Spatio-temporal Assessment of Pollution Levels in the Southern Gulf of Lake Tana

Mestawot Girma Bekele[1,3] , Nigus Gabbiye [1], Agegnehu Alemu[2,3*]

[1]*Bahir Dar institute of technology, Bahir Dar University, P.O Box 26, Bahir Dar, Ethiopia*

[2]*Bahir Dar University, College of Science, Department of Chemistry, Bahir Dar, P.O Box 79 ,Ethiopia*

[3]*Blue Nile Water Institute, Bahir Dar University, Bahir Dar, Ethiopia*

*Corresponding author: agegnehua@gmail.com

Abstract

This study investigates the spatial and seasonal patterns of pollution in the southern Gulf of Lake Tana, Ethiopia. Lake Tana plays a crucial role in supporting aquatic biodiversity and supplying water to surrounding communities; however, escalating human activities have raised concerns about its water quality. Through systematic sampling and analysis, the study assesses the distribution of pollutants and their seasonal and spatial variability. An integrated methodological framework combining GIS, remote sensing, and physicochemical water quality assessment was employed to provide a comprehensive understanding of pollution dynamics. The results show that dissolved oxygen concentrations recorded mean values ranging from 8.21 to 9.52 mg/L during both dry and wet seasons. Mean total dissolved solids ranged from 97.32 to 99.75 mg/L in the dry season and from 97.81 to 104.02 mg/L in the wet season, revealing a decreasing trend from near shore reference points toward the open lake with increasing horizontal distance. In contrast, turbidity values increased horizontally, rising from an average of 11.48 to 16.43 NTU. Phosphate concentrations exhibited marked seasonal and spatial variability, with mean values ranging from 9.43 to 9.53 mg/L in the dry season and from 0.64 to 1.22 mg/L in the wet season, indicating significant differences among sampling stations. Overall, the study demonstrates that the physicochemical characteristics of Lake Tana vary both spatially and seasonally, particularly in areas adjacent to the shoreline near Bahir Dar City, highlighting clear evidence of pollution impacts within the lake.

Keywords: Physicochemical parameters, Spatio-temporal variations, GIS, Lake Tana, pollution

1. Introduction

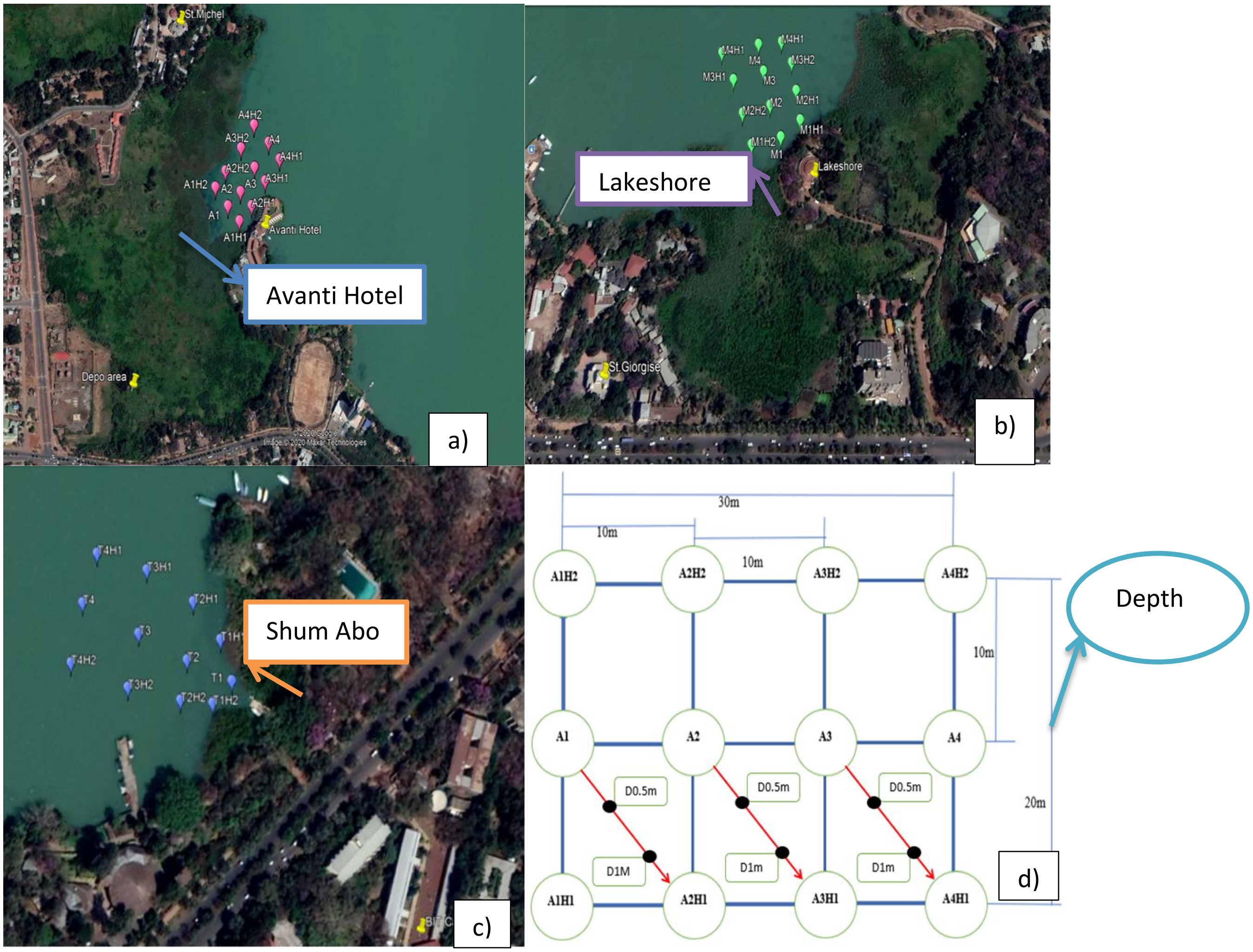
Lake Tana provides vital benefits to both local communities and the nation, serving as a key source of drinking water, fisheries, tourism, transportation, hydroelectric power, and irrigation. The lake alone contributes more than half of Ethiopia's fishery potential. However, despite its social and ecological importance, Lake Tana's ecosystem has been significantly altered by human activities along its shoreline(Wondie, 2010a). Although some studies have examined pollution levels and contributing factors in the lake's littoral zone (Moges et al., 2017);(Wondie, 2010b), the influence of seasonal variation and spatial differences on physicochemical water quality remains insufficiently explored. The littoral zone, characterized by shallow, nutrient-rich waters near the shore, supports rooted aquatic plants and diverse aquatic life (Bongomin, 2011).

Spatial interpolation predicts attribute values at unsampled locations using measurements from known points(Wipki et al., 2017). In this study, spatiotemporal variations in water quality were estimated using the ordinary kriging method, a geostatistical interpolation technique that relies on the statistical relationships among sampled points (Dersseh et al., 2019). The research assessed selected physicochemical parameters across three catchments of Lake Tana in Bahir Dar City (**Figure 1**). Surface waters are highly susceptible to pollution, as both natural processes and human activities such as nutrient-rich agricultural runoff and discharges from septic systems introduce substantial inorganic and organic contaminants, leading to significant declines in water quality worldwide. This study investigates the spatio-temporal distribution and variation of pollution in the southern Gulf of Lake Tana. It identifies the most affected areas by assessing pollution levels across locations and seasons. The research also examines the sources and contributing factors of pollutants to clarify their origins.

2. Methodology

2.1 Study Area

Lake Tana is situated in northwest Ethiopia, approximately 565 km from Addis Ababa. It lies between coordinates UNESCO Biosphere Reserve: 11°54'29.11"N - 37°20'40" E. The Lake has an average depth of about 9 m and reaches a maximum depth of 15 m (Ayana, 2007)Lake Tana plays a vital role in regional transportation, hydropower generation, irrigation, fisheries, and eco-tourism. However, water quality is increasingly threatened by point-source pollution from Bahir Dar city and diffuse agricultural runoff, which elevate sediment and nutrient loads in the lake (McCartney et al., 2010). To assess land-use patterns and their associated pollution potential, Google Earth imagery and ArcView GIS 10.5 were employed to identify and characterize land uses within the study area (**Figure 1**).



Finger 1. Sampling station (a, b &c) and sampling point description in horizontal surface and vertical depth (d).

2.2. Sample Collection

To analyze the effect of seasonal variation on pollution level, water samples were collected both in the wet season and dry seasons and transported to the laboratory for further analysis. The study also investigated spatial variation by sampling water from three locations: Lakeshore Hotel, Shum Abo Area, and Avanti Hotel. For each season, 120 lake water samples (72 horizontal and 48 vertical) were collected and analyzed, totaling 240 samples.

Sampling points were chosen based on accessibility and the presence of pollution sources. the temporal span of the field investigations was meant to cover both dry (for 3:30, 4:35, 5:15 am 01/07/2019) and wet season (for 3:40, 4:55, 5:59 am 24/10/2019) in, Shum Abo area, Lakeshore Hotel, Avanti Hotel respectively. The data were collected in March 2019 (dry season) and June (rainy season). To ensure consistency, sampling points were mapped using a handheld GPS and a boat, and coordinates were stored for future reference. Mapping was done after a rain event to trace runoff paths.

2.3.1. Water sample analysis

Whereas temperature (^{O}C) , EC, TDS and pH were measured with probes YSI (Model Pro 30, 12E101564, USA) and Turbidity was measured with turbid metric(serial No and made in MICRO TPW, 20000,201703516 4Xalkaline, AAA.1.5V and U.S.A respective); DO was measured with HANNA HI98193 (SN: 02190067991).In-situ measurements were taken by dipping the probe about 3-5 cm below the water surface. the orthophosphate ion (PO_4^{3-}) with filtering the sample was analyzed by the ascorbic acid method (Altahan, 2022) .

2.3.2 Data Analysis

Statistical analyses were conducted using Microsoft Excel (2013), ArcGIS 10.5, the Statistical Package for the Social Sciences (SPSS) version 23, and Sigma Plot version 12.5. Microsoft Excel (2013) was used to compute descriptive statistics, including maximum, minimum, mean, and standard deviation, to assess differences among sampling points based on pooled data from the entire study area. Analysis of variance (ANOVA) was applied to determine the presence of significant variations in selected physicochemical parameters among sampling sites, while an independent *t*-test was employed to evaluate seasonal differences between the two sampling periods.

3. Results and discussion

3.1 Spatial and temporal variations of pollution level within the horizontal surface

Depending on the experimental design, physicochemical parameters were measured at all sampling stations during both the dry and wet seasons. In total, 120 water samples were collected across the two seasons, comprising 36 sampling points in the horizontal direction and 24 sampling points in the vertical profile. The field and laboratory results of the selected water quality parameters obtained from these samples are summarized in **Table 1**.

Table 1 Physicochemical analysis of the southern gulf of Lake Tana both in the dry and wet seasons

Avanti	Unit	Dry season		Wet season		WHO
Hotel Area		Mean	STD	Mean	STD	

DO	mg/L	8.95	0.48	9.52	0.38	4-6
EC	µ S/cm	154.34	0.74	160.82	5.54	1000
pH	-	8.29	0.30	7.84	0.15	6.5-8.5
Temp.	^{o}C	25.18	0.13	24.07	0.09	25
TUR.	NTU	11.48	1.89	13.19	1.35	5
TDS	mg/L	99.75	0.54	104.02	3.54	1000
PO_4^{3-}	mg/L	9.53	0.06	0.64	0.39	0.005 -0.02

Lakeshore Hotel Area	Unit	Dry season		Wet season		WHO
		Mean	STD	Mean	STD	
DO	mg/l	8.72	0.01	8.50	0.18	4-6
EC	µ S/cm	153.29	1.26	154.38	3.04	1000
pH	-	7.84	0.15	7.84	0.01	6.5-8.5
Temp.	^{0}C	24.07	0.09	24.07	0.09	25
TUR.	NTU	16.34	0.14	16.43	0.92	5
TDS	mg/L	99.53	0.43	102.14	1.86	1000
PO_4^{3-}	mg/L	9.43	0.10	0.91	0.25	0.005 -0.02

Shum Abo Area	Unit	Dry season		Wet season		WHO
		Mean	STD	mean	STD	
DO	mg/L	8.58	0.47	8.21	0.39	4-6
EC	µ S/cm	148.76	0.61	147.35	0.42	1000
pH	-	7.84	0.15	7.79	0.09	6.5-8.5
Temp.	^{O}C	24.07	0.09	24.07	0.09	25
TUR.	NTU	13.78	0.26	15.07	0.00	5
TDS	mg/L	97.32	0.50	97.81	0.14	1000
PO_4^{3-}	mg/L	9.51	0.008	1.22	1.14	0.005 -0.02

3.2. Effect of seasonal variation and sampling station on water quality parameters

Samples were gathered throughout two seasons (the dry season and the rainy season) from three different sampling locations to assess how seasonal changes and spatial differences affect the chosen water quality parameters (Avanti Hotel, Lakeshore Hotel, and ShumAbO).

The results from laboratory and in-situ measurements were analyzed using an independent sample t-test to examine seasonal variation and a one-way ANOVA to investigate differences between the sampling locations. The results for each water quality parameter are discussed and presented in the following sections.

3.2.1. Temperature

In the dry season, average temperatures ranged from 24.07 °C to 25.17 °C, while they were consistently 24.07 °C across all sites in the wet season (Table 1). ANOVA and independent T-test results show significant temperature-related variations in pollution load across sampling stations in both seasons. Seasonal variations impacted temperature at all sites except Avanti Hotel. Higher dry season temperatures, peaking at 25.18 °C at Avanti Hotel, are attributed to increased solar radiation, lower water levels, and clearer atmospheric conditions. These higher temperatures affect dissolved oxygen solubility, as cooler water holds more gas.

Elevated temperatures can boost photosynthesis in aquatic plants and algae, potentially leading to harmful algal blooms (Kale, 2016a)) and disrupting metabolic processes in aquatic organisms. Similar findings were noted in studies of Lake Tana and Lake Hawassa (Abate et al., 2015); (Tesfaye & Warkineh, 2022a); (Wondim, 2016).

3.2.2. pH

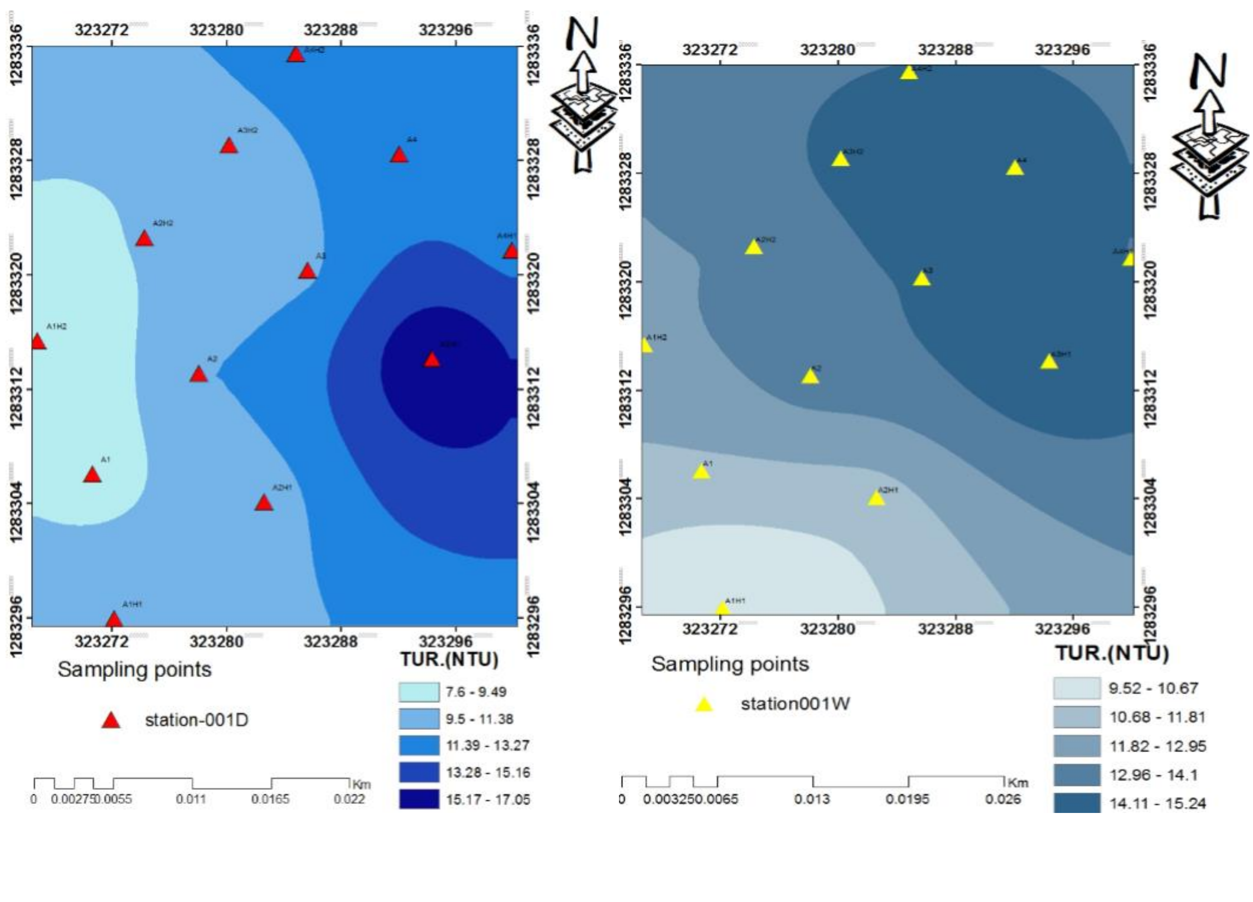
In this study, pH values ranged from 7.79 to 8.29, with the lowest average at Shum Abo Area during the wet season and the highest at Avanti Hotel during the dry season (**Table 1**). These values indicate slightly basic water in Lake Tana and fall within the WHO water quality standards of 6.5 to 8.5 (WHO, 2004).

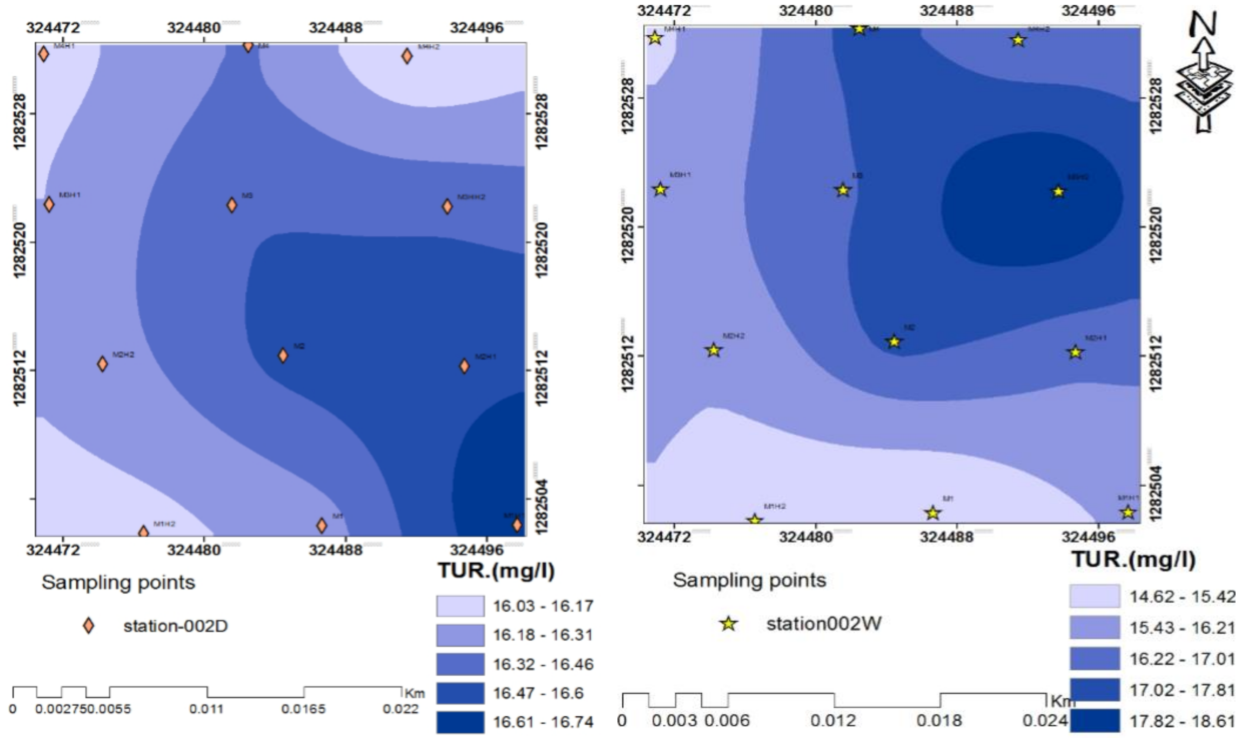
The pH values observed in this study are consistent with previous studies on Lake Tana, which reported pH values of(Goshu et al., 2010) , (Tibebe, 2017), (Ewnetu et al., 2014a), and (Zinabu, 2002b), but differ from Lake Victoria, which had a pH of 8.98 ± 0.69 during the dry season. The average pH values do not significantly vary across different study sites and seasons, except at Avanti Hotel and Shum Abo Area, where significant seasonal variations were noted. Generally, pH values were higher in the dry season than in the wet season at all study sites. This could be due to the removal of CO_2 during photosynthesis by aquatic plants, affecting pH levels. High pH levels (greater than 9.5) or very low levels (below 4.5) are unsuitable for most aquatic organisms.

3.3. Surfaces water pollution level distribution with Arc GIS soft were

Surface water pollution distribution was assessed using ArcGIS by accounting for seasonal variation, differences among stations, and intra-station variability influenced by dilution effects. To analyze surface dispersion, twelve samples were collected at 10 m intervals within each station (Figure 1). Following preliminary analysis, the spatial distribution of surface pollution was mapped in ArcGIS using standardized classifications of water quality parameters across all stations and seasons.

Station-003D: Shum Abo Area dry season, 2019
Station-003W: Shum Abo Area wet season, 2019
Station-002D: Lakeshore Hotel Area dry season, 2019
Station-002W: Lakeshore Hotel Area wet season, 2019
Station-001D: Avanti Hotel Area dry season, 2019
Station-001W: Avanti Hotel Area wet season, 2019





324472
324480
324488
324496
1282528
1282520
1282512
1282504
TUR.(mg/l)
16.03 - 16.17
16.18 - 16.31
16.32 - 16.46
16.47 - 16.6
16.61 - 16.74
Sampling points
station-002D
0 0.00275 0.0055 0.011 0.0165 0.022 Km
324472
324480
324488
324496
1282528
1282520
1282512
1282504
TUR.(mg/l)
14.62 - 15.42
15.43 - 16.21
16.22 - 17.01
17.02 - 17.81
17.82 - 18.61
Sampling points
station002W
0 0.003 0.006 0.012 0.018 0.024 Km
N

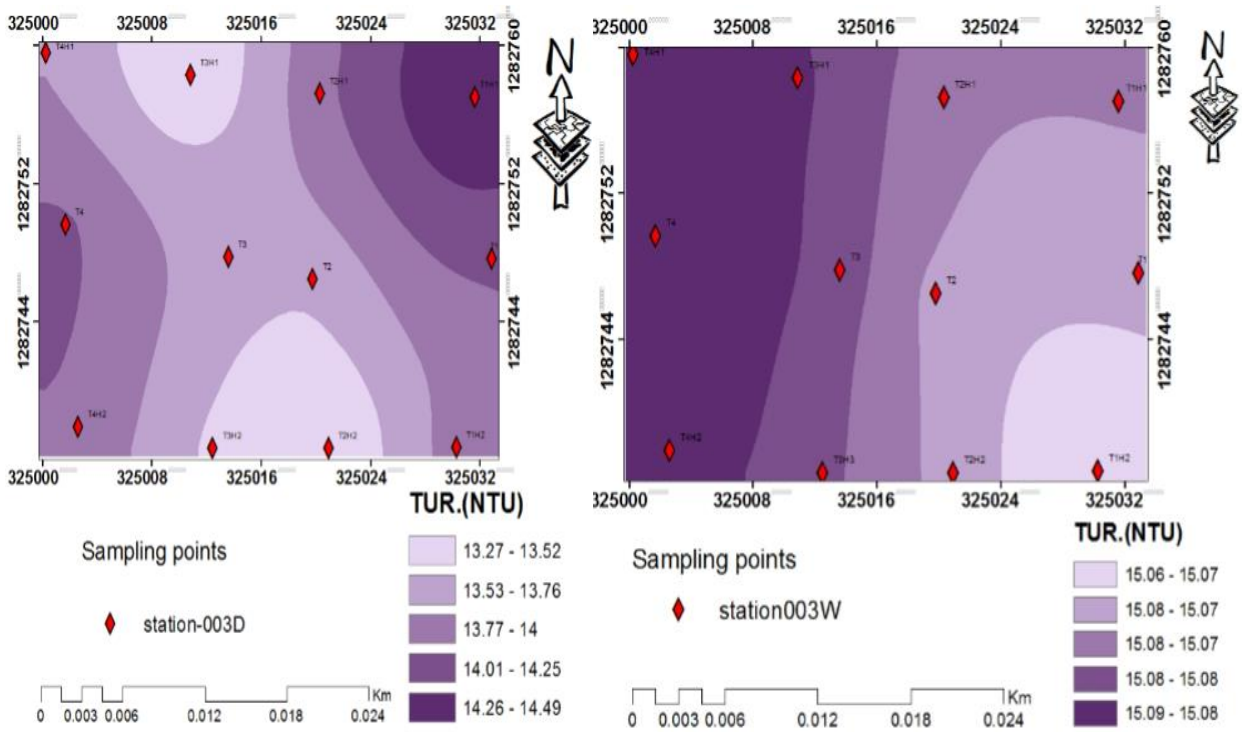
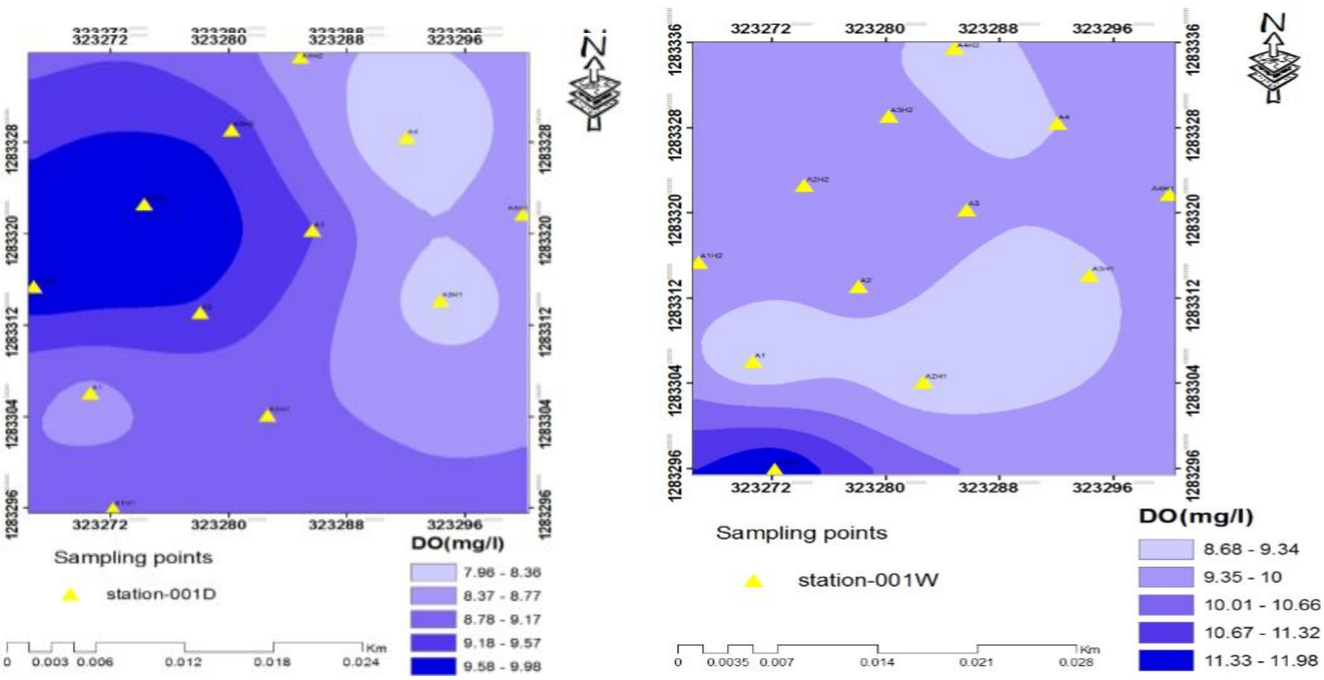


Figure 2. Spatio-temporal distribution of Turbidity in the sampling points

The spatial and seasonal patterns of turbidity varied markedly among the sampling stations (**Figure 2**), reflecting the combined influence of site-specific human activities and natural processes. In the Avanti Hotel area during the dry season (A3H1), elevated turbidity was mainly attributed to the direct discharge of untreated hotel effluent, together with inputs of inorganic substances such as chloride, nitrate, sulfate, phosphate, and cations including sodium, magnesium, calcium, iron, and aluminum.

During the wet season (A3, A3H1, A3H2, A4, A4H1, A4H2), turbidity increased further as a result of cumulative effluent releases from both the Avanti Hotel and St. Michael Church, coupled with higher loads of organic materials (algae, plankton, and decomposing matter). These effects were intensified by stronger winds, urban runoff, and soil erosion, which introduced additional silt and clay into the water column. Similarly, in the Lakeshore Hotel area, dry-season turbidity (M1H1) was associated with untreated wastewater discharge, cloth-washing activities, and erosion-derived inorganic particles, whereas wet-season conditions (M3H2) were dominated by enhanced runoff, microorganisms, decomposing biological material, and urban debris, resulting in higher turbidity levels.

At Shum Abo, turbidity during the dry season (T1H1) was largely driven by effluent discharge from Lake Tana Hotel and cloth washing, while wet-season sites (T3H1, T4, T4H1, T4H2) experienced increased turbidity due to wind-induced mixing, suspended solids, organic matter, algal growth, and runoff from surrounding areas. Overall, turbidity was consistently greater in the wet season than in the dry season, owing to the increased input of suspended sediments such as silt, inorganic particles, organic matter, and colored dissolved organic substances (Kale, 2016a) ; (Nugusu, 2015). Such conditions can substantially affect aquatic ecosystems by altering species dominance, increasing biomass production, accelerating sedimentation, reducing biodiversity, and potentially promoting anoxic conditions (Edokpayi et al., 2017). As illustrated in **Figure 2**, peak turbidity values varied among sites depending on both the sampling location and the season.



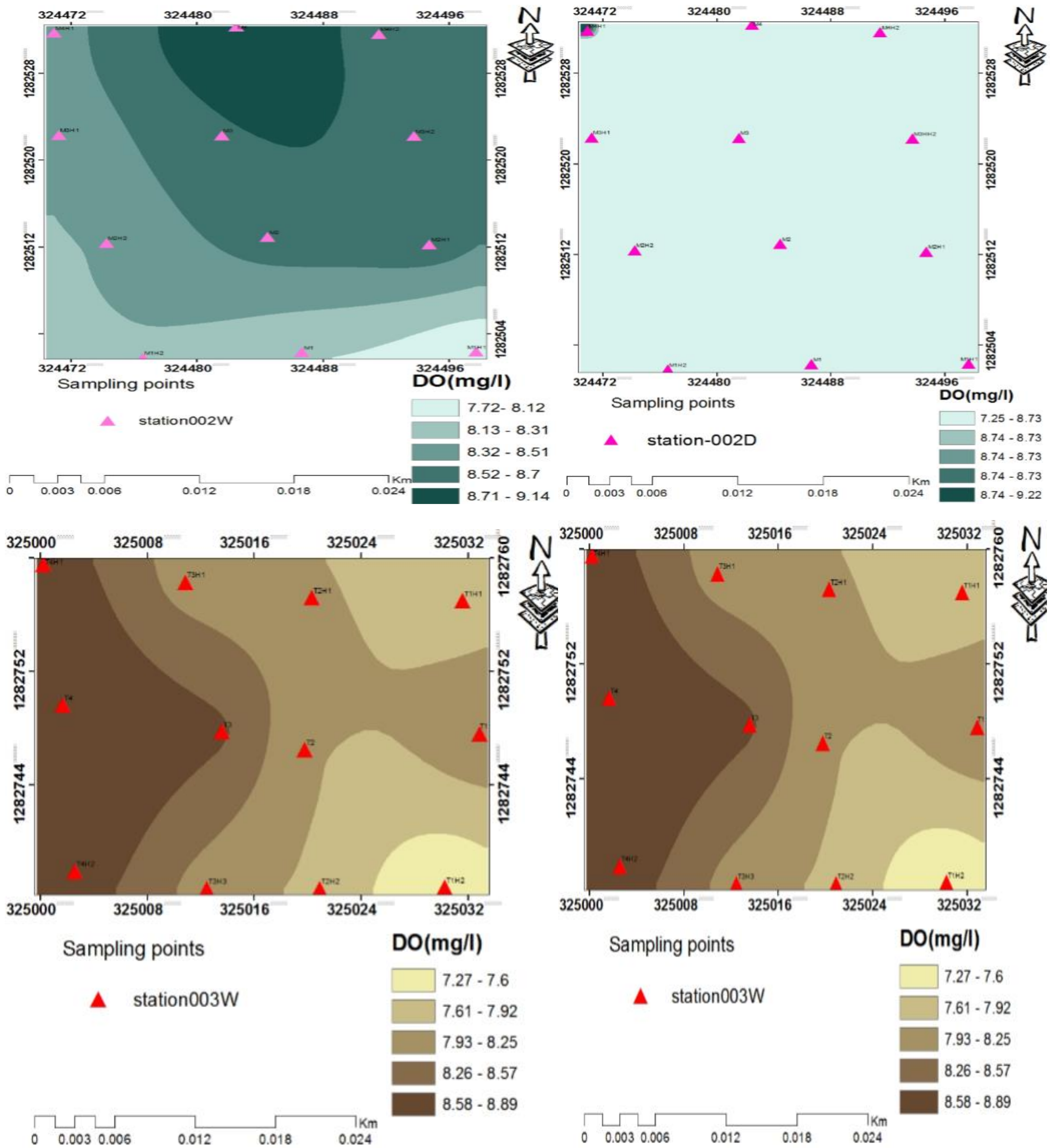
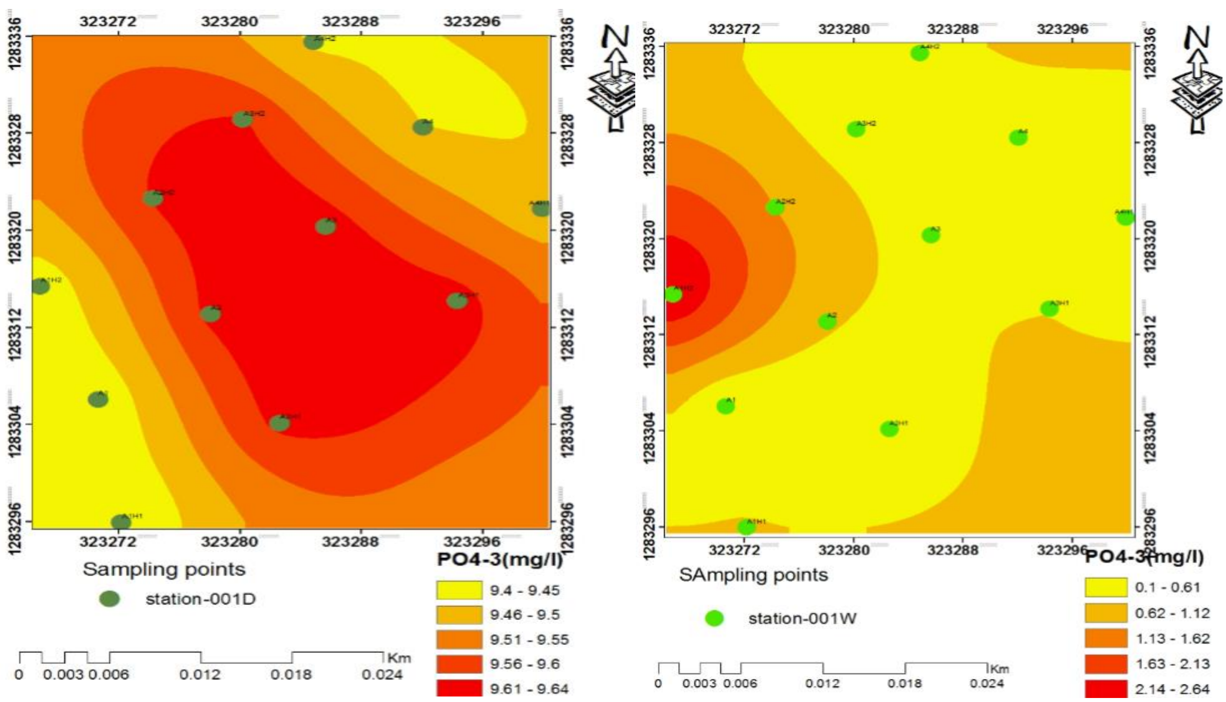


Figure 3. Spatio-temporal distribution of DO at the sampling points

The spatio-temporal variation of dissolved oxygen (DO) across the sampling sites is illustrated in **Figure 3**. In the Avanti Hotel area during the dry season (A1H2 and A2H2), relatively high DO concentrations were attributed to enhanced aeration caused by strong winds and wave action, along with increased diffusion of oxygen from the atmosphere. However, the abundance of algae and dense chimba (Dengel) vegetation may also influence DO dynamics by limiting light penetration and reducing overall photosynthetic productivity. During the wet season (A1H1), higher DO levels were mainly supported by cooler water temperatures, which increase oxygen solubility, together with improved mixing from wind-driven turbulence and comparatively lower pollution inputs, resulting in pronounced seasonal and site-specific differences governed by both biological and environmental factors.

In the Lakeshore Hotel vicinity, maximum DO values in the dry season (M1H1) were associated with lower water temperatures and higher water pressure, whereas during the wet season (M4), increased aeration and atmospheric diffusion enhanced oxygen availability. In the Shum Abo area, dry-season DO levels (T4H1) were largely controlled by photosynthetic activity, while in the wet season (T4, T4H1, and T4H2), elevated DO concentrations resulted from intensified atmospheric diffusion and more effective water–air exchange. Overall, spatial and seasonal variations in DO reflect the influence of localized environmental conditions.

Generally, higher DO concentrations suggest lower biomass accumulation and reduced rates of organic matter decomposition, supporting the concept that cooler, well-mixed waters retain more oxygen, whereas areas with intense biological activity may experience DO depletion due to increased oxygen consumption (Hailu, 2017)



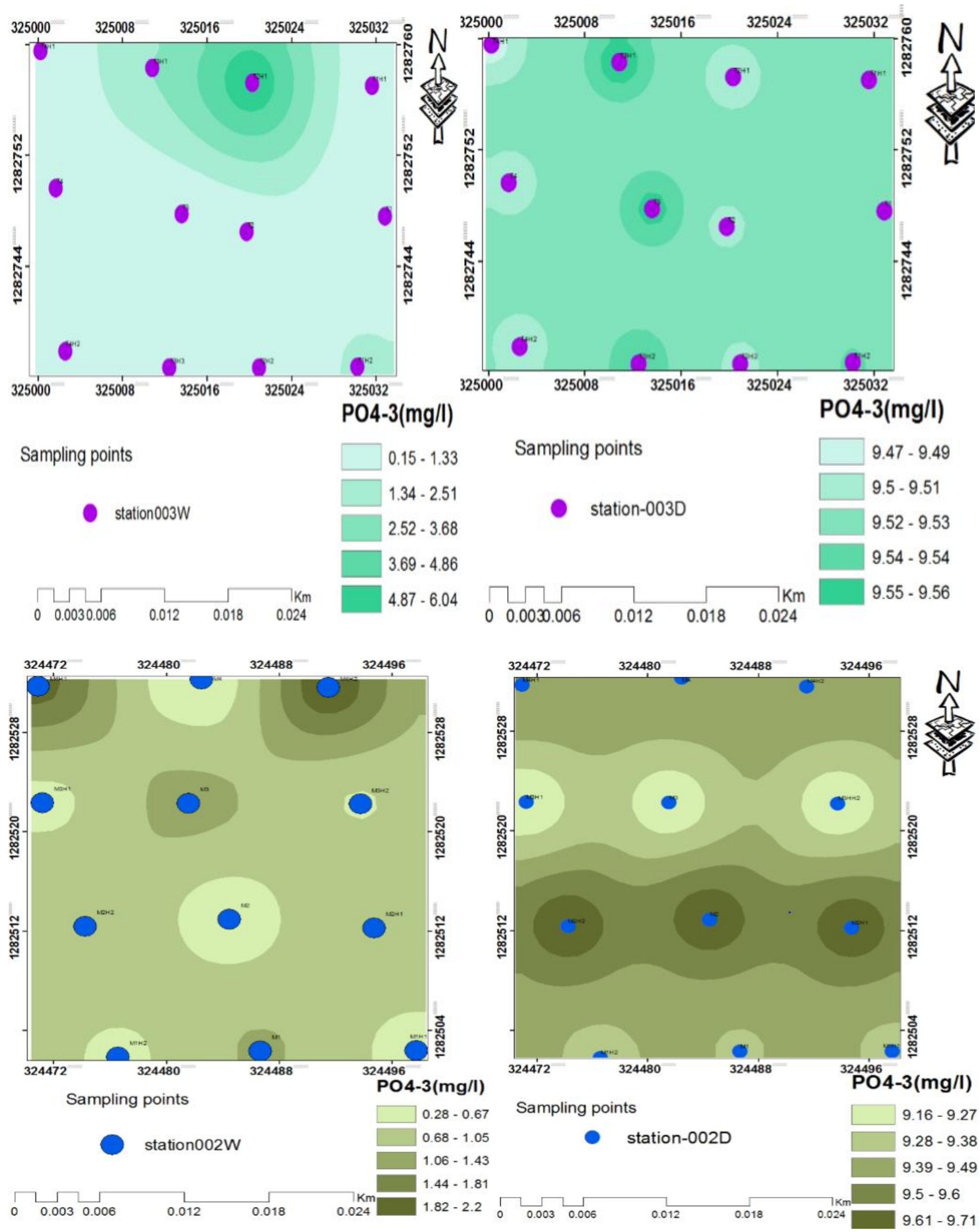
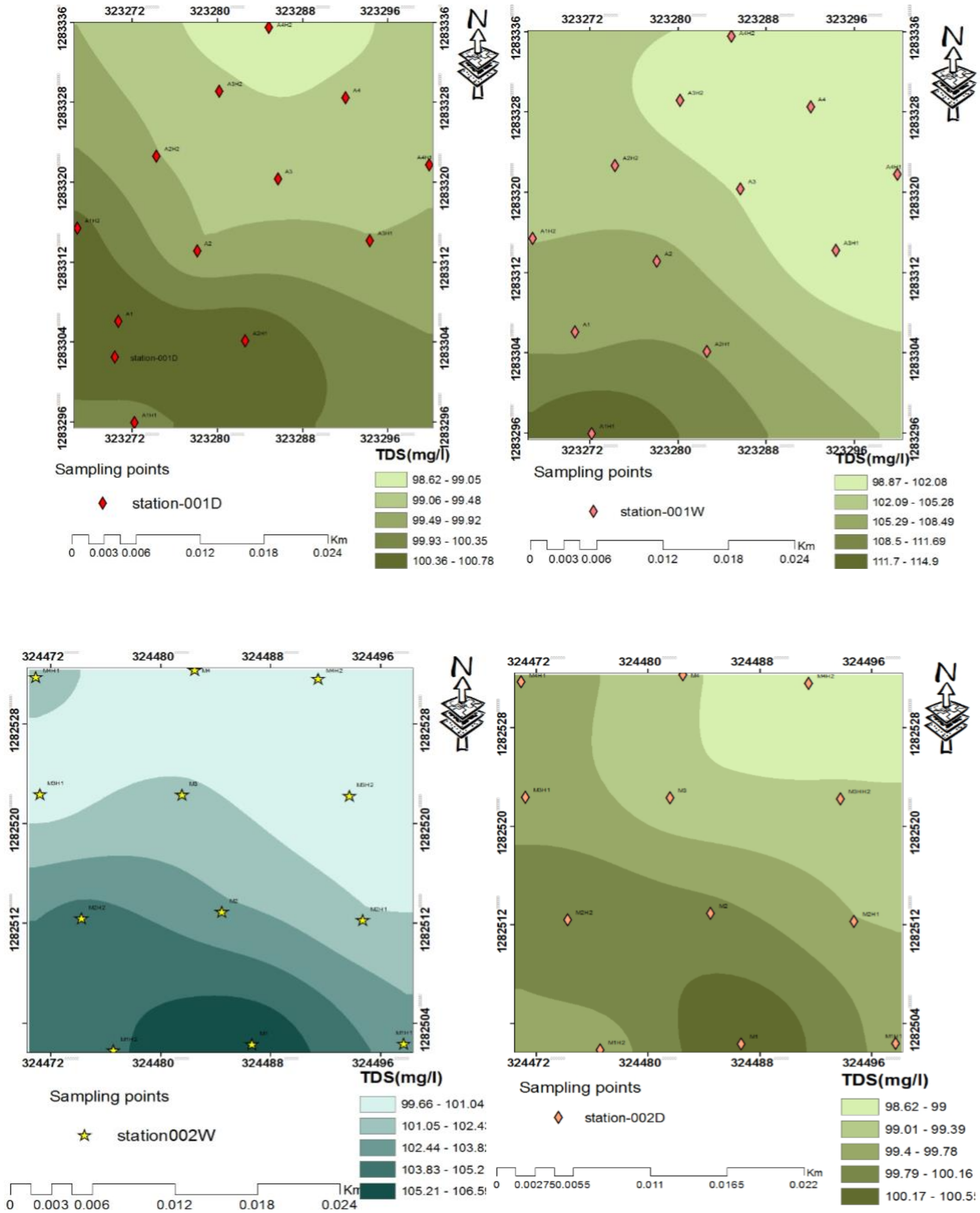


Figure 4. Spatial distribution of orthophosphate in the sampling points

The spatial distribution of reactive phosphate across the sampling sites exhibited clear variations among locations and seasons, largely influenced by differences in human activities, biological dynamics, and hydrodynamic conditions (**Figure 4).** In the Avanti Hotel area during the dry season (A2H1, A2H2, A3, A3H1, A3H2), elevated reactive phosphate concentrations were mainly attributed to the release of inorganic constituents such as chloride, nitrate, sulfate, and phosphate ions—together with cations including sodium, magnesium, calcium, iron, and aluminum originating from decomposing organic matter and nearby waste inputs. Additional inputs arose from the growth and subsequent decay of algae and aquatic macrophytes, as well as from poorly functioning septic systems and runoff from sites where animal manure is stored.

During the wet season (A1H2), phosphate levels increased due to the discharge of untreated waste from St. Michael Church, combined with enhanced inputs of organic and inorganic materials such as algae, plankton, and decaying vegetation, along with intensified water mixing caused by wind action and sediment transport associated with erosion. In the Lakeshore Hotel vicinity, the highest dry-season reactive phosphate concentrations (M2, M2H1, and M2H2) were linked to untreated effluents, detergent-rich laundry wastewater, wind-borne soil particles, and nutrient-laden commercial cleaning products entering the lake through drainage channels.

In the wet season, elevated levels at this site (M1, M3, M4H1, and M4H2) resulted from combined organic and inorganic inputs and greater dispersion driven by human activities. Similarly, in the Shum Abo area, increased dry-season concentrations (T3, T3H1, and T3H2) were associated with wastewater discharges from Lake Tana Hotel and nutrient release following algal growth and decomposition, whereas wet-season peaks (T2H1) were primarily influenced by wind-induced mixing, suspended sediments, and substantial organic matter inputs, particularly from algae. Overall, these spatial patterns highlight the dominant roles of waste disposal, biological processes, erosion, and hydrodynamic mixing in controlling the distribution of reactive phosphate in the studied aquatic system.


TDS(mg/l)
Sampling points
station-001D
98.62 - 99.05
99.06 - 99.48
99.49 - 99.92
99.93 - 100.35
100.36 - 100.78
TDS(mg/l)
Sampling points
station-001W
98.87 - 102.08
102.09 - 105.28
105.29 - 108.49
108.5 - 111.69
111.7 - 114.9
TDS(mg/l)
Sampling points
station002W
TDS(mg/l)
Sampling points
station-002D
98.62 - 99
99.01 - 99.39
99.4 - 99.78
99.79 - 100.16

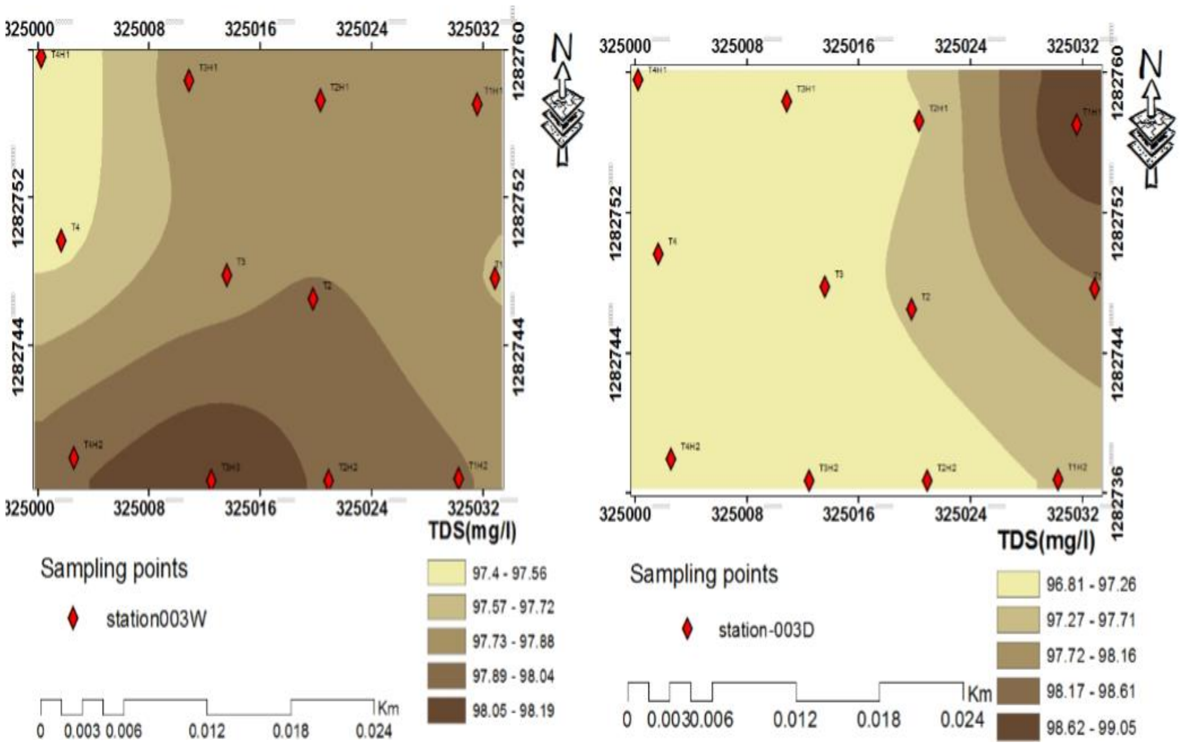


Figure 5. Spatial distributions of Total Dissolved Solids in the sampling points

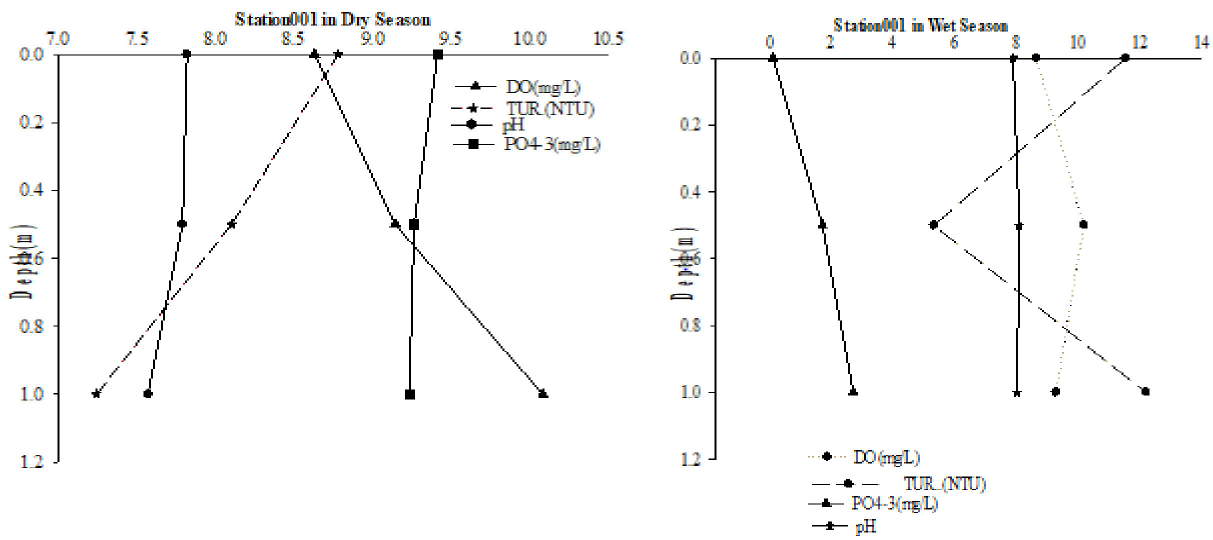
The spatial variability of Total Dissolved Solids (TDS) across the sampling stations exhibited clear seasonal and site-specific differences, mainly driven by anthropogenic discharges, natural mixing processes, and the presence of both inorganic and organic constituents (**Figure 5**). In the Avanti Hotel area during the dry season (A1, A1H2, A2H1), elevated TDS concentrations were primarily associated with untreated wastewater released from Avanti Hotel and St. Michael Church, along with high loads of dissolved inorganic ions, including chloride, nitrate, sulfate, phosphate, magnesium, calcium, iron, and aluminum.

During the wet season (A1H1), TDS levels further increased due to additional inputs of organic and inorganic materials such as algae, plankton, and decomposing vegetation, combined with wind-induced mixing and erosion that enhance the suspension and dissolution of substances within the water column. Similarly, at the Lakeshore Hotel site, the highest dry-season TDS values (M1) resulted from untreated effluent discharges, detergent-contaminated water from laundry activities, and inorganic-rich soil particles.

In the wet season at this location (M1), increased TDS concentrations were linked to enhanced runoff and mixing, which promoted the diffusion of dissolved organic and inorganic matter. In the Shum Abo area, dry-season TDS elevations (T1H1) were attributed to waste discharge from Lake Tana Hotel, whereas wet-season peaks (T3H2, T4H2) were influenced by wind-driven mixing and increased inputs of dissolved organic and inorganic substances. Overall, the observed TDS patterns across the sampling sites reflect the combined effects of human waste inputs, biological processes, erosion, and hydrodynamic mixing on water quality(Ewnetu et al., 2014b) (Cressie & Wikle, 2011)and (Ewnetu et al., 2014c)

3.4. Temporal and spatial variation of pollution levels in vertical depth

To investigate the effect of seasonal variation, sampling station, and sampling point along with vertical depth, the study collects water samples from three-level of sampling points (at the surface, at 0.5m below the surface, and 1m below the surface) for each sampling stations in both dry and wet season (**Figure 6**). As shown in the following figure, the results from the field and experimental work were displayed using sigma plots.



(A) (B)

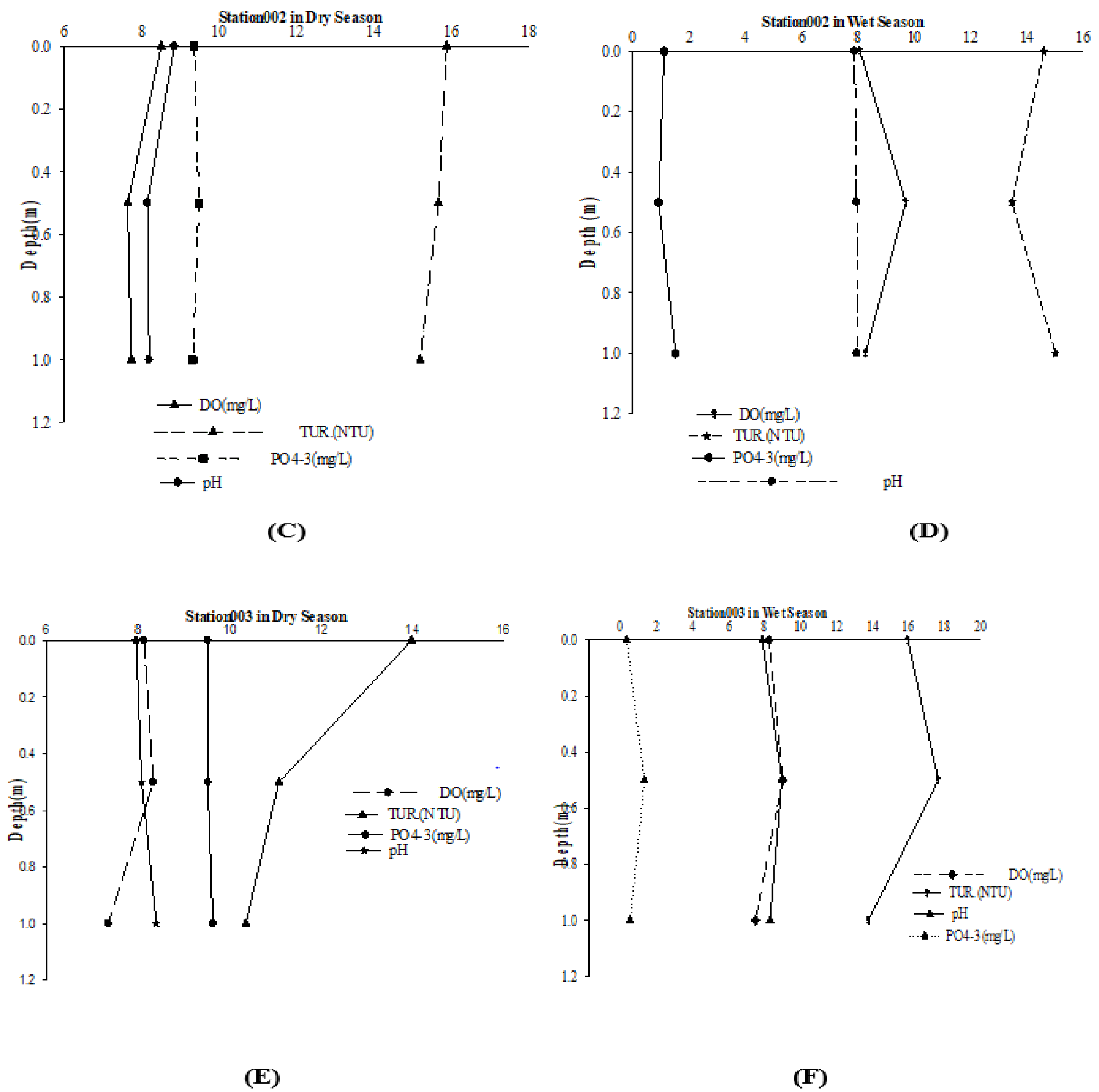


Figure 6. Temporal and spatial variation of Selective water quality parameters at various depth

3.4.1. Temporal and spatial Variation of DO concentration

Dissolved Oxygen (DO) levels in water vary by season, sampling station, and depth. As shown in **Figure 6**, the lowest DO (7.33 mg/L) was recorded during the dry season at Shum Abo Area, and the highest (10.19 mg/L) during the wet season at Avanti Hotel. At Avanti Hotel, DO increases with depth, influenced by air diffusion, water movement, and surface irregularities (Kale, 2016b). Generally, DO decreases with depth due to reduced photosynthesis and higher oxygen demand for organic matter decomposition. Aeration plays a crucial role in oxygen distribution near the water surface, influencing oxygen concentration levels (Berninger & Epstein, 1995).

3.4.2 Temporal and Spatial Variation in Ortho-phosphate Concentration

As shown in **Figure 6**, the sigma plot indicates that the maximum mean values of ortho-phosphate (PO_4^{3-}) were recorded during the dry season. Specifically, Avanti Hotel had 9.41 mg/L, Lakeshore Hotel had 9.47 mg/L, and Shum Abo Area had 9.62 mg/L. This suggests that PO_4^{3-} levels are higher in the dry season than in the wet season, likely due to the lack of dilution by water runoff. Additionally, the concentration of ortho-phosphate varies by sampling location. The highest value is 9.62 mg/L at Shum Abo Area, while the lowest mean value is 9.23 mg/L at Avanti Hotel during the dry season. This variation comes from the geographical location and pollution sources, like discharge from poly campuses. The sigma plot shows a slight decrease in ortho-phosphate concentration as the sampling depth increases. This happens because aquatic microorganisms near the water bed consume less. Changes in vertical distribution likely result from strong turbulent mixing due to wind action in the water column and nutrient uptake by phytoplankton. Increased nutrient load can occur when particulate nutrients settle from top to bottom or when inorganic phosphorus is released into the water column from the sediment bed under anaerobic conditions.

3.4.3. Temporal and Spatial Variation in Turbidity Concentration

The sigma plot shown in Figure 6, presented the maximum (17.63NTU) and the minimum (5.31NTU) turbidity values were recorded in the wet season at Shum Abo Area and Avanti Hotel respectively. The reason could be the high amount of pollutant effluent from the poly campus (having a lot of discharged wastes through the drainage system) which leads to an increase in the value of turbidity. The possible justification for maximum turbidity recorded in the wet season might be because of high water flow due to rain or wind in the wet season as compared with dry season(Akpor & Muchie, 2011) .

4. Conclusions

The study demonstrated that intense anthropogenic interference in the lake’s coastal zone was reflected by elevated values of all analyzed physicochemical parameters. Most parameters showed significant spatial and seasonal variations across the study sites. Among the locations examined, the Shum Abo area exhibited the highest level of pollution, primarily due to the direct discharge of untreated wastes into the lake and the absence of natural buffering or treatment mechanisms in the surrounding environment. In contrast, the Avantie Hotel area was comparatively less polluted, which can be attributed to the presence of aquatic plants, algae, and well-developed riparian vegetation that enhance natural purification processes.

Seasonal variation played a critical role in pollution dynamics within the southern Gulf of Lake Tana. Pollution levels were notably higher during the dry season, largely because of reduced dilution capacity compared to the wet season. Analysis of water quality parameters across all sampling stations revealed that the water in the southern Gulf of Lake Tana is unsuitable for drinking purposes. ArcGIS-based spatial analyses indicated variable dispersion patterns, with both increasing and decreasing trends observed among the parameters. During the rainy season, total dissolved solids (TDS), dissolved oxygen (DO), turbidity (TUR), and electrical conductivity (EC) generally exhibited increasing trends, whereas pH, temperature, phosphate (PO_4^{3-}), and biochemical oxygen demand (BOD_5) showed decreasing trends. No parameter displayed a stable or uniform overall pattern across seasons and locations.

The assessment of spatial and temporal variations in pollution load within the horizontal surface provided detailed insights into how physicochemical pollution fluctuates over time and space. In contrast, surface water pollution load distribution mapping using ArcGIS emphasized the spatial visualization of pollution patterns, with less focus on temporal dynamics. Together, these complementary approaches enhance the understanding of pollution processes, as physicochemical analyses identify trends while GIS-based mapping effectively illustrates their spatial distribution.

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