Assessment of pollution status and spatial-temporal distribution of physico-chemical parameters using the STORET index and GIS methods in Lake Laut Tawar, Aceh, Indonesia

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Abstract. Lake Laut Tawar (LLT) is the largest freshwater lake in the Aceh Province, and its water quality is affected by the influx of waste and pollution. The objective of this study was to assess the water quality of LLT, which is significantly affected by anthropogenic activity. Water samples were collected at nine sampling points within the lake during both the dry and wet seasons. Twelve physico-chemical parameters were analyzed: water transparency, temperature, total dissolved solids, total suspended solids, pH, dissolved oxygen, biochemical oxygen demand, chemical oxygen demand, nitrate, total phosphorus, nitrite, and ammonia. The parameters were estimated using the Indonesian National Standard Protocol (SNI 6989.57-2008). Water pollution status was determined using the Storage and Retrieval (STORET) method based on the US EPA grading system. Water quality distribution maps were used to obtain a detailed understanding of the distribution patterns of physico-chemical parameters of the lake. Spatiotemporal distribution maps were created using ArcGIS software, employing inverse distance-weighted (IDW) interpolation of the mean values of physico-chemical parameters across all hydrological seasons. Temporal changes in physico-chemical parameters indicate better water quality during the dry season. The spatiotemporal distribution map revealed that discharge from residential areas, fish farming in floating net cages, and conversion of rice fields were the primary sources of water pollution in the study area. The water quality status of LLT, at the studied sampling locations, falls under the category of severe pollution (STORET index -56) according to class I water quality standards, and in the moderate pollution category (STORET index -28 and -20) according to class II and III water quality standards. The results from the evaluations of water quality and IDW analysis helped identify key areas requiring control in LLT, highlighting the need for better lake management.

Key Words: physico-chemical, STORET, GIS, IDW, spatio-temporal.

Introduction. Lake water quality is an important aspect of the environment that affects the health and well-being of humans and aquatic life. Despite efforts to improve lake water quality, many lakes are affected by various factors, including pollution, climate change, and human activity (Stefanidis et al 2016; Hampton et al 2018; Plisnier et al 2018; Woolway et al 2020; Yuan et al 2023). Some of the most common factors affecting lake water quality are pollution, eutrophication, sedimentation, invasive species, and climate change (Bhateria & Jain 2016; Goshu & Aynalem 2017; Small 2017; Purmalis et al 2021). In addition, pollution in lakes has an important influence on the environment and survival of aquatic organisms (Adejumoke et al 2018; Malik et al 2020). The increase in the endangered status of the depik fish species *Rasbora tawarensis* is partly due to the decline in water quality caused by pollution (Muchlisin et al 2018).

The level of community dependence on Lake Laut Tawar (LLT) was very high. Lake water, provided by a regional drinking water company, is a source of raw drinking water for communities (Muchlisin et al 2018; Zamzami et al 2018) and a source of irrigation for agricultural activities and plantations in the catchment area (Adhar et al 2023). In addition, the lake's outlet flow to Krueng Peusangan is a source of energy that drives the turbines of the Peusangan Hydroelectric Power Plant (PLTA). The complexity of lake water utilization affects ecological, social, economic, health, aesthetic, and energy conditions. It is important to protect the aquatic ecosystem of LLT because pressure on the lake ecosystem can negatively affect the lives of the surrounding population.

Increasing anthropogenic activities in catchment areas threaten the sustainability of LLT ecosystems. This threat arises from the increasing population in catchment areas, which leads to increased water use (Bao & Fang 2012; Bhateria & Jain 2016). Agricultural activities, in the form of plantations covering 4,576 ha (24.24%) and rice fields covering 1,061 ha, are sources of pollution in lake waters (Adhar 2021). Similarly, the activities of floating net cages in water bodies have reduced the water quality in LLT because of excess feed (Iriadi et al 2015a; Adhar et al 2021). Tourism activities have also contributed to the decline in water quality owing to the increasing number of tourists (Iriadi et al 2015b). This affects the level of water pollution in LLT. The resulting water pollution poses risks to aquatic ecosystems, human health, and productivity (UNEP 2016).

The pollution status of LLT is based on the Water Quality Index (WQI). The WQI was first proposed by Horton (1965) and Brown et al (1970). Subsequently, several authors have developed different methods for calculating the WQI (Debels et al 2005; Saeedi et al 2009; Tsegaye et al 2006). WQI is a measure of the overall quality of a water body that considers the quality standards of various water quality parameters, according to its designation. This index provides a numerical value that represents the water quality level (Bordalo et al 2006; Sánchez et al 2007). This method was used by Sutadian et al (2018) as the simplest and most promising method and has been improved and further developed by various institutions and researchers (Li et al 2019). Ewaid et al (2020) developed WQI to assess river water quality in Iraq. Lobato et al (2015) and Quevedo-Castro et al (2018) formulated a new WQI standard based on the hydrological cycle when evaluating water quality in reservoir areas. Kangabam et al (2017) generated WQIs for specific lake waters, while Sim & Tai (2018) and Sutadian et al (2018) generated WQIs for tropical rivers in Malaysia and West Java, Indonesia.

In Indonesia, the method for determining lake water quality generally adopts the Storage and Retrieval (STORET) method, which compares water quality data with water quality standards adjusted to the water class and designation. Since 2021, the quality standards for lake water quality parameters refer to the implementation of Government Regulation No. 22 of 2021 concerning the Implementation of Environmental Protection and Management, as an update of Government Regulation No. 82 of 2001 concerning water quality management and water pollution control. The most fundamental difference from the implementation of Government Regulation No. 22 of 2021 lies in the division of quality standards based on the type of water, namely, rivers and lakes, which were not determined in the previous regulation. The implementation of Government Regulation No. 22 of 2021 has been adopted to evaluate river water quality (Yustiani et al 2021; Soeprobowati & Jumari 2022; Tanjung et al 2022; Herawati 2023), lake pollution status (Suhartawan et al 2022; Khalik et al 2023), reservoir water quality status analysis (Iraguha et al 2022) and estuarine pollution index (Hidayah et al 2021).

Extensive in situ environmental monitoring of LLT water has also been conducted. Iriadi et al (2015b) calculated the LLT water pollution load. Kartamihardja et al (2017) monitored limnological aspects and potential fish production. Biological factors and conditions of endemic fish in Muchlisin et al (2018) and Fahma et al (2022) and an ecosystem approach to endemic fish conservation (Kamal et al 2021). Adhar et al (2020) estimated fish production potential using the morphological index approach. Adhar et al (2021) and Adhar et al (2023) also reported on the assessment of water brightness and total suspended solids distribution in LLT. Although the in situ sampling technique is quite accurate, it is time-consuming to analyze the data. In situ measurements are often limited to selected sampling points, resulting in spatial and temporal constraints for broad-scale assessments and monitoring of lake water quality (Asmat et al 2018; Usali & Ismail 2010). Traditional methods cannot reveal the spatial heterogeneity of lake water (Chu et al 2018). Monitoring techniques using Geographic Information System (GIS) approaches are needed to manage water pollution incidents that may occur so that effective countermeasures can be formulated (Asmat et al 2018). The use of GIS interpolation methods helps to understand the extent, pattern, distribution, and risk assessment of diffuse pollution (Oke et al 2013). The most commonly used GIS interpolation method is inverse distance weighting (IDW) (Ajaj et al 2018). The development of water quality monitoring methods using GIS interpolation may be useful for identifying areas with potential pollution stress.

The main objectives of this study were (i) to assess the physico-chemical properties of LLT water by taking water samples in two different seasons and testing the water quality parameters; (ii) to represent the spatiotemporal variation of these parameters using the IDW method and GIS-based overlay analysis; and (iii) to assess the pollution status of LLT from the perspective of physico-chemical parameters using the STORET index, which refers to the application of the latest water quality standards for lake waters in Indonesia. To date, no study used GIS interpolation techniques to assess spatiotemporal water quality parameters in LLT. Up-to-date assessments and information on the status of water pollution can help in the investigation of areas most vulnerable to pollution, minimize the impact on organisms and people's lives that depend on these water resources, and provide important information for determining policies for the proper use and management of lake water.

Material and Method

Description of the study sites. LLT is located in Central Aceh Regency, Aceh Province, Indonesia. The geographical location of the LLT is 4°34'46"-4°38'34" N, 96°51'25"-96°59'48" E, with an altitude of 1,230 m (Adhar et al 2023). LLT has a water area of 5,862 ha and is classified as a medium-sized lake by area (Jorgensen et al 2013), with an average depth of 25.19 m and a maximum depth of 84.23 m (Husnah & Fahmi 2015). The catchment area of LLT is 18,922.07 ha, with 7 types of land use: forests, plantations, settlements, livestock, rice fields, hunting parks, and agriculture (GIS Analysis 2023). LLT has 17 river inlets and tributaries with water discharge varying between 0.04-1.44 m^3 s^{-1} with a total discharge of 8.80 m^3 s^{-1} (Husnah et al 2013; Iriadi et al 2015b) and only 1 outlet, the Peusangan River with a discharge of m^3 s^{-1} (Iriadi et al 2015b). Administratively, LLT is directly adjacent to the sub-districts of Bebesan (in the west), Kebayakan (in the north), Bintang (in the east) and Lut Tawar (in the south) (Government of Central Aceh 2019).

This study was conducted in June and September 2021 in LLT waters, representing seasonal variations. Sampling in June was performed for the dry season, and September for the rainy season. The observed physico-chemical parameters included water transparency, temperature, total dissolved solids, total suspended solids, pH, dissolved oxygen, biological oxygen demand, chemical oxygen demand, nitrate, phosphate, nitrite, and ammonia. The observation stations were determined by purposive sampling based on the criteria of land use in the catchment area, location of the inlets where the water flows into the lake, and representative locations for the lake activity (Figure 1). The coordinates and characteristics of each observation station are listed in Table 1.

Table 1

Identification of sampling sites with their geo-coordinates in LLT

Station	*Latitude*	*Longitude*	*Characteristics of sites*
Station 1	4°38'03.410"	96°51'45.260"	The sub-catchment area dominated by residential land use
Station 2	4°37'40.200"	96°56'52.740"	The water source from spring
Station 3	4°37'05.240"	96°55'21.990"	The center area of lake
Station 4	4°37'11.000"	96°57'58.000"	The sub-catchment area is dominated by tourism facilities
Station 5	4°35'15.700"	96°59'30.970"	The sub-catchment area is dominated by rice fields and tourism activities
Station 6	4°34'58.710"	96°58'17.850"	The sub-catchments are dominated by forests and plantations

Station	Latitude	Longitude	Characteristics of sites
Station 7	4°36'24.970"	96°53'32.850"	The sub-catchments are dominated by forests and agriculture
Station 8	4°36'40.630"	96°52'01.030"	The floating net cage area
Station 9	4°37'04.070"	96°51'07.240"	Outlet lake to Peusangan River

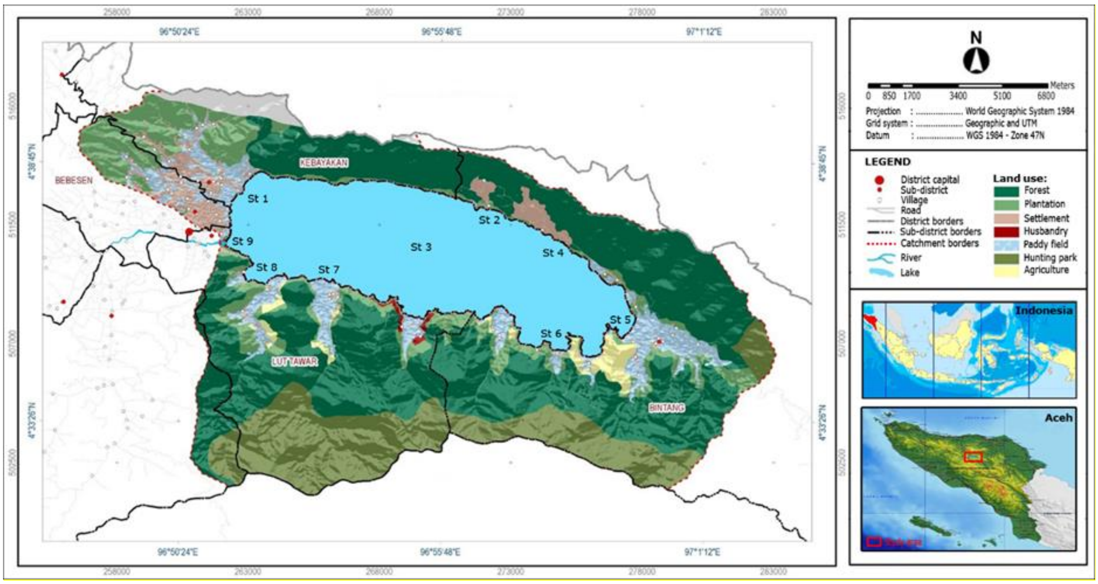

Figure 1. The map of study area.

Measurement and analysis. Water sampling was conducted at each sampling station in accordance with the Indonesian National Standard (SNI 6989.57-2008) for surface water sampling. Water quality parameters, such as water transparency, temperature, pH, and dissolved oxygen, were measured directly in the field, whereas biochemical oxygen demand (BOD), chemical oxygen demand (COD), nitrate, nitrite, total phosphorus, and ammonia were measured using water samples for further analysis at the Environmental Laboratory of the Central Aceh District Environmental Office. Water sampling was conducted at two depth strata (i.e., surface and middle) in the morning using a 5 L capacity Kemmerer water sampler and combined (depth composite). Water samples were collected in two containers: 1) clean plastic bottles with 500 mL capacity (without preservatives) for total suspended solids (TSS) and total dissolved solids (TDS) parameters, and 2) clean plastic bottles with 1,000 mL capacity for BOD, COD, nitrate, nitrite, total phosphorus, and ammonia (stored in a cool box at 4°C). The values of the water quality parameters were compared with the water quality criteria in the Government Regulation No. 22 of 2021 on the Implementation of Environmental Protection and Management, replacing the revoked Government Regulation No. 82 of 2001.

The spatial distribution pattern of water physico-chemical parameters in the LLT was determined using a geospatial approach with GIS applications. The data processing software used was the ArcGIS Desktop 10.8 Ver. 10.7.0.10450 using the IDW method, which is a raster data-point interpolation technique. The IDW method is a common GIS technique that is widely used for variable mapping (Ajaj et al 2018; Khouni et al 2021). This method was used to predict the values at unmeasured locations by measuring the values near the predicted locations (Childs 2004; Yasser et al 2017; Khouni et al 2021). Predetermined points were used to calculate the weighted average of the unknown points (Ke et al 2011; Dale & Fortin 2014). IDW interpolation was calculated as a function of the distance between the observed sample position and the position at which the prediction was determined (Sallam & Elsayed 2018). The IDW technique is mathematical (deterministic) and assumes that values closer to a function are more correlated than those farther from it (Chum et al 2017; Asmat et al 2018).

The general equation for IDW interpolation is $\hat{Z}(S_o) = \sum_{i=1}^{N} \lambda_i Z(S_i)$, where $\hat{Z}(S_o)$ is the predicted value of location. N is the number of sample points measured around the prediction location and is used in the prediction. **λ**i is the weight assigned to each measurement point. The weight decreased with increasing distance. $Z(S_i)$ is the observed value at location (S_o) (Tomislav 2009; Effendi & Wardiatno 2015; Chum et al 2017; Khouni et al 2021). IDW analysis uses a spatial analysis tool under the arc toolbox in the Arc Map (Shivakrishna et al 2020). Figure 2 shows the GIS interpolation procedure using the IDW method.

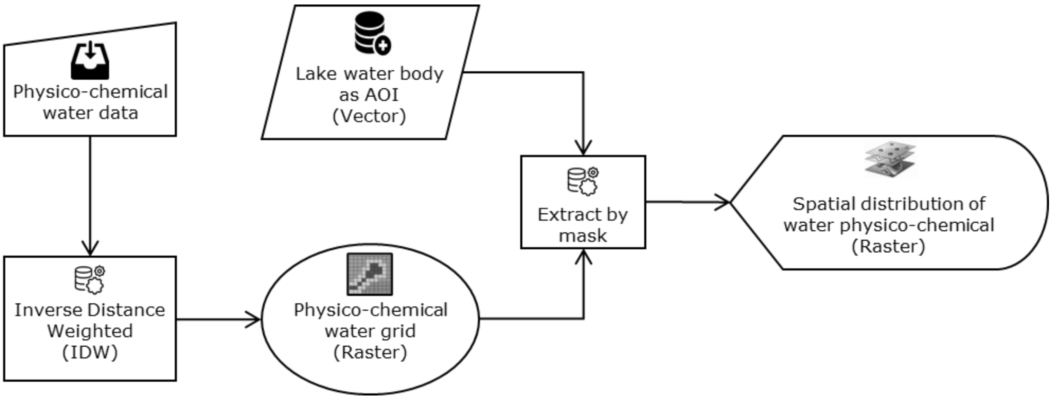

Figure 2. GIS mapping procedure with IDW interpolation.

The lake shape vector file with sampling point positions represents the area of interest (AOI) of the study area. All measurement points (average water physico-chemical value data) were used to calculate each interpolated cell (sampling point). A feature dataset (lake water) was used as the mask. Only cells whose feature dataset had a specific shape- (lake water) received the first input raster value (sample points) from the output raster (average water physico-chemical value results). The output raster is an extraction of the cells of the average water physico-chemical values (input raster) corresponding to the shape specified by the mask (Figure 2). The range of the distribution data for each physico-chemical water parameter was adopted from the natural break classification method (Feizizadeh & Blaschke 2013; Mushtaq et al 2015; Kindie et al 2019). The natural break (or Jenks optimization) classification method used in this study groups values into classes, resulting in classes of similar values separated by break points (Feizizadeh & Blaschke 2013).

The determination of the water pollution status of LLK using the Storage and Retrieval (STORET) method refers to the Decree of the Minister of Environment No. 115 of 2003 concerning the Guidelines for Determining Water Quality Status (Soeprobowati 2017). In Indonesia, the STORET method is a popular water quality status determination technique based on the United States Environmental Protection Agency (US EPA) grading system, which classifies water quality into four grades (http://www.epa.gov/store/) (Table 2).

Table 2

Classification of Water quality from the USEPA value system

Score	*Class*	*Characteristics of water quality*
0	A	Meet the quality standard
-1 to -10	B	Lightly polluted
-11 to -30	C	Moderately polluted
≥-31	D	Highly polluted

The determination of LLT water pollution status using the STORET method begins with the periodic collection of water quality data based on the representation of the dry (June) and rainy (September) seasons. The measurement data for each water quality parameter were compared with the quality standard values according to the water class. A value of 0 was assigned to each parameter that met the water quality standard (actual measurement < water quality standard). If the measurement results did not meet the water quality standards (measurement results > water quality standards), the score is given in Table 3. The negative sum of all parameters was calculated, and the pollution status was determined from the total score obtained using the specified scoring system.

Table 3
Parameter scoring of water quality (Ministry of Environment Republic of Indonesia No. 115/2003)

Number of samples	*Value*	*Parameters*		
		Physical	*Chemical*	*Biological*
< 10	Maximum	-1	-2	-3
	Minimum	-1	-2	-3
	Average	-3	-6	-9
≥ 10	Maximum	-2	-4	-6
	Minimum	-2	-4	-6
	Average	-6	-12	-18

Results

Monitoring physico-chemical parameters. The physico-chemical parameters measured in this study were water transparency, temperature, TDS, TSS, pH, DO, BOD, COD, nitrate, total phosphorus, nitrite, and ammonia. The physico-chemical parameters estimated from the nine selected sampling sites in the LLT varied from the dry to the wet season. The results of dry season and wet season water quality parameters from nine sampling stations are presented in Tables 4 and 5. LLT water transparency ranged from 2.53 m to 4.32 m during the dry season and from 1.67 to 3.68 m during the wet season. These measurement results are not different from the to 2016-2017 measurements, which ranged from 1.40 to 4.40 m (Adhar et al 2021). The LLT water transparency in the dry season was brighter than that in the wet season. Decreased rainfall around the lake catchment area during the dry season causes water to flow through the inlet to the lake, which tends to be more stable and reduced, thereby reducing the concentrations of suspended and dissolved particles in the water. Seasonal differences and rainfall intensity affect the stirring process of particles in water, thereby affecting the transparency of lake water (Elvince & Kembarawati 2021). In addition to season and rainfall, the transparency of LLT water bodies is influenced by phytoplankton abundance. An increase in phytoplankton biomass reduces the brightness of lake water (Adhar et al 2021).

Water temperature is a fundamental physical property that describes the nature of surface water and directly affects the flora and fauna of aquatic ecosystems (Jurgelenaite et al 2012). Temperature plays an important role in the metabolic activities of organisms (Mushtaq et al 2020) and affects the growth, reproduction, and disease immunity of aquatic organisms (Ujianti et al 2018; Bhateria & Jain 2016). The temperature parameters of the water samples in the study area were measured between 22.24°C to 25.95°C during the dry season and 21.90°C to 25.60°C during the wet season. These measurement results are not very different from the results of previous years' monitoring between 21.9°C and 25.6°C (Iriadi 2015b; Sari et al 2019; Setiawati et al 2020). The highest average temperature was found at Station 1 (residential area) and the lowest at Station 3 (middle of the lake). These results indicate that the water temperature in LLT still meets the water quality standards according to Government Regulation of the Republic of Indonesia No. 22 of 2021 and still supports the habitat of depik endemic fish, which is 18.0°C to 22.0°C (Muchlisin & Hasri 2015).Total dissolved solids (TDS) are very small particles dissolved in a true solution, consisting of organic and inorganic matter including living organisms, detritus, soil particles, calcium, salts, minerals, and metals that can pass through a 2 μm filter (Boyd 2014; Rice et al 2012). TDS concentrations in LLT waters varied from 45.06 to 75.26 mg L^{-1} during the dry season and from 54.15 to 125.09 mg L^{-1} during the wet season. The highest average TDS concentration was observed at Station 5, which is thought to be related to the conversion of rice fields into tourist attractions and inns. However, the TDS concentration of LLT waters is still below the maximum limit of class I, II, and III water quality standards based on the Government Regulation of the Republic of Indonesia No. 22 of 2021, which is 1,000 mg L^{-1}.

Table 4

Results of water quality measurements during the dry season at Lake Laut Tawar

Sampling stations	*Water transparency (m)*	*Temp. (^0C)*	*TDS ($mg\ L^{-1}$)*	*TSS ($mg\ L^{-1}$)*	*pH*	*DO ($mg\ L^{-1}$)*	*BOD ($mg\ L^{-1}$)*	*COD ($mg\ L^{-1}$)*	*Nitrate ($mg\ L^{-1}$)*	*Total phosphorus ($mg\ L^{-1}$)*	*Nitrite ($mg\ L^{-1}$)*	*Ammonia ($mg\ L^{-1}$)*
Station 1	2.98±0.23	25.95±0.13	73.1±7.3	18.93±3.18	7.82±0.21	5.12±0.10	0.92±0.25	14.12±0.55	0.624±0.040	0.199±0.012	0.0072±0.0005	0.073±0.006
Station 2	3.63±0.24	22.24±0.13	45.98±3.12	15.72±0.75	7.58±0.25	6.69±0.46	0.30±0.47	15.88±2.18	0.665±0.003	0.171±0.022	0.0041±0.0004	0.020±0.002
Station 3	4.32±0.23	22.29±0.10	45.06±3.22	10.0±0.56	8.43±0.05	6.65±0.48	0.33±0.46	16.29±1.96	0.443±0.073	0.181±0.019	0.0041±0.0005	0.019±0.002
Station 4	3.59±0.23	23.58±0.03	50.87±1.43	15.87±0.76	8.38±0.03	5.52±0.29	0.41±0.16	12.27±4.89	0.602±0.013	0.240±0.016	0.0080±0.0007	0.026±0.019
Station 5	2.53±0.31	23.67±0.03	75.26±17.63	26.82±25.28	8.09±0.10	5.61±0.13	1.26±0.21	12.02±0.34	0.598±0.004	0.236±0.007	0.0103±0.0003	0.058±0.007
Station 6	4.10±0.24	22.86±0.10	48.89±2.13	13.18±1.71	7.80±0.18	6.16±0.03	0.32±0.42	10.44±3.61	0.628±0.004	0.177±0.022	0.0053±0.0002	0.031±0.003
Station 7	3.52±0.16	24.16±0.06	48.02±2.48	10.64±3.19	7.79±0.20	6.16±0.34	0.30±0.01	10.41±3.75	0.630±0.004	0.171±0.003	0.0053±0.0005	0.008±0.001
Station 8	3.17±0.31	24.65±0.05	53.51±7.34	18.91±3.64	8.10±0.07	5.11±0.02	1.65±0.37	10.45±2.60	0.681±0.011	0.288±0.008	0.0116±0.0003	0.059±0.003
Station 9	3.34±0.33	23.73±0.01	54.88±10.72	19.2±3.91	8.30±0.03	5.70±0.12	1.10±0.19	11.75±0.32	0.643±0.023	0.213±0.009	0.0072±0.0005	0.101±0.004
Min	2.53	22.24	45.06	10.00	7.58	5.11	0.30	10.41	0.443	0.171	0.004	0.008
Max	4.32	25.95	75.26	26.82	8.43	6.69	1.65	16.29	0.681	0.288	0.012	0.101
Aver.	3.46	23.68	55.06	16.59	8.03	5.86	0.73	12.63	0.613	0.208	0.007	0.044
Stdev	0.55	1.17	11.31	5.17	0.30	0.59	0.51	2.29	0.069	0.040	0.003	0.031

Table 5

Results of water quality measurements during the wet season at Lake Laut Tawar

Sampling stations	*Water transparency (m)*	*Temp. (^0C)*	*TDS ($mg\ L^{-1}$)*	*TSS ($mg\ L^{-1}$)*	*pH*	*DO ($mg\ L^{-1}$)*	*BOD ($mg\ L^{-1}$)*	*COD ($mg\ L^{-1}$)*	*Nitrate ($mg\ L^{-1}$)*	*Total phosphorus ($mg\ L^{-1}$)*	*Nitrite ($mg\ L^{-1}$)*	*Ammonia ($mg\ L^{-1}$)*
Station 1	2.33±0.24	25.60±0.13	93.74±7.30	27.92±3.19	8.41±0.22	5.41±0.11	1.60±0.25	12.59±0.54	0.513±0.040	0.231±0.012	0.0085±0.0005	0.089±0.006
Station 2	2.97±0.24	21.90±0.13	54.79±3.12	17.84±0.75	8.27±0.25	7.97±0.46	1.62±0.47	22.01±2.17	0.657±0.003	0.231±0.022	0.0052±0.0004	0.025±0.002
Station 3	3.68±0.23	22.00±0.11	54.15±3.22	11.57±0.56	8.28±0.06	7.99±0.48	1.60±0.45	21.82±1.96	0.648±0.073	0.232±0.019	0.0053±0.0005	0.023±0.002
Station 4	2.96±0.22	23.50±0.03	54.91±1.43	18.01±0.76	8.30±0.03	6.31±0.28	0.85±0.16	26.09±4.89	0.638±0.013	0.197±0.016	0.0063±0.0007	0.078±0.019
Station 5	1.67±0.31	23.60±0.03	125.09±17.62	98.29±25.27	8.37±0.10	5.28±0.12	1.83±0.20	12.97±0.34	0.608±0.004	0.253±0.007	0.0109±0.0003	0.075±0.007
Station 6	3.44±0.24	22.60±0.10	54.90±2.13	18.00±1.71	8.30±0.18	6.11±0.02	1.50±0.42	20.65±3.62	0.639±0.004	0.237±0.022	0.0057±0.0002	0.025±0.003
Station 7	3.08±0.16	24.00±0.06	55.03±2.49	19.65±3.19	8.34±0.20	7.11±0.34	0.32±0.01	21.02±3.76	0.619±0.004	0.177±0.003	0.0065±0.0005	0.006±0.001
Station 8	2.32±0.30	24.50±0.06	74.25±7.34	29.19±3.64	8.28±0.07	5.15±0.02	2.67±0.37	17.79±2.60	0.652±0.011	0.309±0.008	0.0123±0.0003	0.065±0.003
Station 9	2.41±0.34	23.71±0.01	85.20±10.72	30.25±3.92	8.39±0.04	6.01±0.11	0.57±0.20	10.85±0.32	0.578±0.023	0.188±0.009	0.0059±0.0005	0.090±0.004
Min	1.67	21.90	54.15	11.57	8.27	5.15	0.32	10.85	0.513	0.177	0.005	0.006
Max	3.68	25.60	125.09	98.29	8.41	7.99	2.67	26.09	0.657	0.309	0.012	0.090
Aver.	2.76	23.49	72.45	30.08	8.33	6.37	1.40	18.42	0.617	0.228	0.007	0.053
Stdev	0.63	1.19	24.89	26.34	0.05	1.09	0.72	5.20	0.046	0.039	0.003	0.033

TSS are materials suspended in the water column, >1 μm in diameter, consisting of silt, fine sand, and microorganisms (Boyd 2014), and are organic and inorganic substances retained by filters with pore sizes ≤2 μm (Rice et al 2012). They cause turbidity, block light from entering the water column (Adhar et al 2021), are insoluble, and are unable to settle directly at the bottom of the water (Iriadi 2015b). TSS concentrations in LLT waters ranged from 10.00 to 26.82 mg L^{-1} during the dry season and 11.57 to 98.29 mg L^{-1} during the wet season. The highest and lowest concentrations were recorded during the wet and dry seasons, respectively. High TSS concentrations were related to increased rainfall intensity in the catchment area, which affected the loading of the river flow carrying organic and inorganic particles into the lake.

In general, TSS concentrations in LLT waters are still below the water quality standards for classes I, II, and III, as regulated in the Government Regulation of the Republic of Indonesia No. 22 of 2021, except at Station 5, which has exceeded the water quality standards for class I (25 mg L^{-1}) and class II (50 mg L^{-1}), but is still below the water quality standards for class III (100 mg L^{-1}). Based on visual observations, the water at Station 5 was brown with high turbidity because of the conversion of paddy fields into tourist attraction sites and the construction of lodges. Suspended solids (TSS) are positively correlated with turbidity (Kant et al 2016) and affect water color and clarity (Boyd 2014). High concentrations of TSS are particularly sensitive to plankton, periphyton, and benthic invertebrates, ultimately disrupting food webs (Chapman et al 2017).

LLT waters are alkaline, with hydrogen ion activity (pH) values ranging from 7.58 to 8.43 in the dry season and 8.27 to 8.41 in the wet season. The pH value of LLT waters is relatively stable, not much different from previous years' measurements, between 7.0 and 8.9 (Husnah et al 2013; Iriadi 2015b; Gayosia et al 2015; Sari et al 2019; Setiawati et al 2020) and still meets the quality standards based on the Government Regulation of the Republic of Indonesia No. 22 of 2021. There was no significant difference in pH with seasonal variation. The horizontal distribution of pH in LLT increased with depth. Although natural, vertical changes in pH decreased with depth. However, the dominance of bottom sediment types in the form of hard substrates in the middle of the lake is thought to affect the solubility of carbonates, thereby increasing the pH of the water (Husnah et al 2013). Composite water sampling, which causes variations in pH values, does not represent the depth of the water.

According to Kant et al (2016), a pH value from 7.0 to 8.7 is ideal for supporting aquatic life. Freshwater fish have a pH between 6.8 and 8.5 (Kulla et al 2020), and the pH range from 6.8 to 7.3 is very suitable to support the growth of depik endemic fish in LLT (Saputri et al 2019). In closed water bodies, such as lakes, it is very important to maintain a stable pH because it affects the growth of aquatic organisms, availability of P in water, and toxicity of ammonia and H_2S in water (Gayosia et al 2015). Acidic (<5) and alkaline (>11) conditions can cause fish death (Kulla et al 2020).

DO is available in the water during photosynthesis and during the diffusion of air in direct contact with the water surface. Dissolved oxygen measurements in the study area varied from 5.11 to 6.69 mg L^{-1} during the dry season and 5.15 to 7.99 mg L^{-1} during the wet season. In general, the average DO concentration during the dry season was below the Class I water quality standard with a minimum DO limit of 6 mgL^{-1}, but still met the Class II and Class III water quality standards with minimum limits of 4 and 3 mg L^{-1}, respectively. The average DO concentration during the rainy season still met the quality standards. The DO concentration profile in LLT waters has also experienced a downward trend over the past 7 years with a range from 5.28 to 6.9 mg L^{-1} (Husnah et al 2013; Iriadi 2015b; Setiawati et al 2020). This condition is feared to suppress aquatic biota, especially depik fish, which are endemic to LLT. The DO concentration that guarantees fish life is at least 3 mg L^{-1}. DO concentrations between 5 and 6 mg L^{-1} are considered ideal for supporting the growth and development of aquatic organisms (Harlina 2021).

Three stations had DO concentrations below the water quality standard: Station 1 (dense residential area and hospital), Station 5 (rice field and tourism area), and Station 8 (floating net cage area). Domestic sewage containing biodegradable organic compounds from Station 1 was responsible for the decrease in DO because of microbial activity during decomposition (Inglezakis et al 2016). Increased land conversion activities contributed to the increase in TSS concentrations at Station 5, increasing turbidity and interfering with the penetration of sunlight into the water column, thus inhibiting photosynthesis for the supply of DO in lake waters (Sumiarsih 2021). The low DO concentration at Station 8 was attributed to the rampant activity of floating offshore net cages. Food residues deposited at the bottom of the water triggered an increase in the aerobic decomposition activities of aquatic microorganisms, resulting in a decrease in DO in the water. The same was reported by Iriadi (2015b), who found that the waters around floating net cages in LLT had a low DO concentration of 5.28 mg L^{-1}. Low DO values in lake water are generally caused by domestic waste inputs (Muthifah et al 2018), land use changes (Habib 2020), and increased activity of floating net cages (Awaliyah et al 2019).

Biochemical oxygen demand (BOD) is used as an index to determine the concentration of oxygen required by aerobic microorganisms involved in the decomposition of organic matter (Nartey et al 2012). The BOD content describes only biodegradable organic matter (Iriadi 2015b; Harlina 2021). The range of BOD values of LLT waters from 0.30 to 1.65 mg L^{-1} during the dry season and 0.32 to 2.67 mg L^{-1} during the wet season. In general, the average BOD concentration at all observation stations is still below the water quality standards for classes I, II and III based on Government Regulation of the Republic of Indonesia No. 22 of 2021, except at Station 8 (floating net cage area) which has exceeded the Class I water quality standard of 2 mg L^{-1}, but is still below the Classes II (3 mg L^{-1}) and III (6 mg L^{-1}) of the water quality standards. Referring to the monitoring results by Iriadi (2015b), the average BOD concentration around the activity of floating net cages increased by 0.33 mg L^{-1} in the last 7 years.

The deposition of feed residues from fish farming activities in floating net cages is thought to be the cause of the high BOD concentrations at this station, in addition to feces and urine. Residual feed from floating net cages containing nitrogen (N) and phosphorus (P) is also the main cause of increasing BOD concentrations in lake waters (Ardi 2013; Moraes et al 2015), and feces and urine are sources of N and P, respectively (Astuti & Krismono 2018). An increase in BOD concentration can cause a decrease in DO concentration in water (Komala et al 2019), thus endangering aquatic biota, especially LLT-endemic fish, which are highly sensitive to environmental changes.

Chemical oxygen demand (COD) values in LLT waters ranged from 10.41 to 16.29 mg L^{-1} during the dry season and 10.85 to 26.09 mg L^{-1} during the wet season. The COD concentrations obtained exceeded the Class I water quality standard of 10 mg L^{-1} at all observation stations. The COD concentrations in LLT water are higher than the BOD concentrations because the chemically degraded organic matter is greater than the biological degradation process (Saputra et al 2017). The average COD value during the rainy season was higher than that during the dry season. High rainfall causes run-off water entering the lake waters to increase, which causes stirring of the lake bottom sediments. When the bottom sediments were stirred, there was a reversal and mixing of organic matter from the bottom to the water column, which triggered an increase in the COD concentration of the water. High COD concentrations in the water column are caused by oxygen-free (anoxic) conditions that occur at the bottom of the lake water and cause slow decomposition (Piranti et al 2018).

The nitrate concentration in water is an important variable for assessing water quality, especially in freshwater (Mushtaq 2020). Nitrate is the result of the complete oxidation of nitrogen compounds in water through the Nitrobacter nitrification process, which is the main nutrient for plant and algal growth (Iriadi 2015b) and is one of the water fertility parameters that can trigger eutrophication and algal blooms (Smitha et al 2013). The range of nitrate concentrations in LLT waters was from 0.443 to 0.681 mg L^{-1} during the dry season and 0.513 to 0.657 mg L^{-1} during the wet season. There was no significant difference in nitrate concentration based on the season. The nitrate concentrations at all observation stations were still below the water quality standards based on the Government Regulation of the Republic of Indonesia No. 22 of 2021. Referring to the Regulation of the Minister of Environment of the Republic of Indonesia No. 28 of 2009, LLT waters are classified as oligotrophic waters with an average nitrate concentration ≤0.65 mg L^{-1}.

Total phosphorus (TP) is the total amount of phosphorus in water, including inorganic and organic phosphorus in particulate and dissolved forms (Rahim & Soeprobowati 2019).

The test results showed that the TP concentrations in LLT waters ranged from 0.171 to 0.288 mg L^{-1} during the dry season and tended to increase in the wet season to 0.177 to 0.309 mg L^{-1}. High rainfall encourages dissolved orthophosphate compounds to dissolve more easily and experience stirring in the water column (Aisyah & Nomosatryo 2016). Referring to the water quality standard based on the Government Regulation of the Republic of Indonesia No. 22 of 2021, TP concentrations at all observation stations in the dry and wet seasons exceeded the water quality standard values of class I (0.01 mg L^{-1}), class II (0.03 mg L^{-1}), and class III (0.10 mg L^{-1}), being categorized as hypertrophic waters (TP concentration ≥0.1 mg L^{-1}) based on the Regulation of the Minister of Environment of the Republic of Indonesia No. 28 of 2009.

The spike in TP concentrations in LLT waters exceeding the quality standard is thought to originate from fish farming activities in floating net cages spread across Station 8, namely, from the release of phosphorus-containing fish feed residues into the lake water column (Indrayani et al 2015; Ardi 2013; Moraes et al 2015), as well as fish feces and urine (Astuti & Krismono 2018). This is reinforced by Adhar et al (2021), who reported that tilapia aquaculture activities in floating net cages in LLT waters produced phosphorus waste of 0.09 kg m^{-2} floating net cage area. This condition has also been observed in several other lakes in Sumatra. The TP concentration in the waters of Lake Maninjau-West Sumatra is in the higher range of 0.26 to 0.60 mg L^{-1} with hypertrophic status (Komala et al 2020), and has caused *Microcystis aeruginosa* blooming (Henny & Santoso 2019). The total TP pollutant load to Lake Toba reached 2,297.57 tons $year^{-1}$ (Sunaryani et al 2018), where 87% of the TP pollutant load came from fish farming activities in floating net cages (Lukman et al 2019). The TP concentration of Lake Toba waters ranges from 0.01 to 0.05 mg L^{-1}, indicating an increase in trophic status from mesotrophic to hypereutrophic (Habib 2020).

High concentrations of TP in closed waters, such as lakes, will become a serious environmental problem because it not only causes a decrease in water quality but also contributes to the eutrophication process in lake waters (Adesuyi et al 2016, Paitaha 2020). High TP concentrations often coincide with cyanobacterial blooms in water (Li et al 2018). *Cyanobacterial* blooms are very dangerous because they are toxic to both humans and biota (Komala et al 2020). If eutrophication occurs in DLT waters, it threatens biodiversity and aquatic biota (Wang et al 2021).

Nitrite is a compound produced during the nitrification process and is the result of oxidation by Nitrosomonas bacteria to ammonia compounds in water (Iriadi 2015). Nitrite and nitrate play important roles as primary producers in the formation of aquatic organisms and phytoplankton biomass (Indrayani et al 2015). Nitrite concentrations tend to be inversely proportional to nitrate concentrations in water. High nitrite concentrations tend to be followed by low nitrate concentrations because of nitrification (Aisyah & Nomosatryo 2016). In general, the nitrite concentration in water is lower than the nitrate concentration. This is because nitrite compounds are unstable and easily oxidized when DO concentrations are sufficient (Indrayani et al 2015). This condition is also experienced by LLT water. The nitrite concentration in LLT water ranged from 0.004 to 0.012 mg L^{-1} during the dry season and 0.005 to 0.012 mg L^{-1} during the wet season. Referring to the water quality standard based on Government Regulation of the Republic of Indonesia No. 22 of 2021, nitrite concentrations at all observation stations are still below the specified water quality standard of 0.06 mg L^{-1}.

Ammonia is an important parameter for determining the level of pollution in the lake water. The range of ammonia concentrations in LLT waters was 0.008 mg L^{-1} to 0.101 mg L^{-1} during the dry season and 0.006 to 0.090 mg L^{-1} during the wet season. Ammonia concentrations at all observation stations were still below the water quality standard except at Station 9 (lake outlet) during the dry season, which showed 0.10 mg L^{-1}, above the Class I water quality standard. The high ammonia concentration at Station 9 (lake outlet) is thought to be due to the accumulation of polluting waste from settlements, floating net cage fish farming activities, and agricultural activities around the LLT. As an estuary, the lake outlet accommodates and flows pollutants into the Peusangan River.

Considering the results of Iriadi et al (2015), the ammonia concentration in DLT waters averaged 0.019 mg L^{-1}, indicating an increase in ammonia concentration of 0.034 mg L^{-1} over the past seven years. Ammonia levels increased with increasing pH and water temperature. This condition needs to be monitored, considering that ammonia concentrations occur at observation stations with high pH values (>7), so that it can increase the toxicity of water that will endanger aquatic biota. Increasing ammonia concentrations also cause an increase in phytoplant density, resulting in blooming. This condition is followed by the mass death (die off) of phytoplantons, which will worsen the quality of lake waters, especially because of the drastic decrease in water DO concentration (Paitaha 2020). Several years ago, this condition was thought to be the cause of mass fish mortality in LLT water.

Analogous to the results of this study, the accumulation of various pollutants from floating net cage activities, urban waste, and agriculture increased ammonia concentrations in the waters of Lake Buyan Bali (Saputra et al 2017), and the same also occurred in the waters of Lake Todanao (Maniagasi et al 2013). Fish farming activities in floating net cages have caused a significant increase in ammonia compounds in Lake Maninjau-West Sumatra and have led to a decline in endemic bada (*Rasbora argyrotaenia*) and rinuak (*Psylopsis* sp.) fish populations (Mustaruddin et al 2018).

Spatio-temporal distribution of physico-chemical parameters. The spatial map created using the IDW method and GIS interpolation technique (Figure 3) clearly shows the distribution of the average values of physico-chemical pollutants from various selected locations in the LLT surface water. The colors used in the interpolation technique for the spatial distribution of different pollutants indicate risky areas with darker colors and safe areas with brighter colors. The gradual variation in each color corresponds to the variation in the mean value of LLT water quality using the natural break classification method (or Jenks optimization), which is divided into five classes. Similarly, the variation in the size of the circles corresponded to the variation in LLT water quality, representing the seasons.

Determination of water quality status. Overall pollutant levels were determined using the STORET method. The STORET method can describe parameters that meet or exceed the water quality standards. The basic concept of the STORET index is to compare each water quality data point with its standard and then assign a score. The scoring value was based on the United States Environmental Protection Agency (US-EPA 2021) system. Eleven physico-chemical parameters were used to calculate the STORET index: Temperature, TDS, TSS, pH, DO, BOD, COD, nitrate, total phosphorus, nitrite, and ammonia. Based on calculations using the STORET method, the scores for each physico-chemical parameter of LLT water obtained are listed in Table 6.

Table 4 shows the water quality status of LLT using the STORET method with the classification of water quality status from the Government Regulation of the Republic of Indonesia No. 22 of 2021, which can be described as follows: Class I, which is used as a drinking water source, has a pollution index of -56; Class II, which is used for recreation, animal husbandry, and fish farming, has a pollution index of -28; Class III, which is used for animal husbandry, fish farming, and agriculture, has a pollution index of -20. The parameters causing water pollution in class I water quality standards include TSS (-4), DO (-4), BOD (-4), COD (-20), TP (-20), and ammonia (-4); class II water quality standards include TSS (-4), COD (-4), and TP (-20); and class III water quality standards include the parameter TP (-20). Based on the water pollution index from STORET, the LLT water quality status was severely polluted for class I quality standards, and moderately polluted for classes II and III (Figure 4).

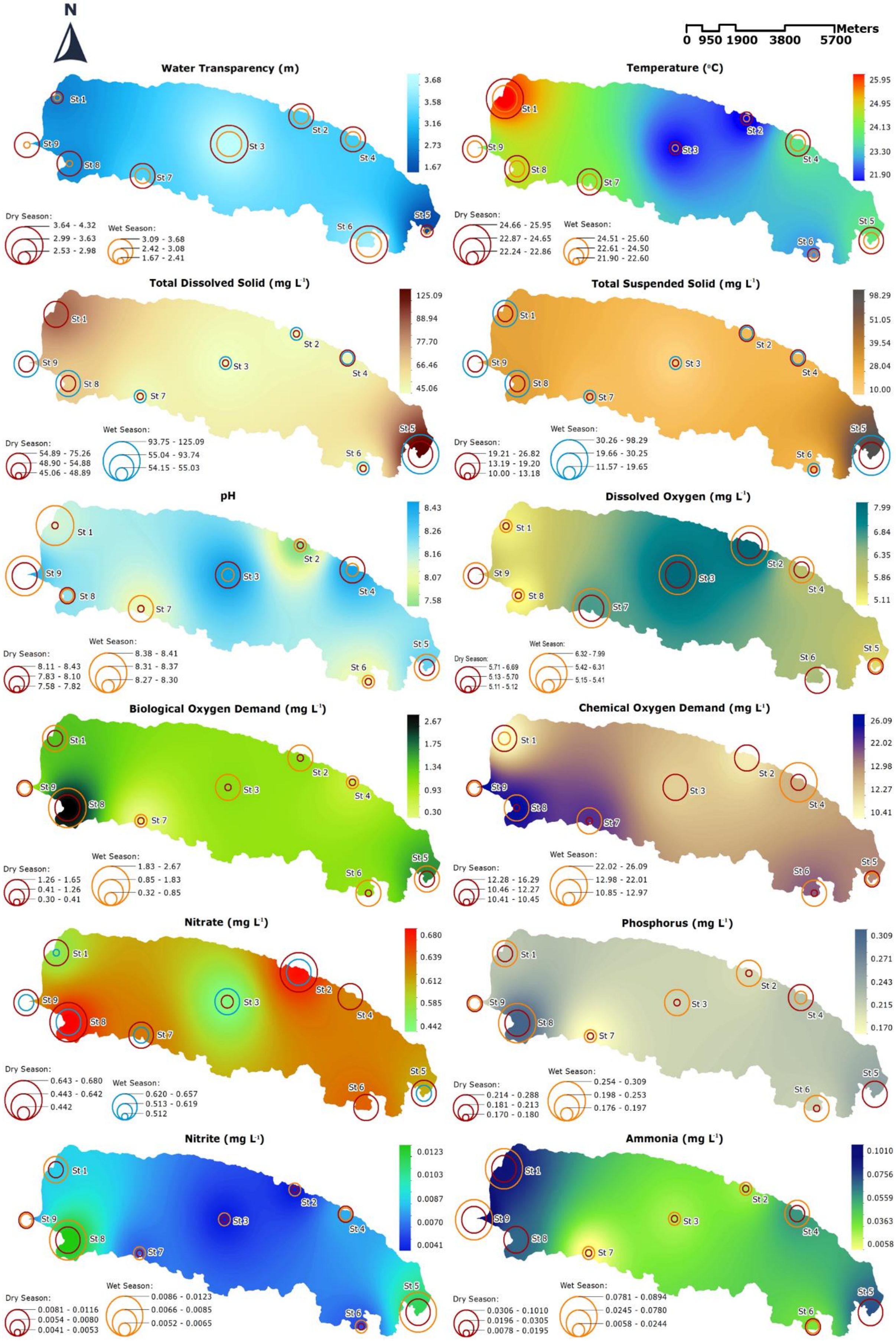

Figure 3. Spatial distribution maps of physico-chemical parameters in LLT.

Table 6

Scores of physico-chemical parameters in LLT

Parameters	Units	*Water quality standard*[*)]			*Measurement result*			*Score*		
		Class I	*Class II*	*Class III*	*Maximum*	*Minimum*	*Average*	*Class I*	*Class II*	*Class III*
Temperature	^0C	Normal ±3	Normal ±3	Normal ±3	25.95	21.90	23.59	0	0	0
TDS	mg/L^{-1}	1000	1000	1000	125.09	45.06	63.76	0	0	0
TSS	mg/L^{-1}	25	50	100	98.29	10.00	23.33	-4	-4	0
pH	-	6-9	6-9	6-9	8.43	7.58	8.18	0	0	0
DO	mg/L^{-1}	6	4	3	7.99	5.11	6.12	-4	0	0
BOD	mg/L^{-1}	2	3	6	2.67	0.30	1.07	-4	0	0
COD	mg/L^{-1}	10	25	40	26.09	10.41	15.52	-20	-4	0
Nitrate	mg/L^{-1}	10	10	20	0.681	0.443	0.614	0	0	0
Total phosphorous	mg/L^{-1}	0.01	0.03	0.10	0.309	0.171	0.218	-20	-20	-20
Nitrite	mg/L^{-1}	0.06	0.06	0.06	0.012	0.004	0.007	0	0	0
Ammonia	mg/L^{-1}	0.10	0.20	0.50	0.101	0.006	0.048	-4	0	0
Pollution index								-56	-28	-20
Number of sample 11 ≥ 10										

*) = National Government Regulations of Republic Indonesia No. 22 of 2021.

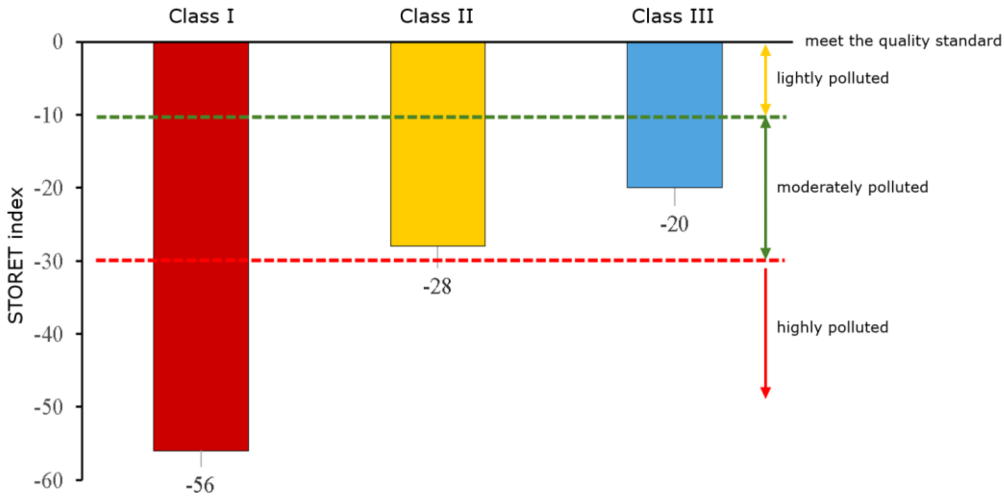

Figure 4. Water quality status based on physico-chemical parameters in LLT.

The results of the comparison between the STORET index calculation and that performed by Iriadi (2015b) show an increase in LLT water pollution for all water quality classes. The status of Class I waters, previously in the Class C category (moderately polluted), increased to Class D (heavily polluted). Similarly, the status of Class II and III waters, previously in the Class B category (lightly polluted), increased to Class C (moderately polluted). A comparison of the STORET index values with those of previous studies showed a significant increase in TP over the last 7 years. Fish farming activities in floating net cages scattered around Station 8 were strongly suspected to be the main source of TP pollution in LLT waters. Several rivers, such as lake inlets with a "heavily polluted" status (STORET score ≥-31) in class II water quality standards (Gayosia et al 2015), significantly affected the increase in LLT water pollution status. Water polluted by TP triggers a eutrophication process that has a fatal impact on aquatic biota (Wang et al 2021), especially on endemic depik (R. tawarensis) biota, which currently has a highly endangered status (Lumbantobing 2019) and ultimately impacts socioeconomic and environmental conditions (Elias et al 2019).

Conclusions. LLT undergoes temporal physico-chemical changes that are influenced by the season. Pollutant parameters increased with rainfall intensity in the catchment area and pollutants entered the lake through the inlet. Physico-chemical parameters, namely, temperature, TDS, TSS, pH, DO, BOD, COD, nitrate, total phosphorus, nitrite, and ammonia, were used to evaluate the water quality of LLT with reference to water quality standards based on Republican Government Regulation No. 22 of 2021. Then, using GIS and inverse distance weighted interpolation (IDW) methods to study the spatial-temporal distribution of these pollutant parameters, the distribution map of physico-chemical parameters shows that the study area is highly contaminated, especially in fish farming areas in floating net cages, dense residential areas, and rice field conversion activities. The water quality of LLT is in the category of severe pollution (STORET index -56) for class I water quality standards and the category of moderate pollution (STORET index -28 and -20) for class II and III water quality standards, with TSS, DO, BOD, COD, TP, and Ammonia as polluting parameters. This condition is feared to put pressure on the habitat and population of endemic depik fish in LLT, which are currently included on the list of highly endangered species. Therefore, this study encourages further monitoring, particularly during rainy seasons.

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