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Full Length Research Paper

Determining and modeling the dispersion of non point source pollutants in Lake Victoria: A case study of Gaba Landing site in Uganda

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Lake Victoria is an important source of livelihood that is threatened by rising pollution. In this study, pollutants in runoff are characterized and their dispersion after they enter the lake is measured and modeled at different points in the study areas. The objective is to develop a one dimensional mathematical model which can be used to predict the nutrient (ammonia, nitrite, nitrate, and phosphate) dispersion distances within the lake. A comparison between rain period nutrient concentrations and dry period nutrient concentrations within the Lake showed an elevation in nutrient levels during the rainy season, with exception of nitrate. However, nitrate had high levels during the dry season. Ammonia was found to disperse to horizontal distances of 38 m; nitrite 45 m, with nitrate and phosphate each attaining distances of 34 m. Measured nutrient concentration within the Lake compared well with model estimations.

Key words: Modeling, water quality, nutrients, lake Victoria.

INTRODUCTION

Lake Victoria is one of the largest freshwater bodies of the world. Although Lake Victoria is bordered by Kenya, Tanzania, and Uganda, streams and rivers stretching as far as Burundi and Rwanda also flow into it. Lake Victoria is a source of food (fish), water, use for transport, hydroelectric power generation, and recreation. In recent years, it is also being used as dumping ground for various types of waste ranging from household waste, mechanical waste, municipal waste (Chege, 1995; Matagi, 2002; MWLE, 2006). According to Kyomuhendo (2002), the once clear, life-filled Lake Victoria is now murky and smelly. The ecological health of Lake Victoria has been affected profoundly as a result of rapidly increasing human population due to migration to the area by plantation workers, clearance of natural vegetation along the shores to establish plantations of coffee, tea and sugar (MWLE, 2006), and dumping of untreated effluent by several industries (Matagi, 2002) leading to prolific growth of algae (Kyomuhendo, 2002; Larsson, 2002) The National Water and Sewerage Corporation charged with treating and supplying water to Kampala City dwellers are complaining of rising cost for treating water (Banadda et al., 2009). A number of studies (Chege, 1995; Makundi, 2001; Matagi, 2002; Kyomuhendo, 2002; Larsson, 2002; Campbell et al., 2004) have documented pollution as one of the major problems causing water quality deterioration. Agriculture remains as the single greatest contributor of these pollutants to soil and water resources (Humenik et al., 1987). The most common non point source (NPS) pollutants include eroded sediments, fertilizers, pesticides, organic manures, salts, trace elements and sewage sludge. As pointed out by Duda (1993), the magnitude of NPS pollution is so complex and difficult to characterize that it defiles proper evaluation with respect to its environmental impact. Nevertheless, NPS pollutants are recognized as the major contributors to surface and

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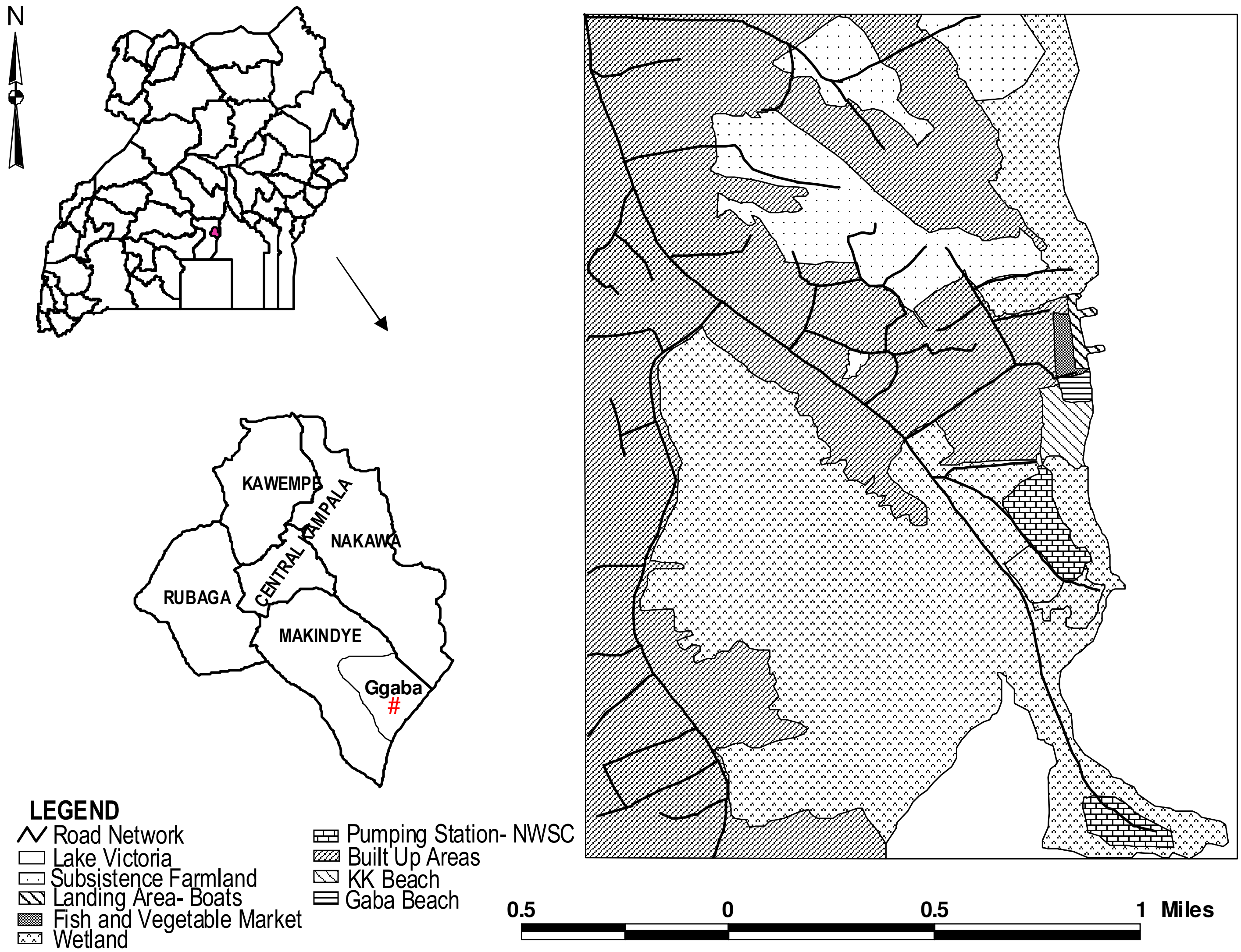

Figure 1. Land use activities in Gaba, Kampala, Uganda.

groundwater contamination worldwide (Duda and Nawar, 1996). Even within the highly industrialized, NPS pollutants impair far more rivers and lakes than point sources (USEPA, 1994). In spite of the enormous attention that has been paid to the pollution problem during the last three decades, it has persisted. In this study, NPS is the main focus. Although NPS often impacts at a larger scale and some authors such as Makundi (2001) have reported the situation in the Lake Victoria, literature indicates that no studies aimed at developing first principles models capable of predicting dispersion of such type of pollution have been carried out. The aim of this study is twofold (1) to characterize pollutants in surface runoff originating from shore settlement around Lake Victoria, and (2) to develop a one dimensional mathematical model, which can be used to predict nutrient dispersion distances within the lake.

MATERIALS AND METHODS

Study area

The study was being carried out at Gaba landing site located in Makindye division, Kampala (Uganda) as shown in Figure 1.

Sample collection and analysis

Samples were taken during 2010, two rainy seasons were considered while one dry season was used for comparative purposes. Sixty eight samples were taken for each rainy season and 64 samples for dry season and analyzed. To ensure that samples were always taken from the same spot within the lake, sampling points were geo-referenced by taking the coordinates using a geographical positioning system (GPS) on a boat. The sampling coordinates were stored in a GPS and later traced during subsequent sampling. The land surface mapping was done after rain event in order to locate the path/areas these runoff normally follow when released into the Lake. Samples were stored in a cooler and transported within less than two hours for laboratory analysis that include nutrients (such as Ammonia, Nitrite, Nitrate, and Phosphate). Conductivity (EC), total dissolved solids (TDS), total suspended solids (TSS), temperature (T), dissolved oxygen (DO). HQ10LDO meters were used to measure pH, EC, TDS, T, and DO instantaneously at point of sample collection. Within the lake samples were taken at five points for horizontal transects of 10 m interval over a distance of 50 m starting from the shore where surface runoff was released. For the same sampling points within the lake, samples were drawn at vertical distances of 0.5, 1.0 and 1.5 m from water surface using a hand pump with graduated delivery pipe so as to take samples at the required vertical depth.

Modeling approach

The modeling approach used is based on the fundamental principle of conservation of mass for managing surface water quality (Biswas, 1976), as described by Equation 1.

$$\frac{1}{A}\left\{\frac{\partial}{\partial x}\left[\Psi(x)A(x)\frac{\partial C(x,t)}{\partial x}\right]-\frac{\partial}{\partial x}\left[Q(x,t).C(x,t)\right]\right\}+\vartheta(x,t)=\frac{\partial C(x,t)}{\partial t} \quad (1)$$

where t is time, x is the coordinate of a point on the water body (10, 20, 30, 40 and 50 m), $A(x)$ is cross sectional area at x, $\Psi(x)$ is longitudinal dispersion coefficient at x, $C(x,t)$ is the concentration of nutrient of interest at x and time t, $Q(x,t)$ is flow rate at x and t, and $\vartheta(x,t)$ is the net rate of addition (or subtraction) of nutrient due to sources and sinks at x and t.

Waste water flow within a given time was considered constant under the assumption that the parameters for dispersion $D(x)$ flow $Q(x)$ and area $A(x)$were also constant for all points x within some limited distance along a water course. Therefore, only the concentrations of material of interest at various locations x along the water course need be determined.

$$\Psi\frac{d^2C(x)}{dx^2}-\frac{Q}{A}\frac{dC(x)}{dx}+\vartheta(x)=0 \quad (2)$$

Equation (2) was integrated to give the residual concentration of a pollutant at any distance or point x due to the steady discharge at another point x (Equation 3).

$$C_{ij}=\alpha_{ij}C_i \quad (3)$$

where Cij was the concentration of pollutant at site j resulting from the discharge of pollutant from site i.

Data analysis

Data analysis involved the determination of mean and standard deviation using Microsoft Excel and SPSS software packages.

RESULTS AND DISCUSSION

Close to the Lake shore, the concentration of nutrients was very high due to release of nutrients into the lake by surface runoff. Further into the lake, the variability ceases to exist because of dispersion and mixing. The variability is confined within 20 m distance from lake shore mainly in the vertical direction. This variation in the vertical direction is attributed to the settlement of heavier particles having attained their terminal velocity. These particles carry nutrients that are released into the lake. It was also observed that siltation progresses at a faster rate as some of the points used for sampling could not be used as they have become shallow.

Physico-chemical variables within Lake Victoria

The DO level in surface runoff was 16.7 mg/L. In the Lake water, DO ranged from 9.9 to 6.2 mg/L in the rainy season, while in dry season the level ranged from 3.6 to 7.6 mg/L at the shore and 50 m mark respectively, for a lake depth of 0.5 m. The average DO concentration in rainy season was thus higher than that for the dry season as shown in Figure 2.

The DO concentration decreased from shore into the Lake in rain season and increased from shore into the lake during the dry season. In the rainy season, the low DO concentration close to the shore can be attributed to high discharge of organic waste emanating from human activities. This increases biological activity, and consumes oxygen in the process. There was decrease in DO concentration from the water surface into the lake. There was an exponential decrease from point of surface runoff discharge into the lake. Overall its concentrations both in dry and rain seasons within the lake were still higher than the recommended minimum of 5.0 mg/L.

TDS in runoff was 300 mg/L, lower than the maximum recommended value of 500 mg/L. In the Lake water, its average value ranges from 157.7 mg/L at the shore to 64.7 mg/L at the 50 m mark. In the dry season, its value ranged between 170 and 40.8 mg/L and showed a slight decrease from water surface downwards and an exponential decrease from shore into the Lake. There was slight increase in concentration in the vertical direction for rain season. The concentrations in rain seasons were still higher than the values for dry seasons.

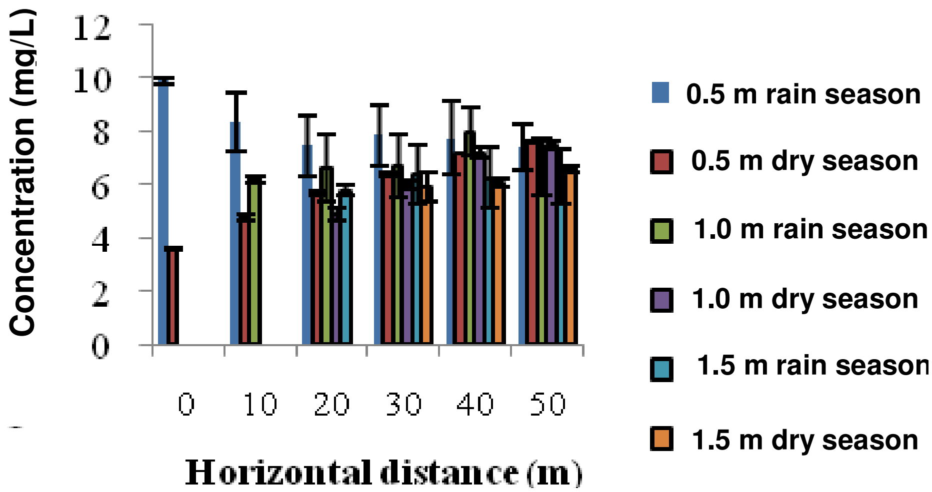

Figure 2. Variation in DO concentration with horizontal distance for different lake depths during dry and rain seasons.

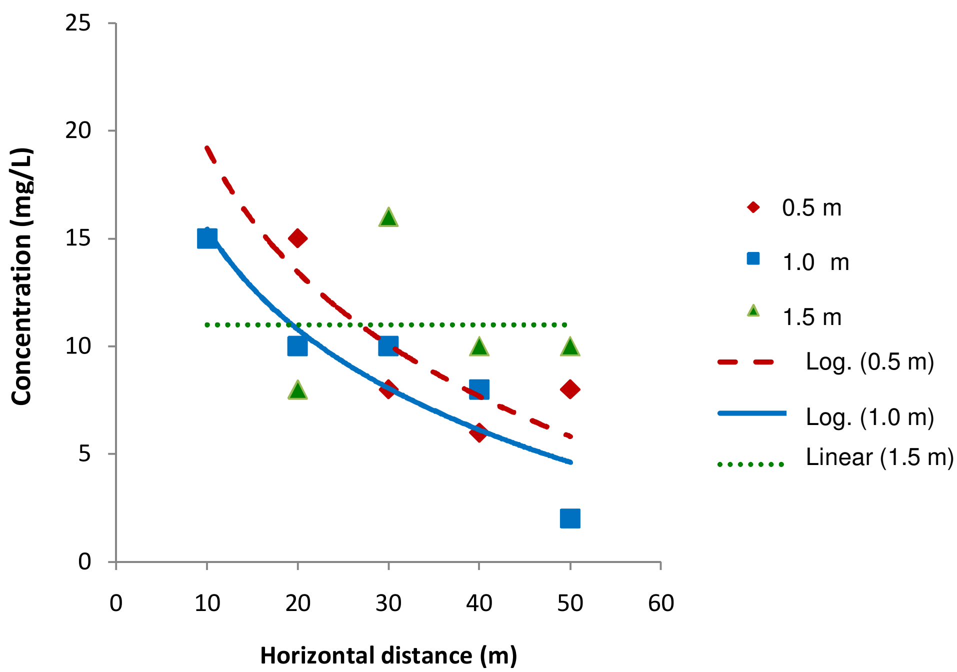

Figure 3. Changes in total suspended solids with depth and distance from lake shore.

EC in runoff was 431.5 µS/cm, still lower than the maximum recommended value of between (1000 to 2000 µS/cm). The concentration values ranged from 313 µS/cm, at the shore, to 105.83 µS/cm at 50 m mark, and 105.31 µS/cm at a depth of 1.5 m at the same 50 m mark. The EC values during the rainy seasons were higher than in dry season but in the horizontal direction, an exponential decrease was observed from the shore. This is possibly because runoff carries a lot of sediments loaded with ions that conduct an electric current.

TSS concentration decreased from shore towards middle part of the lake but in the vertical direction, the concentration increased from water surface inwards into the lake. At 1.5 m depth (that is, close to the lake bottom), the concentration was almost constant as shown in Figure 3. The increase in the vertical direction can be

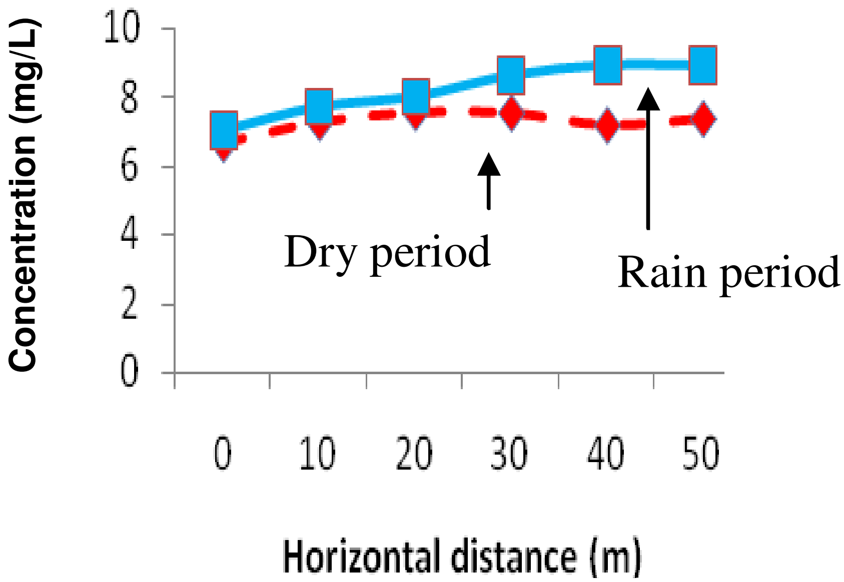

Figure 4. Changes in pH with depth and distance from lake shore

attributed to terminal velocity of heavier particles trying to settle to the bottom. In this process, lighter particles are left close to water surface while heavier ones sink to the bottom. In horizontal direction, the reduction in concentration is due to dilution as the suspended solids traverses the horizontal distances.

The pH of runoff was slightly alkaline (7.02). At the shore, the pH was 6.63 and increased to 7.11 at the 50 m mark and depth of 0.5 m. For the same points in dry seasons, at the shore the pH was 7.02 and increased to 8.98 at the 50 m mark as shown in Figure 4. There was no clearly marked change of pH with depth. The values in the dry season were found to be higher than during the rain seasons, and some of the values were higher than the recommended range of 6.8 to 8.4 (Gordon et al., 1968), This was an indication of possible biological impairment of the Lake functioning and its suitability for other purposes.

The runoff temperature was 24.4℃ and ranged from 24.6℃ at shore to 25.3℃ at 50 m horizontal distance. The water temperature in dry season was higher than during rainy season.

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Runoff contribution to Lake Victoria pollution

The average concentrations of nutrients were 8.47 mg/L for ammonia, 0.4 mg/L for nitrite, 0.56 mg/L for nitrate, and 6.8 mg/L for phosphate. The contributions of ammonia, nitrite, and phosphate were found to be significant (p = 0.287, 0.054 and 0.274), respectively. Nitrate contribution was not significant (p = 1.000). Chapman (1999) reported that concentrations of nitrate in excess of 0.2 mg/L NO_3 - N within lakes tends to promote algal growth, an indication of possible eutrophic conditions. It is therefore evident that runoff process contributes to nutrient input into the Lake Victoria.

Nutrient concentration within the Lake

The changes in rain season concentrations for ammonia, nitrites, nitrates and phosphates at various vertical depth were almost the same. This was an indication that during rain season, these nutrients disperse evenly (Figure 5). For horizontal direction, the concentration decreases gradually from discharge point into the Lake.

Nitrite concentration showed no significant variation in the data for horizontal direction ($p > 0.05$). In the vertical direction at 0.5 m, there was significant difference between the groups (p = 0.000). For dry season, in vertical direction, there was significant difference at 0.5 m depth (p = 0.044) between the groups and in horizontal direction there was no significant difference. Nitrite concentration ranged between 0.06 to 0.02 mg/L and remained constant with depth up to the 50 m mark. This concentration is higher than the dry season. In the rainy season, nitrate showed no significant difference ($p > 0.05$) in horizontal direction. There were changes at 0.5 m depth between groups and the variation was for all the horizontal distance from 10 to 50 m. For dry season, there was no significant difference in both horizontal and vertical direction ($p > 0.05$). Nitrate ranged from 0.13 to 0.03 mg/L and in the vertical direction it ranged between

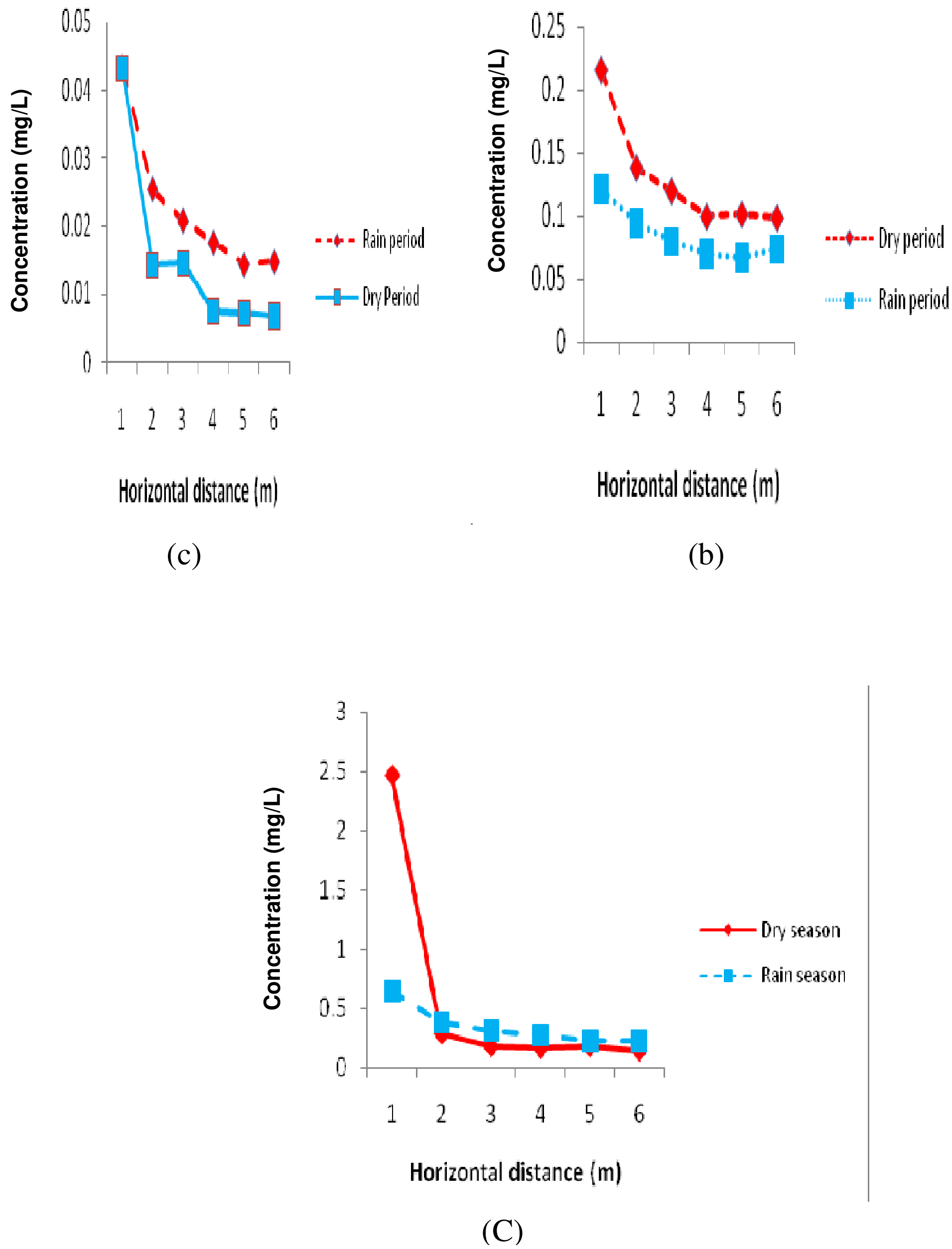

Figure 5. Changes in nutrient concentration during rain and dry periods for (a) Nitrite, (b) Nitrate and (c) Phosphate.

0.08 to 0.09 mg/L. During the dry season, concentrations of nitrate close to the shore (0.18 ≅ 0.2 mg/L) is the minimum limit needed to spark algal bloom further indicating that the near shore areas of lake Victoria are the most highly affected. Dry season nitrate concentrations were higher than the corresponding rain season as shown in Figure 6b. During the rainy season, in the horizontal direction, there was no variation ($p > 0.05$) with depth, but there were changes between groups at 0.5 m vertical depth. There was no significant difference in the horizontal direction for phosphate ($P > 0.05$) in vertical direction at 0.5 m depth, there was significant variation between groups ($p = 0.00$). Phosphate had a concentration of 6.8 mg/L in runoff, values of 0.66 to 0.3 mg/L from the shore inwards at 0.5 m vertical depth and 0.31 to 0.26 mg/L in the vertical direction. Its dry season concentration was lower than the corresponding rain season values as depicted in Figure 6c.

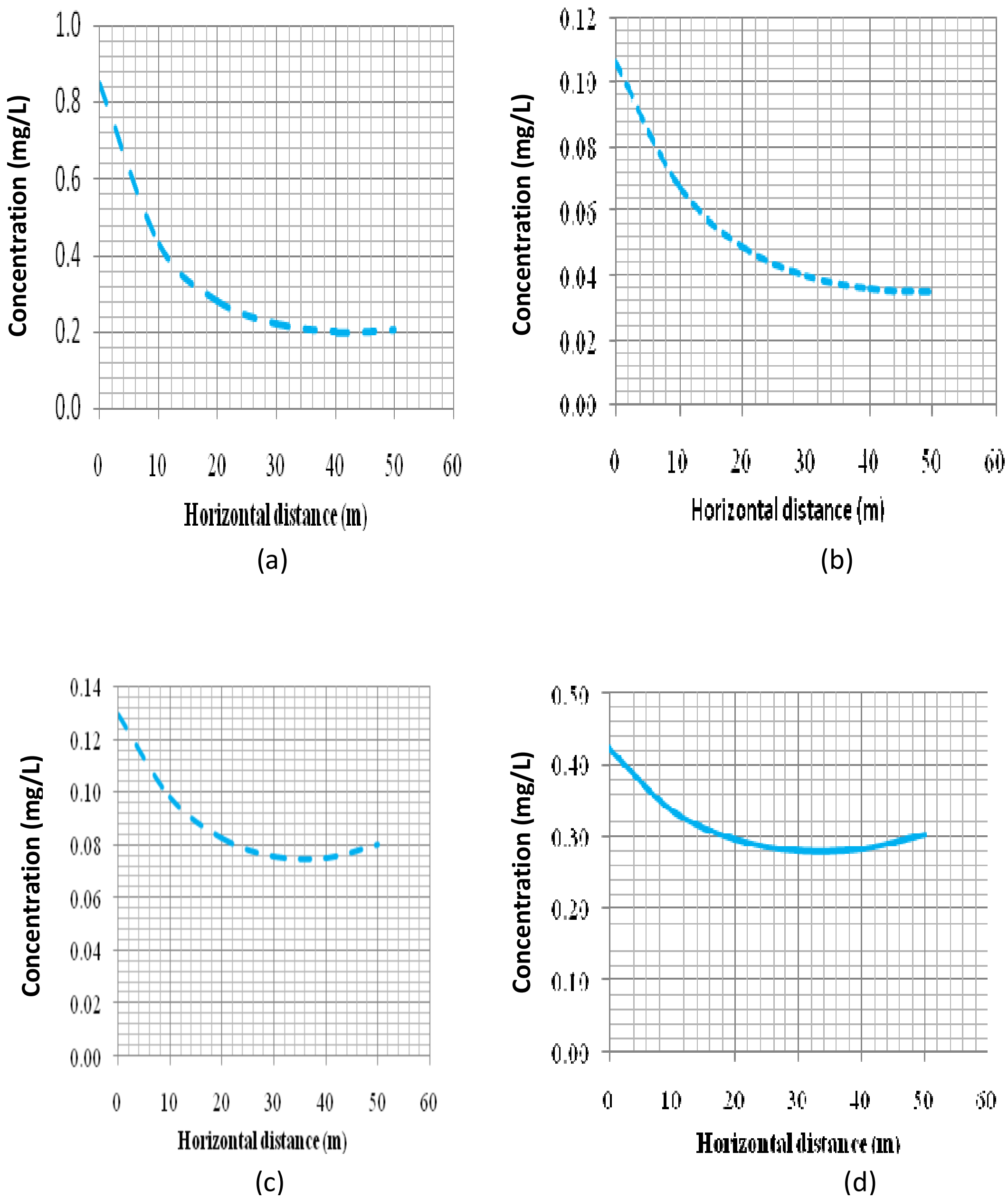

Figure 6. Estimated concentration profiles within a horizontal distance of 50 m for (a) Ammonia (b) Nitrite (c) Nitrate and (d) Phosphate.

Phosphorus concentration in dry season at the shore was higher than the corresponding rain season values probably because of human activities of washing clothes in shallow water thus altering the natural concentration. The measured concentrations were higher than the range in surface water and such high concentration could lead to algal growth. Ammonia showed no significant difference for all the horizontal distances ($p > 0.05$). In the vertical direction, there was a significant difference at 0.5 m depth ($p = 0.002$). Multiple comparisons showed that at depth of 0.5 m, the concentrations at zero horizontal distance were significantly different for horizontal distances of 10 to 50 m. Over the two rain seasons, concentration of ammonia in runoff was 8.47 mg/L. From the lake shore to the 50 m mark, its concentration ranged between 0.82 to 0.13 mg/L. In vertical direction at 50 m mark, the ammonia concentration ranged between 0.13 - 0.15 mg/L at 0.5 m depth. During the dry season, ammonia concentrations were undetectable.

Model prediction of nutrient dispersion

Figure 6 shows model estimations for, ammonia, nitrite, nitrate and phosphate dispersion within Lake Victoria

Ammonia in surface runoff into the lake disperses to 38 m as shown in Figure 6a. At this distance, the predicted model concentration is 0.2 mg/L as compared with the measured concentration ranging between 0.15 to 2.0 mg/L between the given measurement points. Nitrite dispersed to 45 m as can be seen in Figure 6b with predicted model concentration of 0.034 mg/L as compared with the measured concentration of 0.02 mg/L (Figure 5a). Nitrate dispersed to 34 m as depicted in Figure 6c with predicted model concentration of 0.076 mg/L as compared with measured concentration range of between 0.07 to 0.09 mg/L for the horizontal distance of between 30 to 40 m (Figure 6b). Phosphate dispersed to 34 m as shown in Figure 6d with a model concentration of 0.28 mg/L as compared with measured concentration ranging between 0.18 to 0.31 mg/L for the same distance (Figure 5c).

Conclusions

From the results of this study, the following conclusions can be drawn:

1. Water-quality degradation in Lake Victoria is associated with upland land uses.
2. From the model output, there exist a correlation between model predictions and measured data. The model(s) has been able to predict how far pollutants disperse into the lake.
3. Surface runoff discharged into Lake Victoria causes an elevation in nutrient and physico-chemical parameter concentrations.

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