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An Assessment of Bathymetry, Hydrochemistry and Trace Metals in Sediments of Awoye Estuary in Ilaje Area, Southwestern Nigeria

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Abstract This study aimed at determining the depth profile and effects of domestic and economic activities on the accumulation of nutrients and trace metals in Awoye Estuary. Bathymetry profile along an approximately twenty-kilometre profile reveals a shallow water estuary, while its physico-chemical properties are greatly influenced by the influx of seawater, with chloride and sodium being the dominant ions. Low concentrations of calcium and potassium ion were observed across the estuary due to their preferential absorption with magnessium and sodium ion respectively. Nutrients concentrations such as phosphate and sulphate were present in relatively high amounts which can be hazardous to marine lives in the estuary, thus requiring urgent control. Results of trace metals in sediments show that concentrations of Pb, Zn, Cu, Cr and Ni are reflective of their inputs; with concentrations of Pb, Cu and Zn being higher at areas where there is high human population, oil exploration and economic activities. Generally, the estuary has fairly good water quality for the survival of marine lives. Sediments quality, however, needs to be closely monitored for ecological and public health risks associated with anthropogenic activities in the area.

Keywords: *bathymetry, physico-chemistry, nutrients, trace metals, estuary*

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1. Introduction

Estuaries, like other water bodies, are continuously subjected to dynamic state of change due to their geochemical characteristics, physical, biological and chemical processes which can influence water quality [1]. This is demonstrated by continuous circulation, transformation and accumulation of energy and matter by living organisms and their activities [2]. The dynamic balance in this ecosystem is altered by anthropogenic activities thereby affecting biological productivity of marine lives, damage to public health, as well as aesthetic damage to the environment [3].

Moreover, there has been an overwhelming increase in water quality deterioration of estuaries all over the world over the past few decades [4], with rapid industrialization and incessant anthropogenic pressures being identified as major driving forces polluting estuaries [5]. Pollution in coastal waters is more prominent in areas where rivers and streams are contaminated by organic substances from various activities of upstream users [6]. These activities range from agricultural practices, poor waste disposal management, transportation spills (oil from boats), faecal discharge, inefficient environmental monitoring plan among others. The coastal zone of Ilaje area in Southwestern Nigeria is one of such coast that requires regulation and monitoring [7].

Naturally, waters contain some types of impurities whose nature and amount vary with source. Trace metals such as cobalt (Co), iron (Fe), manganese (Mn), copper (Cu), and zinc (Zn) are essential micronutrients to plants at very low concentrations [8]. However, some trace metals are potential toxins to many biological systems especially in high concentrations. For instance, zinc (Zn), copper (Cu), chromium (Cr), nickel (Ni) and lead (Pb) have detrimental health effects on many marine organisms [9]. Sources of some trace metals such as Pb, Zn, Cd, and Cu could be natural through geological modification (dissolution from earth crust), or anthropogenic through atmospheric deposition, industrial and domestic sewage, run-off from agricultural field and chemical wastes discharged into bodies of water [10].

The pollution status of coastal waters of parts of Ondo State, including Awoye was investigated and found to be stressed by pollutants from both anthropogenic and natural sources, with indications of natural contributions of Fe, Mn and Cu from soils in the area [7]. Analyses of heavy metals and ionic radicals in water bodies within five communities in Ilaje area of southwestern Nigeria were also found to contain threatening concentrations of trace metals which calls for environmental/health concern [11]. Moreso, waters from coastal towns in Ilaje area were found to be good, stable and in a healthy aquatic ecosystem, within permissible level of aquatic biodiversity [12].

Since about 90 percent of marine fish and other living resources are found in estuaries and adjacent coastal water bodies [13], there is need to assess and monitor the estuary water quality and its effects on marine organisms; and the general well-being of the populace around it. Awoye Estuary, which is bounded by high economic activities and oil exploration, is well known for high productivity of sea foods [7,14]. The navigability of this estuary is also important to unlock the great socio-economic potential of the area which could lead to the development of a port facility that will boost the economic value of the region, and the nation at large. Public health is therefore at risk if the water gets polluted from all these activities, thus this study aims at assessing the bathymetry and extent of possible pollution in Awoye Estuary. This is with a view to identifying major pollution sources for the purpose of formulating management and conservation policies for the region.

2. The Study Area

Awoye Estuary is located within Latitudes 5.90 °N to 5.98 °N and Longitudes 4.90 °E to 5.02 °E, emptying into the Atlantic Ocean (Figure 1). The area is occupied by the Ilajes in linear settlements along the coast with a fast growing population [15], most of whom utilize the water for various purposes. The study area witnesses high economic activities with active oil exploration, fishing and other agricultural activities, trading and boat making. Boat transportation appears to be the only means of transportation of people and goods in the area. These activities, alongside other municipal use tend to pollute the water and its underlying sediments. The estuary is observed to be highly turbid, and this could be attributed to the silt and clay particles that make up the bottom sediments.

Generally, the area experiences a tropical climate consisting of both wet (April to October) and dry seasons [15]. During the wet season, the average rainfall index is about 3000 mm while the mean temperature is 28°C. The average rainfall index for the dry season is 800 mm with a mean temperature of 32°C [15]. Mangrove swamp is the dominant vegetation type in this area, especially the red mangrove *Rhizophora racemose* and the white mangrove *Avicennia spp*, typical of swamps. A striking feature of vegetation in the area is the desiccation induced by marine water incursion into about 10,000 hectares of freshwater swamp forest [16].

The terrain is characterized by near sea level swamp flat at the estuary which gently rises northward. The area is drained by many perennial streams and rivers, that traverse several settlements of the coast, and empties into the open ocean through this estuary with exchanges of water between the ocean and the coastline [15]. There is also the prevalence of erosion gullies along the river banks, shoreline and coastlines. Mud crack is a common sedimentary structure found in the area during the dry season, usually formed by dried saturated mud.

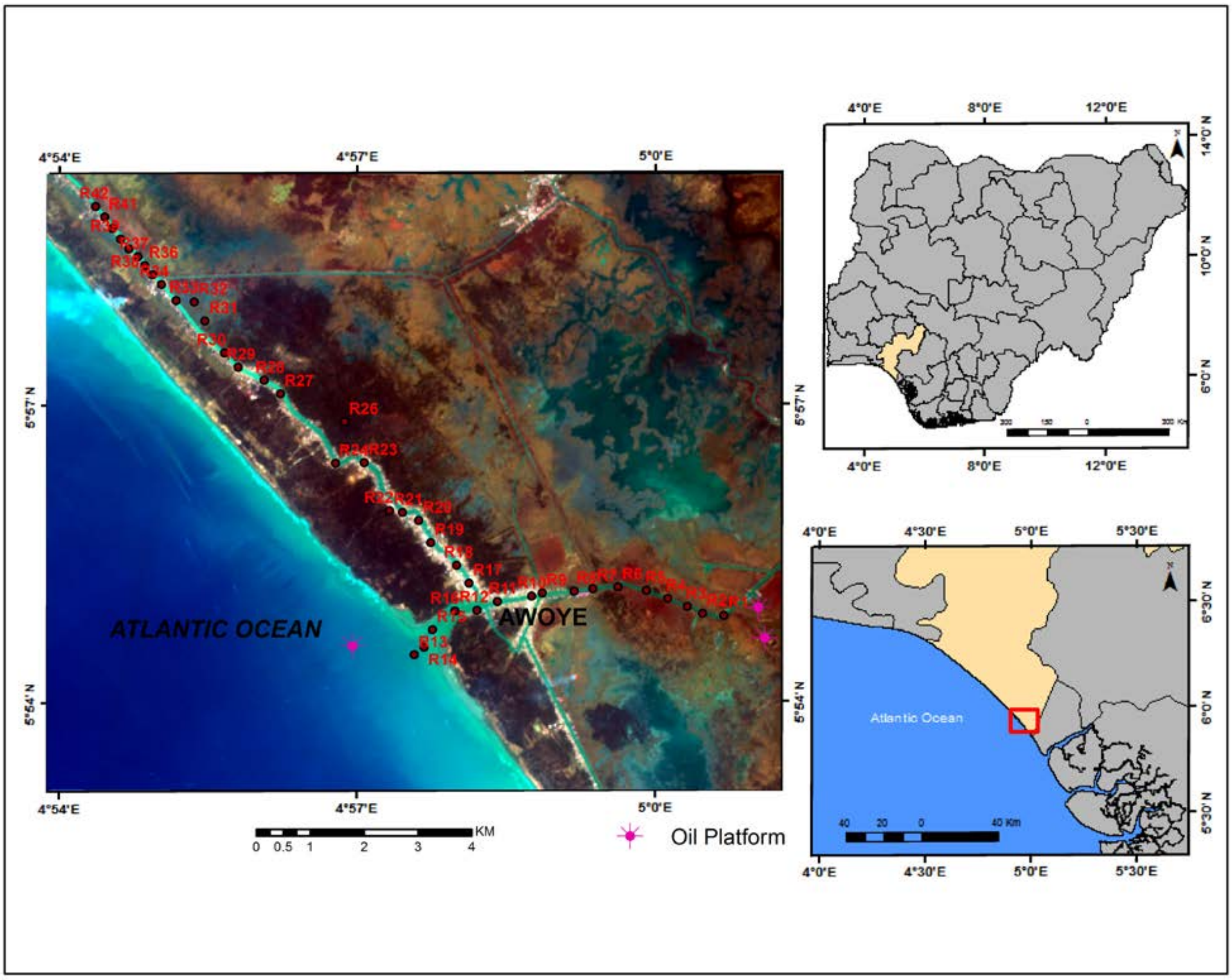

Figure 1. Satellite imagery map of the study area showing sampling points

3. Materials and Methods

3.1. Sample Collection and Preservation

Forty-two sampling points were established along a twenty-kilometre stretch, using a survey boat. The sampling points were determined based on proximity to the ocean, closeness to settlements, oil platforms and other commercial activities from the estuary. Station coordinates were determined using a Global Positioning System (GPS) in-built in the Hanna (Hi 9828) multi-parameter water analyser, which was used to take in-situ measurements of the physico-chemical properties of the surface water. Physico-chemical parameters measured include: temperature, pH, Total Dissolved Solids (TDS), Dissolved Oxygen (DO), salinity, Electrical Conductivity (EC), and density. Depth profiling was also carried out using Furuno 6 single beam echo-sounder, model LS-6100 (dual frequency 50 and 200 kHz) with pole-mounted transducer for depth measurement.

Surface water samples were collected at all locations, alongside representative sediment samples, for laboratory analyses. The water samples collected in plastic bottles were stored in an ice-packed cooler and later refrigerated at about 4^{o}C in the laboratory prior to chemical analyses, for major ion determination. Bottom sediments were collected for trace metal concentrations determination since they play a major role in the transport and storage of potentially hazardous metals in the marine environment [17]. The sediments were collected using a Van Veen sediment grab, and packed into aluminium foils.

3.2. Laboratory Analyses

The water samples were analyzed for chloride, bicarbonate, sulphate, phosphate, nitrate, calcium, magnesium, sodium and potassium at the Chemical Oceanography Laboratory of the Federal University of Technology, Akure. While EDTA Titrimetric method was used to determine calcium, magnesium and bicarbonate, sodium and potassium concentrations were determined by Flame Emission Photometric method using the Atomic flame photometer (PfP7). Argentometric titration was used for chloride determination, while Spectrophotometric analytical method was used to determine nitrate, sulphate and phosphate using Jenway 6705 UV-Visible spectrophotometer. Sediment samples were analyzed for five trace metals namely lead (Pb), zinc (Zn), copper (Cu), chromium (Cr) and nickel (Ni) using the Atomic Absorption Spectrophotometer (AA320N) at Geomodel Nigeria Limited Laboratory, Akure. The laboratory procedures were in accordance with standard methods as specified by the American Public Health Association (1995) [18].

4. Results and Discussion

4.1. Bathymetric Profile

Bathymetric study of the area shows shallow water estuary with depth ranging from 1.5 m to 5.6 m and an average depth of 2.7 m (Table 1). Relatively deep water at locations around R3, R10 and R33 were inferred to be as a result of dredging activities (Figure 2). Since the survey was conducted at the peak of dry season, the shallowness of the water could be as a result of siltation arising from the deposition of fine-grained sediments by the action of low tide energy, therefore posing a threat to safe navigation. With a depth of less than 8 m, the estuary pose a threat to safe navigation [19], thus impeding economic activities through transportation of agricultural produce in commercial quantities to urban areas. Also, depth variation shows no direct influence on the chemistry of the estuary since it shows no significant correlation with estuary water chemistry (Table 2).

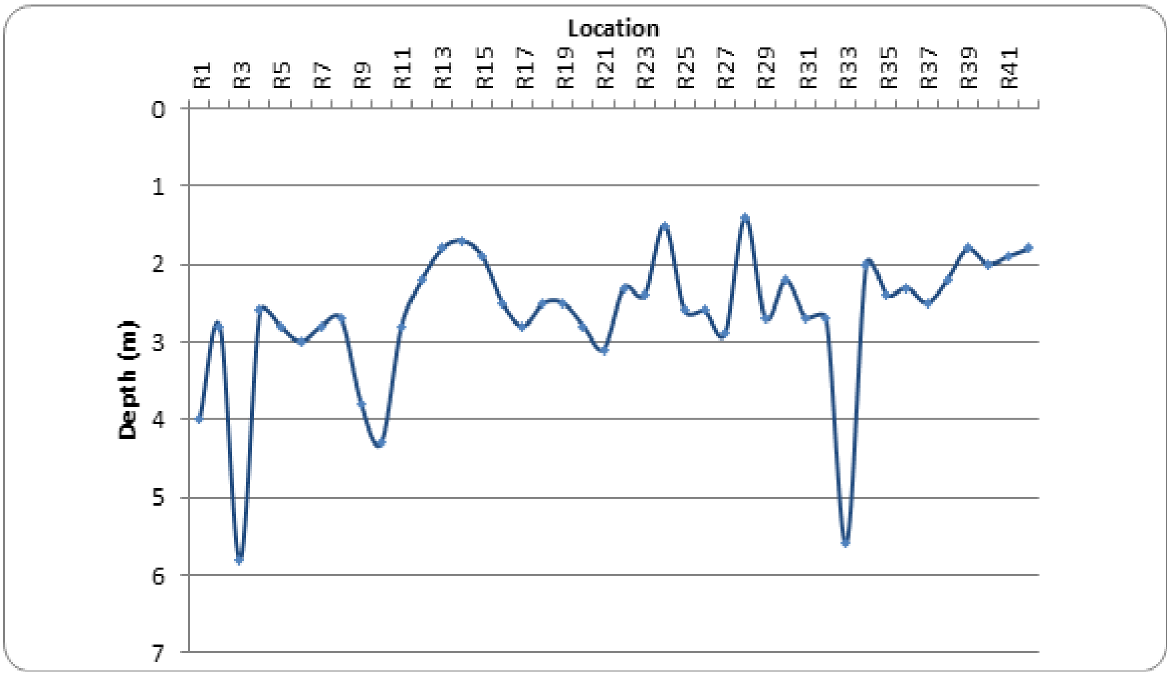

Figure 2. Bathymetric Profile of the Study Area

Table 1. Hydrochemical compositions of Awoye Estuary

Location	Depth (m)	Temp. (°C)	pH	TDS (ppm)	DO	Salinity (ppt)	EC (µS/cm)	Cl^- (mg/l)	HCO_3^- (mg/l)	NO_3^- (mg/l)	PO_4^{3-} (mg/l)	SO_4^{2-} (mg/l)	Ca^{2+} (mg/l)	Mg^{2+} (mg/l)	Na^+ (mg/l)	K^+ (mg/l)
R1	4.0	29.96	7.43	17900	3.68	22.52	36000	5052	1250	3	7.78	1880	83.4	1395	7300	286
R2	2.8	29.66	7.54	18880	3.79	23.82	37760	6012	1189	3.31	7.61	1844	83.6	1447	7468	294
R3	5.8	29.66	7.60	19450	3.85	24.63	38900	6204	1125	3.25	7.59	1797	83.4	1590	7600	306
R4	2.6	29.67	7.58	18490	3.36	23.33	36950	6514	1250	2.19	5.74	1896	131.5	1627	7900	250
R5	2.8	29.7	7.70	20080	4.21	25.25	40150	6647	1375	4.56	4.82	2214	104.0	1585	8250	304
R6	3.0	29.68	7.72	20340	4.01	25.91	40680	8021	1304	4.72	3.96	1997	111.7	1652	8400	318
R7	2.8	29.78	7.72	20450	4.09	26.02	40940	7988	1289	4.65	3.34	2101	108.8	1593	8390	312
R8	2.7	29.79	7.77	20560	4.08	26.22	41120	7356	1250	6.13	2.04	2154	120.2	1386	8500	318
R9	3.8	30.48	7.68	19500	4.82	24.65	38940	6585	1195	4.15	7.63	1843	94.2	1602	7788	307
R10	4.3	30.29	7.67	19130	4.47	24.19	38260	6684	1200	4.12	7.58	1812	87.6	1589	7665	306
R11	2.8	29.91	7.73	20020	4.05	25.41	40030	6524	1198	2.31	5.90	1905	130.5	1597	8040	264
R12	2.2	29.89	7.74	20220	4.11	25.7	40450	6440	1210	2.62	6.12	1879	132.3	1602	8104	278
R13	1.8	29.91	7.73	20600	4.11	26.24	37240	6500	1208	2.42	5.92	1911	128.2	1602	8100	266
R14	1.7	30.06	7.73	20241	4.26	25.72	40490	6455	1147	2.46	5.79	1902	128.5	1600	7998	248
R15	1.9	30.11	7.63	19520	4.21	24.7	39040	6204	1125	3.25	7.59	1905	83.4	1590	7600	306
R16	2.5	30.21	7.50	17590	3.71	21.99	36460	5052	1250	3	7.59	1879	93.4	1395	7300	286
R17	2.8	30.28	7.31	15860	5.11	19.68	31660	4874	1205	2.89	11.67	1757	108.2	1347	6500	214
R18	2.5	30.23	7.27	16330	3.19	20.29	32610	4579	1301	3.12	5.79	1807	117.3	1421	7212	245
R19	2.5	30.43	7.14	12900	3.07	15.6	25800	4326	1305	3.05	7.56	1478	105.6	1359	6350	178
R20	2.8	30.54	7.08	11840	2.94	14.32	23610	3845	1256	2.56	6.87	1271	120.1	1405	4778	156
R21	3.1	30.52	7.07	10970	2.89	13.13	21830	3326	1289	2.34	7.38	1090	104.6	1398	5030	120
R22	2.3	30.53	7.05	10350	2.89	12.32	20580	2578	1302	2.41	7.59	878	121.2	1341	3879	104
R23	2.4	30.56	7.08	8265	2.82	9.61	16530	1281	1250	1.94	9.07	467	152.3	1329	2650	66
R24	1.5	30.66	6.93	7733	2.82	8.94	15470	1421	1287	2.15	8.97	461	145.7	1321	2784	72
R25	2.6	30.63	6.91	7552	3.83	8.72	15100	1387	1297	2.32	8.78	458	148.5	1289	2744	78
R26	2.6	30.67	6.91	7375	2.96	8.49	14750	1403	1302	2.45	8.83	439	132.1	1306	2903	91
R27	2.9	30.69	6.89	6999	2.98	8.04	13980	1348	1104	2.38	7.91	422	137.5	1287	2699	88
R28	1.4	31.03	6.93	7182	3.17	8.29	14290	1352	990	2.41	7.87	425	141.2	1297	2579	90
R29	2.7	30.81	7.01	6814	2.90	7.79	13630	1362	1045	2.41	7.54	418	144.6	1208	2598	78
R30	2.2	30.89	6.99	6613	3.08	7.55	13220	1376	1005	2.33	7.33	408	142.6	1211	2604	83
R31	2.7	31.09	6.99	6509	3.26	7.43	13600	1322	929	2.32	6.90	413	152.5	1195	2551	72
R32	2.7	30.87	7.07	6372	3.18	7.37	12940	1299	876	2.54	6.43	400	149.5	1192	2489	77
R33	5.6	31.04	7.05	6324	3.35	7.19	12650	1243	847	2.27	7.02	406	156.2	1202	2514	81
R34	2.0	30.9	7.06	6240	3.68	6.99	12460	1199	799	2.44	6.19	379	161.5	1189	2345	69
R35	2.4	30.81	6.98	6052	3.26	6.71	12100	1288	754	2.65	4.989	367	151.1	1078	2381	75
R36	2.3	31.08	6.89	5980	3.00	6.59	11960	1211	690	2.58	4.78	358	157.7	1091	2226	73
R37	2.5	31.06	6.93	5909	2.76	6.45	11820	1195	664	2.24	4.124	342	148.5	1102	2217	65
R38	2.2	30.87	7.00	5742	3.28	6.12	11580	1148	625	2.19	2.96	331	160.3	1010	2250	60
R39	1.8	30.89	7.11	5702	2.88	6.02	11400	1124	257	2.99	2.25	334	142.3	1008	2189	52
R40	2.0	30.69	6.98	5556	3.16	5.86	11120	1023	189	4.12	1.45	329	128.8	1023	2108	47
R41	1.9	30.65	6.99	5408	3.04	5.76	10810	1103	200	5	1.11	324	125.1	994	2150	50
R42	1.8	30.79	6.90	5275	2.90	5.46	10550	997	201	5.34	1.21	328	118.4	987	2099	48

4.2. Physico-chemical Parameters

Results of the physico-chemical properties across the study area presented in Table 1 show that surface water temperature across the estuary ranges from 29.7°C to 31.1°C with a mean of 30.4°C; which is relatively uniform but increases gradually away from the estuary. This can be attributed to the increase in temperature as solar intensity increases across the sampling period. Although the mean surface water temperature of 30.4°C is slightly higher than the optimum temperature range of 28°C - 30°C, maximal growth rate and best condition of fish and other aquatic lives, as well as resistance to disease and tolerance of toxins can be achieved [20]. The pH with values ranging from 6.89 to 7.77 (average of 7.26) indicates that the estuary is slightly neutral to slightly alkaline with a non systematic variation away from the sea, and thus doesn't show a consistent transition between freshwater and seawater (Figure 3). On the other hand, Electrical conductivity (EC) with value range of 10550 to 41120 µS/cm, salinity ranging from 5.46 to 26.24 ppt and TDS ranging from 5275 to 20600 ppm show a sharp decrease away from the sea due to mixing of seawater with river water (Figure 3). Therefore TDS, salinity and electrical conductivity are higher at points close to the inlet and gradually reduces farther from the estuary, with profile generally flattening out in the brackish water zone (Figure 3). Nevertheless the pH falls within the required 6.5 - 8.5 for the survival of fishes and other aquatic lives [21], and EC values as reflected by the degree of salinity of the estuary water is an index of total ionic content in the estuary [22].

Dissolved oxygen (DO), which is essential to all forms of aquatic life including the organisms that break down man-made pollutants, ranges between 2.76 to 5.99 ppm (with average of 3.51 ppm). This implies that the estuary could be considered for optimal support for marine lives, and desirable for fish survival [11,23,24].

4.3. Major Ion Concentrations

Result of the major ions (Cl^-, HCO_3^-, NO_3^-, PO_4^{3-}, SO_4^{2-}, Ca^{2+}, Mg^{2+}, Na^{2+} and K^+) in the surface water as presented in Table 1 shows that Cl^- concentration, with values ranging from 997 mg/l to 8021 mg/l (average of 3639 mg/l), is highest at the lower estuary (points closer to the ocean) and gradually reduces to farthest point from the ocean. This is directly related to the physical mixing of seawater with the adjacent river water, as it is also reflected with its strong correlation coefficient with salinity (0.987) and electrical conductivity (0.986) as shown in Table 2. Bicarbonate concentration ranges from 189 mg/l to 1375 mg/l (average of 1037 mg/l). It showed a slightly decreasing concentration from the ocean due to downstream dilution by seawater, but fluctuations occur in the middle reaches (Table 1 and Figure 4) between locations R19 to R22, which are suggestive of contributions from groundwater [25]. Nitrate (NO_3^-) and SO_4^{2-} and PO_4^{3-} are regarded as nutrients for proper growth of marine plants and animals. Sulphate with concentration ranging from 324 mg/l to 2214 mg/l (av. 1310 mg/l) also exhibits a relatively higher concentration under the influence of seawater mixing, while PO_4^{3-} and NO_3^- concentrations ranges between 1.1 mg/l to 11.7 mg/l (av. 6.2 mg/l) and 1.9 mg/l to 6.1 mg/l (av. 3.0 mg/l) respectively do not exhibit similar trend as other anions (Figure 4), suggesting anthropogenic influence (possibly from the decomposition of organic wastes from domestic and agricultural activities around the estuary). Nevertheless, NO_3^- were present in considerable amounts within the USEPA (2002) [26] standard for water quality while sulphate has relatively high concentrations above 250 mg/l across the area which could be hazardous to marine lives in the estuary [26]. PO_4^{3-} have concentration (>0.1 mg/l) greatly exceeding 0.005 mg/l, the recommended maximum concentration in flowing water to prevent eutrophication [27].

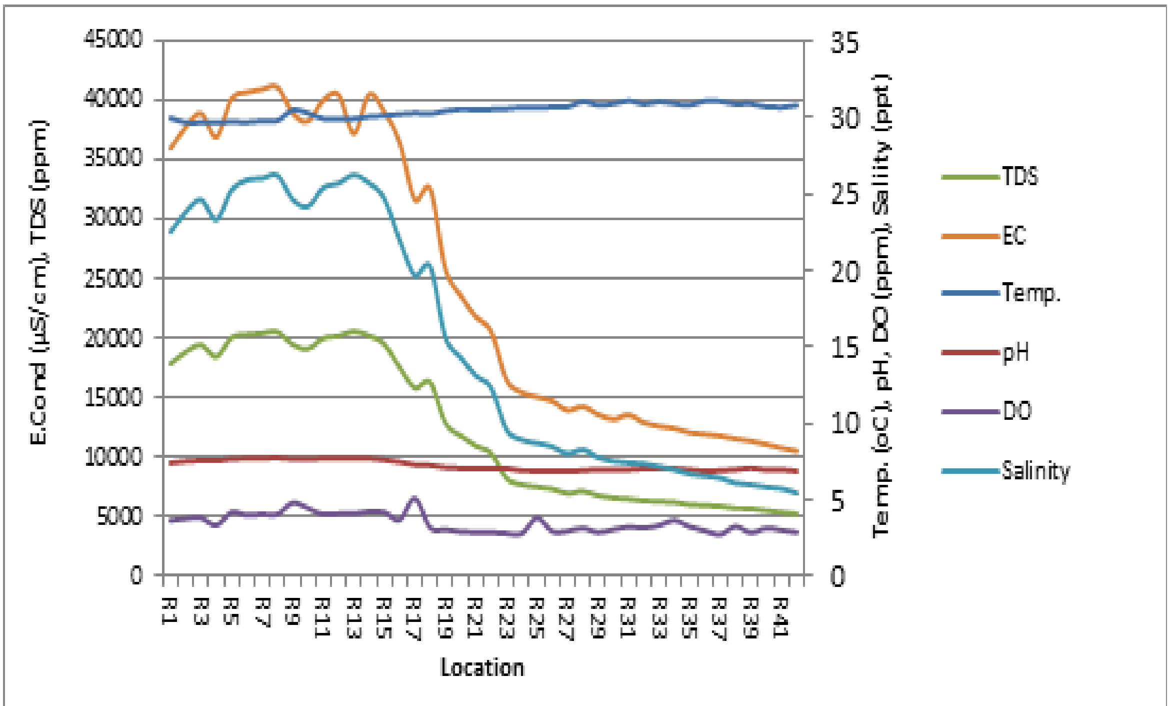

Figure 3. Physico-chemical properties across the Estuary

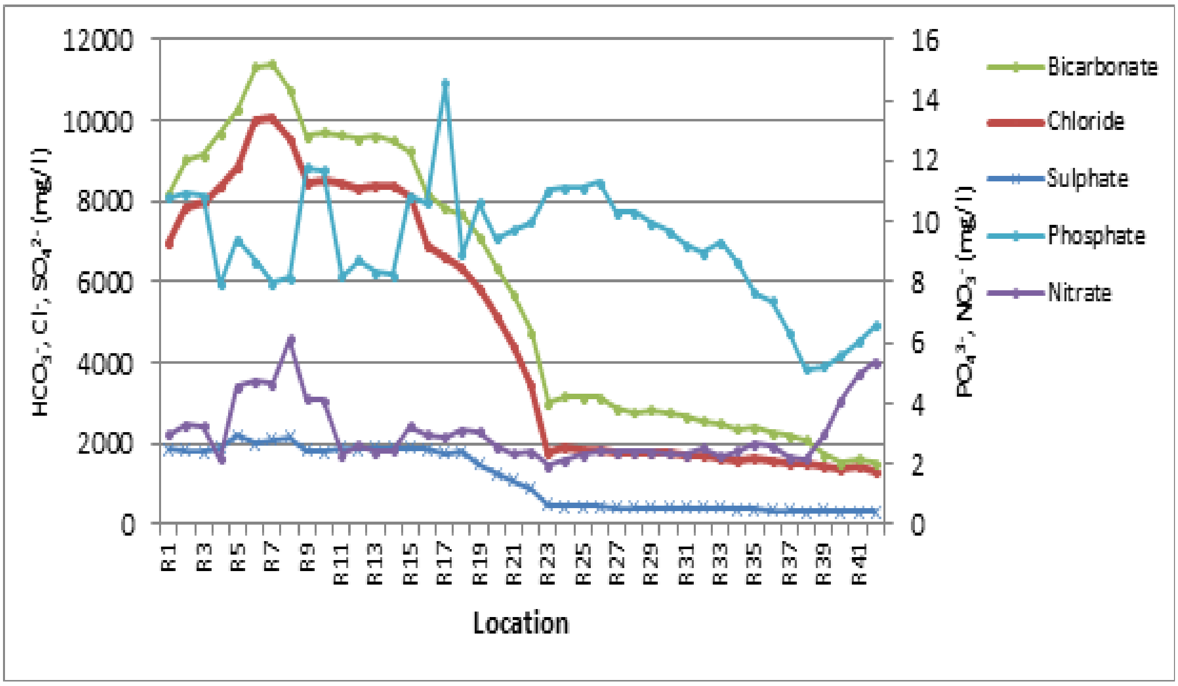

Figure 4. Profile of the major anions across the estuary

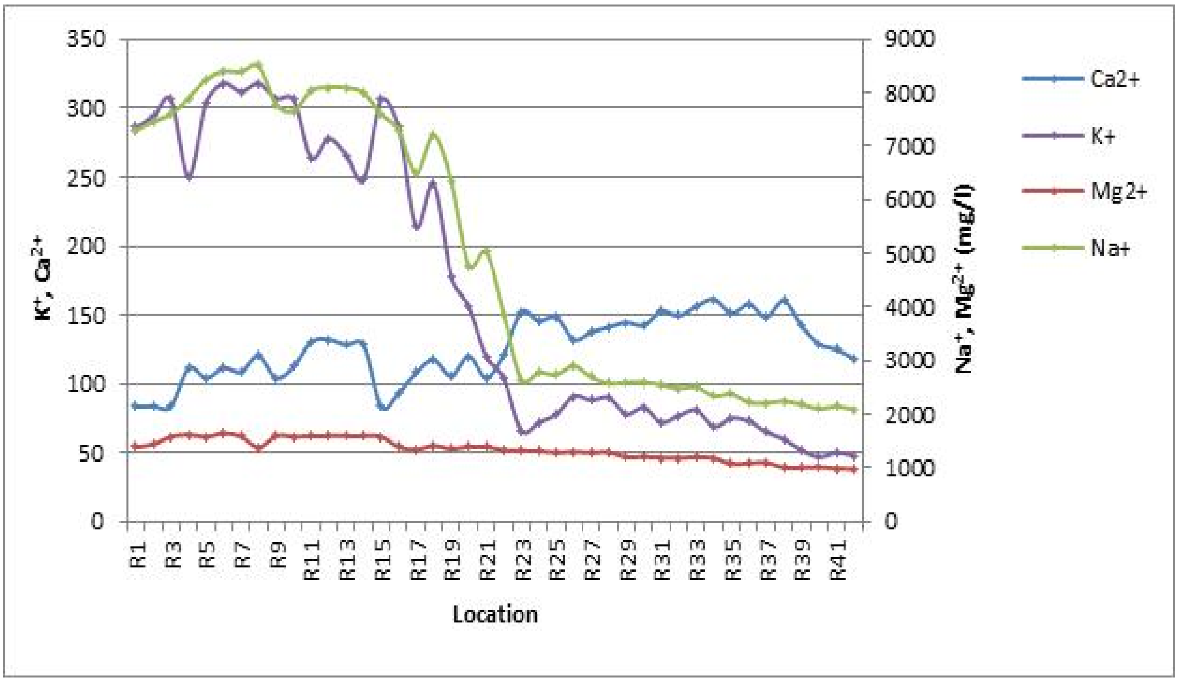

Figure 5. Profile of the major cations across the estuary

Concentrations of the major cations show that Ca^{2+} and Mg^{2+} concentrations ranging from 83.4 mg/l to 161.5 mg/l (av. 125.7 mg/l) and 987 mg/l to 1652 mg/l (av. 1341 mg/l) respectively, have no similar trend (Figure 5). Sodium and potassium showed wide variations, with concentrations ranging from 2099 mg/l to 8500 mg/l (av. 4982 mg/l) and 47 mg/l to 318 mg/l (av. 169 mg/l) respectively, with concentrations decreasing away from the ocean (Table 1 and Figure 5). Potassium concentration was lower than sodium across the estuary, which could be as a result of its preferential absorption and incorporation onto silicates [25,28]. Generally, low concentrations of Ca^{2+} and K^+ were observed across the estuary with values of Ca^{2+} lightly increasing away the ocean and K^+ reducing upstream to the freshwater. Low concentration of Ca^{2+} may be due to the absorption of Ca^{2+} and K^+ through ion exchange by Mg^{2+} and Na^+ on the clay minerals in the estuary. However, Na^+ concentration dominates the cations as a result of mixing of seawater in the lower areas from the inlet to the ocean (Table 1 and Figure 5).

Correlation coefficient of the major ions in the estuary (Table 2) show significant positive correlation between Cl^- and Mg^{2+} (0.893), Na^+ and K^+ (0.981), Mg^{2+} and HCO_3^- (0.797) suggesting similar sources from the ocean, while Ca^{2+} has negative correlation coefficient with all other major ions and salinity suggesting that it is derived from freshwater sources.

Table 2. Correlation matrix relating depth, physico-chemical parameters and major ions in Awoye Estuary

	Depth	Temp	pH	TDS	DO	Salinity	EC	Cl^-	HCO_3^-	NO_3^-	PO_4^{3-}	SO_4^{2-}	Ca^{2+}	Mg^{2+}	Na^+	K^+
Depth	1															
Temp	-0.220	1														
pH	0.248	-0.882	1													
TDS	0.264	-0.921	**0.963**	1												
DO	0.266	-0.613	**0.791**	**0.765**	1											
Salinity	0.266	-0.920	**0.964**	**1.000**	**0.766**	1										
EC	0.273	-0.920	**0.961**	**0.999**	**0.764**	**0.998**	1									
Cl-	0.269	-0.914	**0.962**	**0.986**	**0.757**	**0.987**	**0.986**	1								
HCO_3^-	0.249	-0.562	0.483	**0.630**	0.383	**0.633**	**0.632**	0.594	1							
NO_3^-	0.076	-0.380	0.391	0.337	0.340	0.334	0.344	0.408	-0.172	1						
PO_4^{3-}	0.255	-0.011	-0.035	0.115	0.177	0.118	0.118	0.034	0.662	-0.574	1					
SO_4^{2-}	0.083	-0.451	0.402	0.475	0.249	0.473	0.474	0.458	0.442	0.106	0.137	1				
Ca^{2+}	-0.358	0.684	-0.618	-0.719	-0.508	-0.714	-0.727	-0.705	-0.385	-0.481	-0.150	-0.421	1			
Mg^{2+}	0.288	-0.820	**0.846**	**0.908**	**0.653**	**0.910**	**0.905**	**0.893**	**0.797**	0.094	0.352	0.459	-0.594	1		
Na^+	0.266	-0.917	**0.948**	**0.994**	**0.740**	**0.993**	**0.993**	**0.987**	0.632	0.350	0.098	0.466	-0.730	**0.895**	1	
K^+	0.335	-0.896	**0.946**	**0.984**	**0.767**	**0.984**	**0.986**	**0.976**	0.608	0.397	0.107	0.431	-0.764	**0.874**	**0.981**	1

Depth (m), Temp-Temperature (°C), TDS (ppm), DO (ppm), Salinity (ppt), EC (μS/cm) while all major ion values are in mg/l.

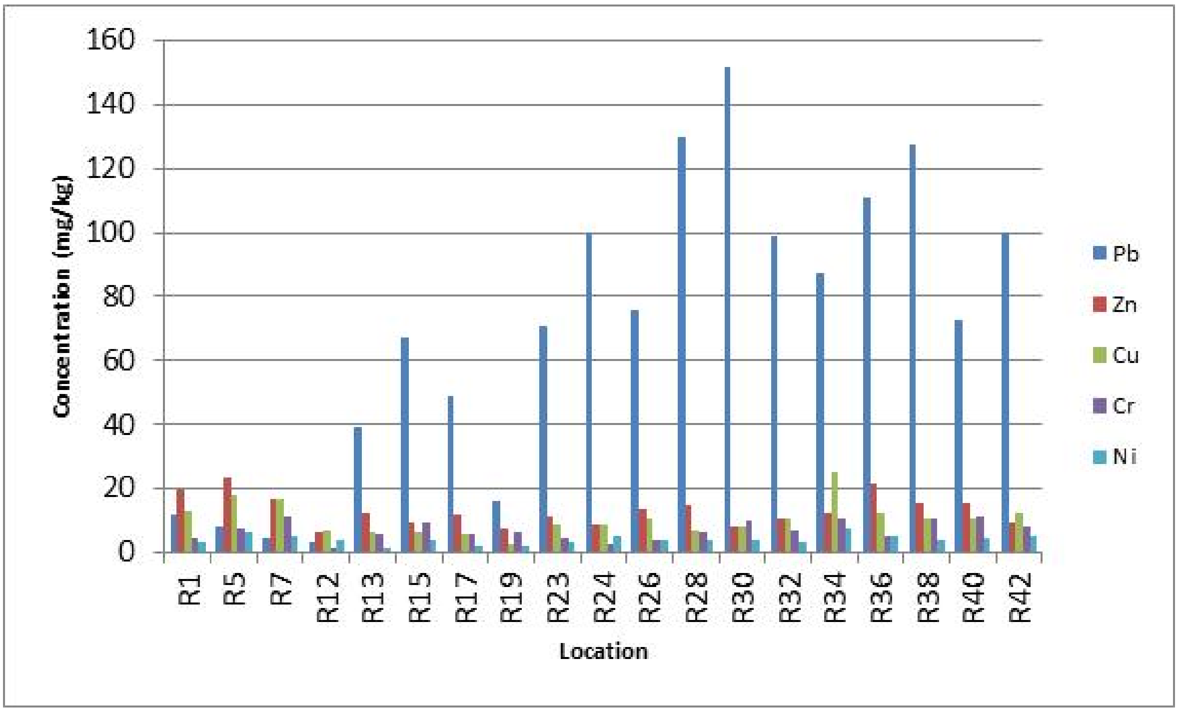

Figure 6. Trace metal distribution across the estuary

4.4. Trace Metal Concentrations

The results obtained for trace metals in sediments in selected parts of the estuary shows that concentrations of Pb, Zn, Cu, Cr and Ni are reflective of their inputs into the estuary (Table 3 and Figure 6). Lead is the most abundant in the estuary with concentration ranging from 3.3 mg/kg to 152.1 mg/kg with a mean of 69.7 mg/kg, followed by Zn with values ranging from 6.4 mg/kg to 23.5 mg/kg (av. 13.1 mg/kg), and Cu ranging from 2.7 mg/kg to 25.4 mg/kg (av. 10.6 mg/kg). While there is dominance of concentrations of Pb Zn and Cu, Cr and Ni concentrations were relatively low at most sites with values ranging from 1.5 to 11.1 mg/kg (av. 6.9 mg/kg) and 1.4 to 7.5 mg/kg (av. 4.0 mg/kg) respectively. In general, the concentrations of Pb in the sediments were higher at locations around the sea inlet and the upper parts of the estuary where there are high human populations and economic activities. The locations closer to the inlets have lower concentrations of Pb (Table 3), thereby suggesting anthropogenic sources. High Pb concentrations could be attributed to discharge from oil spills during offloading of petroleum products from filling stations as well as from emissions from boat exhausts [32]. On the other hand, Zn concentrations were high around locations R1 through R12 (Figure 1) possibly as a result of contributions from nearby oil platforms, possibly made of Zn-based alloys to prevent corrosion. Copper concentration is also high at locations closer to oil platforms (Location R1-R7) possible as a result of oil spills; and further up the estuary due to the effect of human activities. As shown in Table 3, concentrations of Pb and Cu when compared with some sediment quality guidelines exceed water quality criteria for protection of aquatic life, and indirectly on human health [24,30,31]. Nevertheless, the concentration of these trace metals in the estuary should be closely monitored because of their tendency to bioaccumulate in the marine lives, thus posing a public health concern.

Table 3. Trace metal concentrations in sediments of parts of Awoye Estuary (Modified from [29]).

Location	Pb	Zn	Cu	Cr	Ni
R1	11.68	19.41	12.88	4.62	3.11
R5	7.90	23.50	18.11	7.45	6.26
R7	4.61	16.94	16.88	11.13	4.88
R12	3.29	6.39	7.12	1.45	3.93
R13	39.47	12.63	6.30	5.40	1.44
R15	67.33	9.47	6.21	9.24	3.77
R17	48.76	12.03	5.92	5.51	1.76
R19	16.25	7.69	2.74	6.57	1.99
R23	70.82	11.27	9.04	4.23	3.17
R24	99.84	8.62	8.98	2.89	5.36
R26	75.46	13.73	10.55	3.84	3.92
R28	130.03	14.60	6.96	6.51	3.65
R30	152.09	7.90	7.94	9.79	4.15
R32	98.68	10.61	10.30	6.73	3.10
R34	87.20	12.38	25.43	10.83	7.49
R36	110.85	21.67	12.58	4.95	5.27
R38	127.17	15.15	10.77	10.32	3.86
R40	72.90	15.69	10.87	11.08	4.58
R42	100.19	9.25	12.52	8.29	5.10
water quality criteria for the protection of aquatic life					
[31]	100	100	10	100	1000
[32]	10	180	20	50	50

Values are in mg/kg.

5. Conclusions

This study has provided a preliminary assessment of the bathymetry, hydrochemistry (involving physico-chemical parameters and major ions) and trace metal concentration of about 20-kilometer stretch Awoye Estuary for continuous monitoring of the effects of oil exploration and other economic activities in the area. The bathymetry of the estuary shows a relatively shallow water body which requires dredging for safe navigation by large vessels, to boost economic growth in the area. The estuary also possesses water and sediment qualities that vary across the area, with some pollution problems at strategic locations, mainly associated with anthropogenic activities such as high domestic waste discharge and effect of oil exploration. Marine water incursion also plays an important role in controlling the chemistry of the estuary, as shown by the relationships between salinity, TDS and major ions. Although the water is not fit for human consumption, the estuary possesses a fairly good property for the habitation of marine lives; it was observed that the estuary has a high concentration of SO_4^{2-} and PO_4^{3-} which could be harmful to marine lives and thus requiring urgent control. High concentrations of Pb and Cu in areas of high human populations and economic activities could be attributed to spillage of petroleum products from boat users and emission from boat exhausts while relatively high Zn concentrations close to oil platforms can be attributed to contributions from Zn coatings of the platforms into the sediments of the area.

In conclusion, physical mixing of fresh and saltwater, and anthropogenic effects from domestic waste, economic activities and oil exploration appeared to control water and sediment quality across the estuary. Thus this study provides valuable information for further ecological assessment of anthropogenic activities in the area, and overall monitoring of the estuary. There should be continuous pollution assessment in order to determine the effect of seasonal variations on the observed concentrations. Also, concentrations of persistent organic pollutants (POP) and Total Petroleum Hydrocarbon (TPH) in sediments and various marine biota of the estuary should be assessed to determine the ecological risks associated with the estuary.

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