer anthropogenic stresses in this lake [1].
Sulawesi Island including Lake Matano has been identified as a hotspot for biodiversity [7] and biological conservation in Southeast Asia [8] due to its high degree of species endemism. Most of the aquatic biota in Lake Matano are endemic. They consist of 13 species of fish [9], seven species of shrimps [10], three species of crab [11], and four species of mollusc [12]. Most of the endemic fish species (Telmatherina spp.) live in shallow area within water depth of <1 - 20 m with clear waters and soft and hard substrate such as plant, sand, root of plant, aquatic plant, gravel, rock, and cobble [13, 14,15].

Two main issues in Lake Matano are 1) high rate of land conversion and 2) the occurrence of invasive fish species. Land conversion rate in the catchment, from forest to crops, reached 2% per year in 2000 to 2010 [16]. Herder et al. [7] have noted that major threat in this area comes from surface nickel mining and furthermore they have also published first record of invasive fish species i.e. Louhan.

The priceless uniqueness of Lake Matano and various existing threats have become government concern. Lake Matano and its catchment have been established as a conservation area since 1979 as Natural Park for Tourism (TWA: Taman Wisata Alam) based on Decree of Ministry of Agriculture KepMen No. 274/Kpts/Um/1979. Recently, Lake Matano has been included in the list of national priority lakes to be managed or revitalized due to high pressure on the lake ecosystem [17].

In order to implement proper management actions, some scientific measures are needed. In this study, we examine how sediment loads into the lake may threaten the aquatic fauna. We also assess the ecological interaction among littoral dwellers to depict probable threats by the invasive fauna.

2. Materials and Methods
This research is located in Lake Matano, part of Malili Lakes, located at District of East Luwu, South Sulawesi (02°25.00′ -02°34.00′ S and 121°12.00′ -121°29.00′ E), Indonesia. Three large lakes of the Malili lakes system are Lake Matano (164 km²), Lake Mahalona (24.4 km²), and Lake Towuti (561.1 km²). Petea River drains Lake Matano into Lake Mahalona whereas Lake Towuti receives Mahalona’s discharge through Tominanga River (figure 1) [10,14].

This study was started by analysing characteristics of endemic species habitat where secondary data about biodiversity of endemic, native, and alien species referred from earlier publications [7, 9, 10, 11, 12, 18] as well as the habitat type and feeding habit of biota [4, 7, 10, 11, 12, 13, 14, 15, 19, 20, 21, 22]. The next step was identifying littoral zone and habitat area of endemic species. Littoral zone of Lake Matano was reanalyzed based on morphometry of the lake [23]. The lake bottom diagram was obtained by gridding the bathymetry data using SURFER software. Map of habitat area for endemic biota was generated from various data i.e. matrix of habitat (depth) spatial analysis based on morphometry map, slope, and light penetration in water. A two dimensional (2D) layered numerical model [24] was used to simulate the distribution of suspended solid in the lake. In 2016 and 2017 sampling campaigns were conducted to feed model computation. Samples of suspended solid were collected at some stations in the lake (figure 1). Lake water current was obtained using bottom tracking Acoustic Doppler Current Profiler-RD Instrument (ADCP-RDI).
3. Results and Discussion

3.1. Ecology of the endemic and invasive species
Most endemic species of Lake Matano consist of shrimps, molluscs, fish and crabs are also endemic in Malili lakes. There are seven species of shrimp found in Lake Matano, namely Caridina dennerli, Caridina holthuisi, Caridina lanceolata, Caridina loehae, Caridina mahalona, Caridina masapi and Caridina parvula [10]. Caridina dennerli is endemic in Lake Matano while other species of Caridina is endemic in Malili lakes. Furthermore, six endemic species of gastropod such as Tylomelaia gemmifera, T. matannensis, T. molesta, T. patriarchalis, T. turriformis, T. zeamais [12] and three species of crab namely Nautilothelpusa zimmeri, Parathelpusa pantherina and Syntripsa matanensis [11] are found in Lake Matano. In addition, there are nineteen fish species in Lake Matano ecosystem. Eight fish species endemic in Lake Matano are Telmatherina bonti, T. antoniae, T. abendanoni, T.
obscura, T. opudi, T. prognatha, T. sarasinorum, T. wahyu, five endemic in Malili lakes are Dermogenys ebradtii, Oryzias matanensis, Mugillogobius latifrons, Mugillogobius cf. adeia and Glossogobius matanensis [9, 3, 18]. However, there are also fourteen alien species in Lake Matano namely Anabas testudineus, Aplocheilus panchax, Channa striata, Oreochromis mossambicus, Pseudotropheus cyeaneorhabdos, Claris batrachus, Pterygoplichthys pardalis, Cyprinus carpio, Trichopodus trichopterus, Poecilia reticulata, Ophisternon cf. bengalense, Colossoma macropomum, Oreochromis niloticus, and hybrid “flowerhorn” cichlid (Amphilopuscitrinellus x Cichlasoma trimaculatum) [7, 9, 18].

Hybrid flowerhorn, known as Louhan, has been invasive and threatened endemic species of Lake Matano [7]. Some evidences depict the high rate of Louhan invasiveness in Lake Matano viz., being fast dispersal and being competitor in habitat (depth and substrate) and food source. As reported by Herder et al [7], Louhan spread successfully between 2010 and 2012. In 2010, they were only found along the southern shoreline, while in 2012 they reached the northern shoreline with medium to high abundance. Recent study [25] also recorded the high number of Louhan that covers 27% and 42% of catch in May and August 2016, respectively.

| Table 1. Matrix of habitat depth of endemic species and invasive species (Louhan). |
|------------------------|-----------------|---|---|---|---|
| **Species**             | **Depth (m)**   |   |   |   |   |
|                         | <1             | 1-5 | 5-10 | >10 |
| **Endemic fish species** |                |   |   |   |   |
| Telmatherina antoniae   | √              | √  | √   | √   | [13, 14] |
| (spawning & non spawning site) |            |   |   |   |   |
| T. sarasinorum          | √              | √  |     |     | [13]   |
| (spawning site)         |                |   |   |   |   |
| T. wahjui               | √              | √  |     |     | [13]   |
| (spawning site)         |                |   |   |   |   |
| T. “white lip”          | √              | √  |     |     | [13]   |
| (spawning site)         |                |   |   |   |   |
| T. abendanoni, T. opudi, T. sarasinorum, T. wahjui, T. sp”elongated”, T. sp “thick lip” (non spawning site) | √ |   |     |     | [19] |
| Glossogobius metanensis | √              | √  |     |     | [7, 26] |
| Egg found at 0.8 m depth |                |   |   |   |   |
| **Shrimp**              |                |   |   |   |   |
| Caridina dennerli       | √              | √  |     |     | [10]   |
| Caridina loehae         | √              | √  |     |     | [10]   |
| Caridina parvula        | √              |     |     |     | [10]   |
| **Mollusc**             |                |   |   |   |   |
| Tylomelania zeamais     | √              | √ (mostly 2m) | |     | [12]   |
| **Invasive species**    |                |   |   |   |   |
| Louhan                  | √              | √  |     |     | [7]    |
|
Endemic fish species (*Telmatherina* spp.) lives in shallow area within water depth of <1 - 20 m. Endemic goby *Glosogobius matanensis* lives in the water depth ranges from < 0.8 - > 25m. Invasive fish species (Louhan) occupies wider area (<1 to >10 m) compared to most endemic species, except *Telmatherina antoniae* which they both share living space at a relatively same depth (table 1). Littoral area of Lake Matano is also important for spawning of some endemic species. *Telmaterina sarasinorum* generally spawns at area within water depth of 0.30- 0.75 m (table 1).

*Telmatherina* spp. could be found in a clear water with soft and hard substrate such as plant, sand, root of plant, aquatic plant and gravel, rock, cobble (table 2). Other endemic biota also lives on the soft substrate such as aquatic plant, leaf litter, and root of riparian vegetation. Besides shrimps, crabs were observed feed on detritus [11]. That indicates that riparian vegetation in sub catchment area has important function for sustainability of endemic species in Lake Matano. Riparian vegetation supplies energy in the form of leaf litter and other organic debris to fuel the aquatic food webs [27]. Well-developed terrestrial vegetation provides relatively large inputs of organic material to lakes [28]. Lake Matano is an oligotrophic lake, hence, biological community is largely depending on input of allochthonous carbon as the autotrophic production is limited [29]. Louhan also inhabits lake bed with various substrates, both hard and soft substrate. The occurrence of Louhan in the same habitat of endemic species causes a space competition.

Moreover, endemic biota and Louhan have the same food preferences (table 3). Even, Louhan preys on the endemic fish and *Glosogobius matanensis* eggs [19]. It shows that Louhan is a serious threat to the sustainability of endemic species population in Lake Matano.

| Species | Hard substrate | Sand, Mud | Soft Substrate | Aquatic Plant | Riparian Vegetation | Bivalve Shell | Ref. |
|---------|----------------|-----------|----------------|--------------|---------------------|---------------|------|
| **Endemic Fish Species** | | | | | | | |
| *Telmatherina antoniae* (spawning site and non spawning site) | √ | | | | | [13, 19] |
| *T. sarasinorum* (spawning site) | √ | √ | | | | [13] |
| *T. wahjui* (spawning site) | √ | | | | | [13] |
| *T. “whitelips”* (spawning site) | √ | | | | | [13] |
| *T. prognatha* | | | | | | [19] |
| **Shrimp** | | | | | | | |
| *Caridina dennerli* | √ | | | | | [10] |
| *Caridina holthuisi* | | √ | | | | [10] |
| *Caridina lanceolata* | | √ | | | | [10] |
| *Caridina lochae* | | √ | | | | [10] |
| *Caridina masapi* | | | | | | [10] |
| *Caridina parvula* | | | | | | [10] |
| **Mollusk** | | | | | | | |
| *Tylomelania zeamais* | | | | | | [12] |
| *T. gemmifera* | | | | | | [12] |
| *T. matannensis* | | | | | | [12] |
| **Invasive Fish species.** | | | | | | | |
| Louhan | | | | | | [7] |
Table 3. Matrix of food items of endemic biota and Louhan.

| Species                      | Fish | Fish egg | Insect | Mollusc | Shrimp | Detritus | Zooplankton | Periphyton | Crab | Ref. |
|------------------------------|------|----------|--------|---------|--------|----------|-------------|------------|------|------|
| **Endemic Fish species**     |      |          |        |         |        |          |             |            |      |      |
| *Telmatherina antoniae*      | ✔    | ✔        | ✔      | ✔       | ✔      | ❌        |             |            |      | [19] |
| *T. prognatha*               | ✔    | ✔        | ✔      | ✔       | ✔      | ❌        |             |            |      | [19] |
| *T. sarasinorum*             | ✔    | ✔        | ✔      | ✔       | ✔      | ❌        |             |            |      | [15, 20] |
| *T. abendanoni, T. opudi, T. sarasinorum, T. wahjui,* | ✔ | ✔ | ✔ | ✔ | ✔ | ❌ |             |            |      | [21] |
| *T. sp “elongated”, T. sp “thicklip”* | ✔ | ✔ | ✔ | ✔ | ✔ | ❌ |             |            |      |      |
| **Shrimp**                   |      |          |        |         |        |          |             |            |      |      |
| *Caridina spp.*              | ✔    | ✔        | ✔      |         |        |          |             |            |      | [22] |
| **Crab**                     |      |          |        |         |        |          |             |            |      |      |
| *Syntripsa matannensis*      | ✔    |          | ✔      |         |        |          |             |            |      | [11] |
| *Nautilothelpusa zimmeri*    |      |          | ✔      |         |        |          |             |            |      | [4]  |
| **Invasive Fish species**    |      |          |        |         |        |          |             |            |      |      |
| *Louhan*                     | ✔    | ✔        | ✔      | ✔       | ✔      | ✔        |             | ✔          |      | [7]  |
3.2. Littoral Zone of Lake Matano and Habitat Area for Biota
Lake Matano surface area is 20,177 ha which consists of sub system of littoral and pelagic zone (figure 2). Steep slope of lake is found in the northern part and middle of southern part of the lake (figure 3). By setting the habitat of most of endemic biota is up to 20 m depth (table 1) and assuming Secchi depth is 15 m, littoral zone of Lake Matano can be calculated as 3,491 Ha. The littoral zone of Lake Matano is found in different slope. The biggest part is at slope 0-5° with 3000 ha in size and less than 500 ha is located at slope up to 20° (figure 4).

![Figure 2](image2.png)

**Figure 2.** Distribution of bottom elevation of Lake Matano.

![Figure 3](image3.png)

**Figure 3.** The distribution of bottom slope of Lake Matano.
The area of habitat for endemic species is only 17 % of the total lake surface area. The rest, 83 % is a pelagic zone (figure 5). Directly connected to the terrestrial system, this small size of habitat area for endemic biota might be more vulnerable to anthropogenic activities.

3.3. Lake Matano Sedimentation
The spatial distribution of total suspended solid (TSS) input from inlets of Lake Matano generated by a 2D numerical model is presented (figure 6). It shows that sediment accumulation occurred in littoral zone. In some areas of littoral zone, concentration of TSS has exceeded 0.13 mg.L$^{-1}$ (figure 6). Consequently, light penetration has become less than 15 m and sediment has covered the bottom of substrate. As discussed before, the narrow littoral zone of Lake Matano is habitat for most endemic biota, particularly for spawning ground or nursery ground. Previous studies have shown that sedimentation has been affecting aquatic biota negatively in some ways. For example, raising sediment level has disturbed the spawning of tricolor shiner (Cyprinella trichroistia), particularly in laying eggs [30]. Experimental study conducted by [31] showed that turbid water could reduce foraging success within trout population, likewise within rosyside dace (Clinostomus funduloides) [32]. On the other hand, the invasive Louhan could still be tolerant to high turbidity [32].
Under 25 kg day$^{-1}$ of sediment loads scenario, total suspended solid in several littoral zones would reach ~0.13 mg L$^{-1}$. Through this simulation, in order to sustain the littoral zone for the aquatic fauna habitat, load of sediment from a subset of sub catchment area should be ≤ 25 kg day$^{-1}$ (figure 7).

Our study demonstrated that littoral zone is an important habitat for endemic aquatic fauna (e.g. fish, shrimp, mollusc) of Lake Matano. High load of sediments from the adjacent catchment may threaten those vulnerable species. The existence of invasive species in Lake Matano has brought...
another threat to the endemic species. Through this study we recommend three technical measures to sustain Lake Matano biodiversity: 1) reducing sediment load to ≤ 25 kg.day⁻¹; 2) eradicate Louhan population such as by applying intensive catch, and 3) maintain riparian vegetation.

4. References

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