WATER, WATER QUALITY, AND POND BOTTOM SOIL MANAGEMENT IN UGANDAN AQUACULTURE

Production System Design and Best Management Alternatives/Study/16BMA05AU

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ABSTRACT

Fisheries production from lakes and other natural waters in Uganda are declining and expansion of the aquaculture sector is needed to increase aquatic protein for human consumption. The present study was conducted to improve understanding of limitations imposed on aquaculture by the environmental factors of climate, soils, and water quality in Uganda. Although not optimum, the temperature regime in Uganda is conducive to year-around aquaculture in most areas. Rainfall is adequate to maintain water levels in ponds throughout the year in the Western, Eastern, and Central regions. In the Northern region, it would be necessary to store water in farm reservoirs to use for maintaining water levels during the driest months. There is a tendency towards drought in Uganda, and severe droughts could cause water shortages for aquaculture. Water quality was generally suitable in all four regions for fish production. The main limitation would be the need to lime ponds in some areas in all regions. Unfortunately, the liming materials available in the country are of poor quality, and the agricultural limestone currently used by fish farmers is particularly low in quality. There is an urgent need to find better sources of liming materials and begin an effort to promote liming in Ugandan aquaculture. The main limitations of soils for pond sites were coarse soil texture, steep terrain in some areas, and a widespread problem of low acidity. Of course, as in any country, each prospective pond site must be examined for its suitability. There also is cage culture in several lakes in Uganda; Lake Victoria and Lake Albert appear to be the best lakes in which to consider expansion of cage culture operations. In summary, there does not appear to be insurmountable environmental restrains to expanding aquaculture production in Uganda. The major issues relate to selecting good sites for ponds and to finding a source of good quality liming material.

INTRODUCTION

Capture fisheries in Uganda have declined, and there is interest and apparent potential for increasing the production of fisheries product through expansion of the existing aquaculture sector. The present study builds on the previous investigation of the use of water quality test kits in Uganda (Naigaga et al., 2015) to expand knowledge of water quality characteristics of source water for pond aquaculture and suitability of water in the major lakes for cage culture.

In addition, the present study assesses pond soil characteristics and climatic conditions as they affect pond hydrology and fish production, and examines the quality of liming materials available for use in Ugandan ponds. This information is used to provide more details about the potential for aquaculture and methods of pond water quality management that may be necessary.

OBJECTIVES

The specific objective for the study are as follows:

1. Measure water quality in reservoirs, lakes, and ponds, ponds soil characteristics in relation to climatic conditions, pond hydrology, and quality of liming materials.
2. Develop generalized water budgets for rain-fed ponds to ascertain likely variation in water levels.

3. Estimate water inputs necessary for ponds filled from external sources.
4. Evaluate the need for liming and the quality of local liming materials.
5. Assess water quality amendments required in aquaculture ponds.

METHODS AND MATERIALS

Auburn University doctoral student Shamim Naigaga traveled to major aquaculture areas in Uganda, specifically ponds, reservoirs, and lakes to collect water samples. In Uganda, the Aquaculture Research and Development Center-Kajjansi supported the data collection. The study sampled 120 pond water sources and the five major lakes in Uganda (Victoria, Albert, Kyoga, Edward, and George).

The pH, temperature, and dissolved oxygen concentration were measured at time of collection. There was no time allocation for sampling pond water sources but, for the lakes, sampling was between 8 am to 1 pm before diel changes.

Samples of 1L each in plastic bottles were shipped to Auburn University for measurement of specific conductance, alkalinity, hardness, major ions, chemical oxygen demand, and trace elements by standard protocol (Eaton et al., 2005).

Soil samples were collected from five locations in each pond, samples from each pond were combined into a composite sample, dried at 60°C in an oven, and shipped to Auburn University. The samples were analyzed for pH, organic carbon, cation exchange capacity, phosphorus, nitrogen, major ions, trace metals, free carbonate, and particle size.

Weather records were obtained from four locations: Gulu, Mbarara, Jinja and Soroti. The records contain monthly average temperatures, monthly maximum and minimum temperatures, rainfall, and if possible, pan evaporation. The water loss rate was measured from five to ten representative ponds over a period of 2-4 days without rainfall with aid of a stilling well and hook gauge (Yoo and Boyd, 1994).

Five samples of liming materials (200 g each) used in Uganda were collected and analyzed for neutralizing value and particle size at Auburn University.

Information was collected on typical production levels in ponds, amounts of fertilizers, liming materials, feeds and other inputs. The use of aeration in ponds were noted. If aerators are used, information on type, size, and typical operating schedule of aerators were obtained. The data were used to assess the suitability of water and soil quality for aquaculture in Uganda. This assessment includes the following:

- Generalized water budgets for rain-fed ponds were estimated to ascertain likely variation in water levels. Estimates of water inputs necessary for ponds filled from external sources also were made.
- The need for liming were evaluated, and the quality of local liming materials were determined.
- An assessment of other water quality amendments that might be required in ponds were made.
- Climatic variation over the country were assessed for possible effects on aquaculture.
- The assessment results were used to prepare recommendations for water, water quality, and pond bottom soil management in Ugandan aquaculture.

RESULTS

Climate

Mean temperature and mean annual rainfall was higher for the Northern and Eastern regions than the Central and Western regions (Table 1), respectively. There were significant differences between the mean temperature ($F= 836.06$, $p < 0.0001$, $df = 3$, at $p = 0.05$) and mean annual rainfall ($F = 41.66$, $p < 0.0001$, $df = 3$, at $p = 0.05$) among the regions (Table 2).

The post-hoc multiple comparison test by Tukey's Studentized range (HSD) showed mean temperatures were different among regions and mean annual rainfall was also different among regions apart from that of Eastern and Central regions which were similar (Table 2).

Linkages between temperature and optimum temperature range for catfish and tilapia showed that regions other than the Eastern region had mean temperature below the optimum range of 26°C to 32°C (Azaza, et al., 2010) over the years of record (Figure 2).

Seasonal Mann-Kendall output showed, apart from the Eastern region, a positive increasing trend in temperature among the regions (Table 3 and Figure 2). The strength of the slope was weak for the regions that have the trend, as the temperature varied between 0.002° C/yr for the Eastern region to 0.058°C/yr for the Northern region (Table 3). Deviations from the long-term mean (Figure 3) showed that there were higher temperature fluctuations in the Western region than in other regions over the years.

The 12-month Standard Precipitation Index (SPI) (Table 4) revealed a rainfall deficit in the Northern and Western regions, but the deficits were not great enough to be considered outside the normal range in SPI according to guidelines for classifying rainfall deficits given by Mckee et al. (1993). Eastern and Central regions were also near normal, although the Central region had the highest SPI (Table 4). Over the years, all regions fell within -1.5 to 1.5 SPI resulting in classification varying between moderately dry to moderately wet (Figure 4).

Mean evaporation was higher in the Northern region, followed by the Central region, and least in the Western region, but there were missing data for the Eastern region (Table 5). Calculated monthly potential evapotranspiration was highest for the Eastern region, followed by the Northern region, then the Central region, and least potential evaporation was for the Western region (Table 5). On a yearly basis, the potential evapotranspiration was lower than the evaporation estimated for ponds in all regions.

The Western region had the lowest water requirement compared to other regions (Figure 5) despite having the lowest mean SPI. The monthly required inflows for levee ponds showed that all regions required water during the December-February period, which is the longest dry season in all but the Western region where the dry season typically is only during July (Table 6). Nevertheless, the Northern region had the highest water requirements of the four regions.

Water quality

Pond mean concentrations of the different water quality parameters showed that most were within optimum ranges for Nile tilapia and African catfish. The exceptions were in the Central region for total alkalinity and in the Eastern region for pH (Table 7). However, the ranges of each water quality parameter measured were wide. The Northern region had the highest water hardness, total alkalinity and associated buffering capacity, and the greatest specific conductivity as compared to other regions.

Comparisons among the different regions by a chi square test (Table 8) showed that all regions were independent of each other as p-value was less than $\alpha = 0.05$, $df = 3$ at 95% confidence interval. The

ANOVA output showed that mean concentrations for all water quality parameters analyzed were statistically significantly other than for the calcium hardness ($p = 0.0828$, $\alpha = 0.005$, $df = 3$) (Table 9). Further comparison with the Tukey's test revealed that the regions had pH statistically significantly different from each other, while for other water quality parameters, the Northern region was statistically different from other regions other than the Eastern region (Table 9).

Pond frequency distributions for water quality variables (Figure 6) showed that most pond water sources had total hardness concentration out of the optimum range for Nile tilapia and African catfish. The Eastern region had most of its water sources within range as compared to other regions, while the Northern region had most water sources with hard water. Pond frequency distribution for specific conductivity (Figure 7) showed that most water sources were within optimum range for the Eastern region when compared to other regions, however, the specific conductivity concentrations in all regions were within the tolerable range as freshwater species which typically can tolerate up to 5,000 µS/cm (Boyd and Tucker, 2014).

Total alkalinity pond frequency distribution (Figure 8) showed that most water sources for all regions were below the optimum range, except for the Eastern region. The Central region had lowest total alkalinity concentrations when compared to other regions. Pond frequency distribution for pH (Figure 9) showed that regions other than the Eastern region had water sources within the optimum pH range. This observation agrees with studies done by Boyd and Tucker (2014), in which ponds with total alkalinity below 50 mg/L usually had pH between 6 to 8 when sampled in the morning.
Pond trace metal analysis revealed that concentrations of most trace metals were within optimal limits for fish culture. The exceptions were aluminum and iron (Table 10), which sometimes were greater in concentration than the normal concentrations listed for freshwater pond in Boyd and Tucker (1998) and (Boyd, 2015). This also agreed with studies which showed elevated concentrations of iron and aluminum in ground waters of Uganda (UNESCO, 2006).

Frequency analysis of iron concentrations showed that regions other than the Western region had at least 50% of most water sources in the optimal range. This was contrary to the study done on drinking water in Western region by Ngabirano et al. (2017), which showed that most of the water sources analyzed had iron concentrations within optimal range. For the aluminum concentration, the Northern and Western regions at least 50% of the water sources were in the optimum range as compared to Central and Eastern regions (Table 11).

Lake results showed that Lakes George and Kyoga were poor sites for fish cage culture, Lake Edward had its siting as fair, with Lakes Victoria and Albert having suitable site characteristics based on the following parameters: water depth, secchi depth, dissolved oxygen profile, long axis to the bay, currents, connectivity to open water, and distance to pollution sources (Table 12). Further analysis of other water quality parameters of concern in aquaculture (Table 13) showed that these lakes were in optimal range for cage culture. Nonetheless, the low calcium concentration indicated by calcium hardness <20 mg/L in Lake Victoria can be compensated by calcium in the artificial feed given to the fish.

Soil characteristics

The mean soil pH values for the different regions were below the optimum range for fish production (Table 14), with the Central region having the lowest average soil pH. The percentage soil total nitrogen was optimal for all regions, while the percentages of total soil carbon and soil organic matter were within optimum range for all regions other than the Western region. The saturated hydraulic conductivity was higher for the Western region as compared to other regions (Table14).

A chi square test (Table 15) showed that all regions were independent of each other.

The ANOVA output revealed that mean concentrations for all soil quality parameters were statistically significant among the four regions (Table 16). On using Tukey's test (Table 16), soil pH of the Central and the Western regions were statistically different from that of Eastern and Northern regions. For other soil quality parameters, the Western region was statistically different from other regions.

Frequency distribution of soil pH showed that most ponds had a soil pH out of the acceptable range, with the Central and Western regions having the highest number of ponds with a pH less than 6.5 (Figure 10). However, none of the soil samples from any region had a soil pH above the highest recommended soil pH for fish culture.

In most of the ponds, the percentage total carbon content was within the optimal range and especially in the Central and the Northern regions (Figure 11). However, the Western region had most of the ponds that with a carbon content percentage above the recommended level.

Frequency distribution of the organic matter content in soil samples in the different regions revealed similar trends in frequency distribution. The Northern region had the greatest frequency of soil samples within the optimal range and the Western region having most soil samples with elevated organic matter content (Figure 12).

All trace metal concentrations were within the optimal range, apart from the copper concentrations for which some soil samples were above the maximum safe concentration of 2 mg/kg for copper in sediment reported by Abdul-Wahab and Jupp (2009) (Table 17). However, this reference refers to copper in subtidal, estuarine marine environments and unlikely applies well to aquaculture pond soils. Nevertheless, the Northern and Eastern regions had a number of soil samples with copper concentration higher than the recommended range reported for estuarine sediment.

Liming requirement results inferred from the soil pH and buffer pH showed that the Central region had the highest number of ponds (>80%) that required liming and the Northern region the least number of ponds that required liming (60%) (Figure 13). However, a different trend was shown with the lime requirement of the ponds that required liming with onds in the Western region having a higher average liming requirement of 2970 ± 414.42 kg/ha or 743 ± 103.61 kg/pond area (500 m^2) (Table 18). The Northern region still had the least lime requirement as many soils there contain limestone.

The neutralizing value and fineness rating are used to assess the quality of agricultural limestone, but only the neutralizing value is used for burnt and hydrated lime as lime is more soluble than agricultural limestone (Boyd and Tucker 2014). Data in Table 19 reveal that the ENV or effective neutralizing value [(NV % × FV %) ÷ 100] of the four available liming products obtained in Uganda ranged from 8.9 to 51.8%.

According to Table 19, the agricultural limestone products would be very inefficient for use in ponds because a huge quantity would be necessary. The best choice seems to be the Neelkanth Ltd hydrated lime, but it cannot be applied at over 200 kg/ha per application in ponds with fish, because lime can raise pH above the level tolerated by fish (Boyd and Tucker, 2014). As a result, liming would have to be done to the pond bottoms between crops and 2 to 3 weeks allowed for the pH to fall after refilling ponds and before stocking fish.

Liming rates for the best liming material (Neelkanth Ltd hydrated lime class A) were very high for all regions (Table 20). Liming rates followed a similar trend as lime requirement with the Western region having a higher liming rate, followed by the Central region, then the Northern region, and least for the Eastern region.

Observed seepage rates results showed that the Western region had the least seepage rate (0.93 ± 0.17 cm/hr) and the Central the highest seepage rate (3.37 ± 2.03 cm/hr) (Table 21). These results were contradictory to the calculated seepage rates from the saturated hydraulic conductivity, which resulted in the Northern region with least seepage rate, followed by the Eastern region, then the Central region, and finally the Western region. The Western region had higher seepage rates which could be due to the organic soils (Egna and Boyd, 1997). The calculated seepage rates were higher than the observed seepage rates.

DISCUSSION

Climate

The mean annual temperatures and mean annual rainfall totals observed in the different regions agreed with a study done by Phillips and McIntyre (2000). Higher mean rainfall for the eastern region can be attributed to Lake Victoria and Lake Kyoga's influence on the moisture availability in the local atmosphere (Sun et al., 2015). Similarities in the mean annual rainfall of the Central and Eastern regions were in line with data reported by Nicholson (2017) which allowed the Central and Eastern regions to be classified as being in the equatorial rainfall region.

Although the temperatures were out of the optimum range for the culture of African catfish and Nile tilapia, they were within the range for optimum feeding by these species which has a lower limit of 20°C (Azaza et al., 2010; Isyagi et al., 2009). The lower temperature in the Western region possibly could allow culture cold-water fish species, such as trout, in some areas.

The positive trend of temperatures in the different regions by the seasonal Mann-Kendall implies increasing temperatures in those regions which favor aquaculture production in the future. Deviations from the long term mean in the Western region was, however, within 6°C for all regions. This was noted to be suitable for young fish, but not larger fish (Azaza et al., 2010). The negative SPI values in the Northern and Western regions indicate the need for strategies for storing water in reservoirs during the rainy seasons for use in the dry season.

The low water requirement in the Western region, which has a low SPI, likely is the result of lower potential evapotranspiration, and seepage rate in the Western region compared to other regions. The high-water requirement observed in the Northern region has a unimodal rainfall pattern compared to other regions, which have a bimodal rainfall; hence, more precipitation occurs and increases the water table throughout the year. The Northern region is also far away from the influence of the moisture transport from Lake Victoria resulting in drier climate. Therefore, a year-round production cycle is possible in the Western region that would allow for stocking ponds at different times, however, it is best when pond preparation is in June-July when pond bottoms dry out and fertilizer application can be made in the dry season without nutrient leaching problems. The Eastern and Central regions had a similar possible production cycle where pond preparation or fish harvest could be in June-July or December-February. This is advantageous as pond refilling would be easier during the rainy season that follows, and it also presents a competitive market and high profit margin because many poultry products are less available in the local markets during dry season (Maurice et al., 2010).

In the Northern region, a single production cycle is possible with pond preparation in March and fish harvest in December unless water harvesting is done to store water for use during the dry months. Fish harvest in December would be advantageous to the Northern region as fish is a delicacy sought at this time of the year (Jagger and Pender, 2001), and fish harvest during the holiday and vacation season increase profits for the farmers.

Considering all factors, the Western region had the most favorable climate for aquaculture production, followed by the Eastern, then the Central, and finally the Northern region. However, the topological issues associated with the Western region noted by Ssegane et al. (2012), results in the Eastern region being the most favorable for aquacultural production. Nevertheless, in the context of water and soil quality, all regions are suitable for aquaculture production, provided water harvesting strategies are adopted for storing water during the dry periods.

Water quality

The high concentrations of specific conductivity, total alkalinity, and total hardness in the Northern region agree with studies done by Boyd & Tucker (2014) in which moderate to high concentrations of total alkalinity and total hardness were positively correlated with increasing specific conductivity. The Northern region is drier than other regions; hence, more evaporation occurs leading to concentration of ions in water (higher specific conductivity). Similarities between the Northern region and the Eastern region for the mean concentrations of the water quality parameters analyzed could be attributed to similar geological conditions, land uses, and pond management practices.

Higher pH values in the water sources in the Eastern region despite their high total alkalinity could be attributed to excessive photosynthesis by water plants in the ponds as reported to occur in ponds in other parts of the world (Boyd and Tucker, 2014). Most of the water sources in the Eastern region were measured in ponds, and the time of sampling which was done in the early afternoon was at the time of day when pond pH is greatest.

The elevated concentrations of iron and aluminum in the pond water sources could be the result of corrosion of the borehole casings, seepage of the sewage waste and natural weathering of the aquifer matrix which is high in iron and aluminum. Higher occurrence of high aluminum and iron concentrations in the Central and the Eastern regions compared to the Western and the Northern regions could be attributed to the seepage of sewage waste in the Central and Eastern regions, as they have more industries compared to other regions.

Soil characteristics

The soil pH values in all regions were similar to those previously observed in Bogor (Indonesia) by McNabb et al. (1990), who noted that ponds with low pH had low fish production. The high saturated hydraulic conductivity in the Western region is due to the high organic matter in the ponds in the Western region (Hillel, 2008; Oosterbaan and Nijland, 1994). Higher total carbon and organic matter percentages in the Western region possibly can be attributed to the high fertilization rates with manure (Egna and Boyd, 1997).

High copper concentrations above 2 mg/kg in pond soils are fairly common and apparently of no concern (Boyd and Tucker 1998).

All the liming materials analyzed had a very low neutralizing value (NV) and fineness value (FV), which meant higher liming rates (Boyd and Tucker, 2014). Neel-Kanth hydrated lime class A was the only Ugandan liming product with NV and FV similar to those found for pulverized seashells (Boyd and Tucker 2014). Good quality agricultural limestone should have an ENV above 80%, while ENV for lime should be 110%-150% or more (Boyd and Tucker, 2014).

The quality of liming material, and especially of agricultural limestone, in the market in Uganda were extremely substandard. The availability of good quality liming material appears to be a serious limitation to improving pond management in Uganda. Many ponds in the country need to be limed, but the quality of the available products for liming is poor. The cost of agricultural limestone – in spite of its low quality – is high and if quality is considered, the cost of all of the liming materials is outrageous as compared to the costs of these materials in other countries with substantial aquaculture sectors.

The government or private agricultural vendors in Uganda could possibly import liming materials from other countries. It also seems that an effort to improve the quality of the domestic products could be initiated, and possibly there are better liming products which were not located during the present study. Nevertheless, there seems to be good reason to conduct further investigation into this issue.

The seepage rates were all acceptable in aquaculture (Yoo and Boyd, 1994). The seepage rates must be considered approximate because of the crude method used for its determination and the fact that the observed seepage was determined for only three ponds in each region because of time restraints.

It should be mentioned that factors other than the hydraulic conductivity of soil as measured in the laboratory affect seepage rate. During pond construction, soils are compacted to reduce seepage, and organic matter produced in ponds and added to ponds in manure during aquaculture production tends to fill the interstitial spaces among soils to lessen seepage (Yoo and Boyd, 1994). Thus, soil hydraulic conductivity should only be viewed as potential seepage, and soils that have a high potential for seepage should be given special attention for thorough compaction during construction. Of course, with improper construction, a pond constructed on soil with low hydraulic conductivity may seep badly.

CONCLUSIONS

The temperature was sometimes out of the optimum range for production in all regions, but the temperature range would allow fish production. The Western region was considered most favorable among all regions, but it has a steep topography. The Eastern region as the most favorable conditions in Uganda for fish production. However, all areas were noted to be suitable for fish culture, provided water harvesting techniques were employed during the dry period to store water for use in dry weather. Overall, potential climate effects on aquaculture is not that significant in the country if the right production strategies are adopted.

Pond mean concentrations of the different water quality parameters showed that they were within optimum range for African catfish and tilapia culture, but frequency analysis showed otherwise with a high percentage of water sources in all regions being outside of optimal ranges in alkalinity and pH. There is, therefore, a need to analyze water sources from all sites and make applications of agricultural lime to ponds as necessary to increase the pH and alkalinity and favor greater fish production. The Eastern region had better water sources for fish farming as compared to the other regions.

All regions had soil pH below the optimum range for fish culture; hence, liming were required to increase production, especially since most farmers do not apply fish feed. The Northern region generally had the best soil for pond bottoms and the Western region had the most soils with limitations for use as pond soils. All liming materials were of low quality as indicated by low neutralizing value of both agricultural limestone and large particle size distribution in agricultural limestone.

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TABLES AND FIGURES

Table 1: Mean temperature, maximum, minimum temperatures, 1980 to 2016 by region.

	Temperature			Rainfall
Region	**Mean (°C)**	**Minimum (°C)**	**Maximum (°C)**	**Annual mean (mm)**
Central	22.66	17.80	28.90	1248.0 ± 284.39
Eastern	24.94	22.60	34.70	1335.7 ± 210.28
Northern	24.07	19.90	28.30	1476.0 ± 174.30
Western	21.09	19.30	26.20	921.5 ± 203.16

Table 2: ANOVA and Tukey's test (HSD output) by region.

Climate parameter	F-statistic	DF	p-value	Turkey's test	
Temperature	836.06	3	< 0.0001	Central	A
				Eastern	B
				Northern	C
				Western	D
Rainfall	41.66	3	< 0.0001	Central	B
				Eastern	B
				Northern	B
				Western	C

Table 3: Seasonal Mann-Kendall output for the different regions.

Region	Tau b	p-value	Sen's slope	Risk (%)
Central	0.244	> 0.0001	0.015	0.01
Eastern	0.027	0.4222	0.002	43.97
Northern	0.595	> 0.0001	0.058	0.01
Western	0.468	>0.0001	0.038	0.05

Table 4: Mean annual rainfall, and mean standard precipitation indices by region.

Region	Mean SPI
Central	0.1225
Eastern	0.0000
Northern	-0.0003
Western	-0.0005

Table 5: Mean Evaporation and mean Evapotranspiration by region.

Region	Evaporation (mm/year)	Calculated potential evapotranspiration (mm/month)
Central	139.0	4.97
Eastern		5.26
Northern	168.0	5.15
Western	120.8	4.78

Table 6: Monthly water requirement (inflows) in gallons per minute (gpm)/ acre for levee ponds by region.

	Region			
Month	Northern	Central	Western	Eastern
Jan	1.56	0.85	0.00	0.92
Feb	1.41	1.08	0.00	0.83
Mar	0.02	0.00	0.00	0.00
Apr	0.00	0.00	0.00	0.00
May	0.00	0.00	0.00	0.00
Jun	0.00	0.91	0.00	0.00
Jul	0.00	0.90	0.19	0.00
Aug	0.00	0.08	0.00	0.00
Sep	0.00	0.00	0.00	0.00
Oct	0.00	0.00	0.00	0.00
Nov	0.00	0.00	0.00	0.00
Dec	1.01	0.31	0.00	0.68

Table 7: Mean concentrations of the different water quality parameters measured in pond water sources by region.

	Region			
Water parameter	Central	Eastern	Northern	Western
Total hardness (mg/L)	50.3±11.40 (6.3-258.6)	89.0±16.62 (21.5-502.9)	102.7±22.49 (12.7-533.8)	66.0±13.35 (5.5-332.3)
Calcium hardness (mg/L)	20.9±4.97 (0.0-109.0)	43.3±5.94 (8.1-133.6)	34.0±5.86 (3.2-114.2)	31.1±7.38 (0.0-140.0)
Total alkalinity (mg/L)	43.2±8.99 (6.0-69.8)	80±9.16 (7.9-238.1)	106±20.72 (13.7-441.1)	55.5±12.95 (6.4-329.3)
Specific conductivity (µS/cm)	174.7±29.16 (38.4-557)	298.2±46.89 (79.0-469.0)	351.1±71.70 (53.3-1377.5)	157.6±19.52 (25.9-383.9)
pH	7.3±0.20 (5.9-10.6)	9.8±0.34 (7.0-13.0)	8.3±0.24 (5.2-13.0)	7.0±0.19 (5.3-9.4)

Table 8: Chi square test tests for water quality parameters measured by region.

Water parameters	**Chi square**	**P-value**	**Cramer's V**	**DF**
Specific conductivity	10.196	0.017	0.291	3
pH	16.498	0.000	0.371	3
Total alkalinity	14.385	0.002	0.379	3
Total hardness	8.8336	0.032	0.271	3

Table 9: ANOVA output for the different water quality parameters by region.

	ANOVA output			
Water parameter	F-statistic	DF	p-value	Turkey's test
pH	25.44	3	< 0.0001	Central C
				Eastern A
				Northern B
				Western C
Total alkalinity	4.18	3	0.0075	Central B
				Eastern A, B
				Northern A
				Western B
Total hardness	2.00	3	0.1175	Central A
				Eastern B
				Northern B
				Western A
Calcium hardness	2.28	3	0.0828	Central A
				Eastern A
				Northern A
				Western A
Specific conductivity		4.15	0.0056	Central B
				Eastern A, B
				Northern A
				Western B

Table 10: Range of concentration of different water trace metals by region.

	Region			
Element (mg/L)	**Central**	**Eastern**	**Northern**	**Western**
Al	< 0.1- 6.3	< 0.1 – 3.0	< 0.1 – 6.0	< 0.1 – 2.5
As	< 0.1	< 0.1	< 0.1	< 0.1
B	< 0.1	< 0.1 – 0.3	< 0.1	< 0.1
Ba	< 0.1- 2.2	< 0.1 – 3.1	0.1 – 1.9	< 0.1 – 3.7
Ca	1.6 – 45.5	8.9 – 117.0	4.7 – 141.0	1.9 – 103.0
Cd	< 0.1	< 0.1	< 0.1	< 0.1
Cr	< 0.1	< 0.1	< 0.1	< 0.1
Cu	< 0.1	< 0.1	< 0.1	< 0.1 – 0.7
Fe	< 0.1 – 16.7	< 0.1 – 8.2	< 0.1 – 6.5	< 0.1 – 11.9
K	0.4 – 10.0	0.9 – 43.6	0.9 – 26.8	0.3 – 9.0
Mg	0.7 – 58.2	4.0 – 104.0	2.3 – 80.0	1.2 – 43.7
Mn	< 0.1 – 2.3	< 0.1 – 2.2	< 0.1 – 1.2	< 0.1 – 1.5
Na	8.3 – 52.9	12.8 – 77.5	7.7 – 136.0	8.9 – 68.3
Ni	< 0.1	< 0.1	< 0.1	< 0.1
P	< 0.1 – 1.7	< 0.1 – 2.0	< 0.1 – 1.2	< 0.1 – 2.2
Pb	< 0.1	< 0.1	< 0.1	< 0.1
Zn	< 0.1 – 0.2	< 0.1	< 0.1	< 0.1

Table 11: Percentage distribution of pond water sources in terms of iron and aluminum concentrations by region.

	Iron (%)		Aluminum (%)	
Region	**Optimal**	**Non-optimal**	**Optimal**	**Non-optimal**
Central	53.3	46.7	40	60
Eastern	66.7	33.3	40	60
Northern	70.0	30.0	53	47
Western	36.7	63.3	70	30

Table 12: Suitability ratings of different water bodies for cage culture by small to medium sized facilities for five Uganda lakes.

	Lake				
Water parameter	**Victoria**	**Albert**	**Edward**	**George**	**Kyoga**
Water depth	3	3	3	1	1
Secchi depth	3	2	2	1	2
Dissolved oxygen profile	3	2	2	1	1
Long axis to the bay	3	3	2	1	2
Current between the bay and the lake	3	3	2	1	2
Connection of the bay to open water of the lake	3	2	1	1	1
Distance to obvious source of pollution	3	3	2	1	1
Total score	21	18	14	7	10

Table 13: Mean water quality parameters for five Uganda lakes.

	Lake				
Parameter	**Victoria**	**Albert**	**Edward**	**George**	**Kyoga**
Depth (m)	10.80	20.90	13.70	1.60	2.70
Secchi depth (m)	2.90	1.90	1.40	0.30	1.20
Temperature (°C)	25.50 ± 0.03	27.90 ± 0.04	26.40 ± 0.06	27.20 ± 0.11	28.10 ± 0.18
Total dissolved solids	0.06 ± 0.00	0.42 ± 0.00	0.58 ± 0.00	0.32 ± 0.03	0.16 ± 0.01
(mg/L) Salinity (PSU)	0.05 ± 0.00	0.31 ± 0.00	0.44 ± 0.00	0.24 ± 0.02	0.12 ± 0.01
Dissolved oxygen (mg/L)	6.64 ± 0.14	5.31 ± 0.08	5.41 ± 0.40	2.77 ± 1.50	2.76 ± 0.56
Specific conductivity (µS/cm)	97.70 ± 0.06	640.80 ± 2.20	886.40 ± 2.16	485.40 ± 48.77	252.60 ± 17.80
pH	8.40 ± 0.05	8.80 ± 0.07	9.30 ± 0.06	7.90 ± 0.50	7.40 ± 0.16
Total alkalinity (mg/L)	38.65 ± 0.11	265.52 ± 2.78	382.01 ± 0.08	102.36 ± 1.07	43.58 ± 2.04
Total hardness (mg/L)	24.16 ± 0.74	140.32 ± 1.06	215.22 ± 0.08	86.72 ± 1.00	28.06 ± 1.27
Calcium hardness (mg/L)	5.49 ± 1.66	22.36 ± 1.36	26.49 ± 0.05	39.46 ± 0.04	8.92 ± 2.29

Table 14: Mean concentrations of the different soil quality parameters by region.

Soil parameter	Region			
	Central	**Eastern**	**Northern**	**Western**
Soil pH	5.3±0.11 (4.3-6.6)	6.3±0.16 (4.7-7.8)	6.4±0.19 (4.5-8.3)	5.5±0.14 (4.6-7.4)
% Total Nitrogen	0.1±0.01 (0.0-0.2)	0.2±0.02 (0.0-0.5)	0.1±0.01 (0.0-0.3)	0.5±0.10 (0.0-2.1)
% Total Carbon	1.2±0.13 (0.2-2.4)	1.7±0.21 (0.4-4.5)	1.2±0.11 (0.1-3.0)	6.4±1.38 (0.5-30.5)
% Organic matter	2.1±0.23 (0.4-4.2)	2.9±0.37 (0.6-7.7)	2.0±0.18 (0.2-5.2)	10.9±2.38 (0.9-52.5)
Saturated hydraulic conductivity (cm/hr)	0.6±0.07 (0.2-1.3)	0.5±0.08 (0.2-1.6)	0.4±0.05 (0.1-1.1)	0.8±0.13 (0.1-1.3)

Table 15: Chi square test output for the different soil quality parameters in the different regions.

Soil parameters	**Chi square**	**P-value**	**Cramer's V**	**DF**
Soil pH	20.508	0.0001	0.413	3
Total Carbon (%)	16.705	0.0008	0.373	3
Organic matter (%)	12.103	0.0070	0.318	3

Table 16: ANOVA output for the different soil quality parameters analyzed by region.

Soil parameter	**ANOVA output**				
	F-statistic	**DF**	**p-value**	**Turkey's test**	
Soil pH	13.54	3	< 0.0001	Central	B
				Eastern	A
				Northern	A
				Western	B
Total Carbon(%)	12.64	3	< 0.0001	Central	B
				Eastern	B
				Northern	B
				Western	A
Total Nitrogen (%)	14.08	3	< 0.0001	Central	B
				Eastern	B
				Northern	B
				Western	A
Organic matter (%)	12.63	3	< 0.0001	Central	B
				Eastern	B
				Northern	B
				Western	A
Saturated hydraulic conductivity (cm/hr)	3.17	3	0.0269	Central	B
				Eastern	B
				Northern	A,BA
				Western	

Table 17: Trace metal concentration ranges by region.

Element (mg/L)	Region: Central	Eastern	Northern	Western
Al	18.0 – 295.0	19.0 – 350.0	39.0 – 903.0	3.0 – 1153.0
As	< 0.1	< 0.1	< 0.1	< 0.1
B	0.3 – 1.7	0.3 – 2.3	0.3 – 2.7	0.4 – 2.1
Ba	1.4 – 11.2	2.0 – 10.4	0.8 – 7.4	1.2 – 13.0
Ca	104.0 – 1930.0	311.0 – 3299.0	527.0 – 3161.0	457.0 – 3146.0
Cd	< 0.1	< 0.1	< 0.1	< 0.1
Cr	< 0.1	< 0.1	< 0.1	< 0.1
Cu	0.7 – 3.7	0.2 – 11.5	0.3 – 11.5	0.0 – 4.8
Fe	51.0 – 470.0	6.0 – 415.0	7.0 – 847.0	3.0 – 591.0
K	18.0 – 136.0	26.0 – 160.0	18.0 – 209.0	26.0 – 126.0
Mg	40.0 – 596.0	100.0 – 715.0	112.0 – 667.0	123.0 – 1132.0
Mn	10.0 – 279.0	3.0 – 295.0	8.0 – 225.0	4.0 – 336.0
Na	38.0 – 184.0	45.0 – 192.0	55.0 – 298.0	40.0 – 324.0
Ni	< 0.1	< 0.1	< 0.1	< 0.1
P	< 0.1 – 22.0	< 0.1 – 62.0	< 0.1 – 26.0	< 0.1 – 372.0
Pb	< 0.1	< 0.1	< 0.1	< 0.1
Zn	0.6 – 16.5	0.5 – 7.4	0.7 – 14.0	0.2 – 16.0

Table 18: Liming requirement in the different regions.

Lime requirement	Region: Central		Eastern		Northern		Western	
(kg/ha)	1420 ± 259.79	(91 – 4086)	749 ± 151.44	(126 – 1512)	829 ± 274.42	(91 – 3528)	2970 ± 414.42	(272–5400)
(per average pond)	355 ± 64.95	(23 – 1022)	187 ± 37.86	(32 – 378)	207 ± 68.60	(23 – 882)	743 ± 103.61	(68 – 1350)

Table 19: Liming materials with their liming properties and prices.

Type of liming material	Neutralizing value (NV) (%)	Fineness value (FV)* (%)	Effective neutralizing value (ENV) (%)	Price ($/ton)	Price of effective lime) ($/ton)
Grey lime	22.0	46.1	10.1	302	2980
Neelkanth Ltd hydrated lime class A	51.8		51.8	504	973
Stock feed agricultural lime	35.6	25.0	8.9	252	2833
Tororo hydrated lime	38.7		38.7	302	780

Table 20: Liming rate by region using Tororo hydrated lime.

	Region			
Liming rates	**Central**	**Eastern**	**Northern**	**Western**
Lime requirement (kg/ha)	2741	1446	1600	5734
Lime rate (per average pond)	685	362	400	1433

Table 21: Observed seepage and calculated seepage in the different regions.

	Region			
Seepage rates	**Central**	**Eastern**	**Northern**	**Western**
Observed seepage (cm/day)	3.37 ± 2.03	2.27 ± 0.39	2.53 ± 1.41	0.93 ± 0.17
Calculated seepage (cm/day)	14.14 ± 1.67	12.23 ± 1.84	9.29 ± 1.12	16.06 ± 1.79

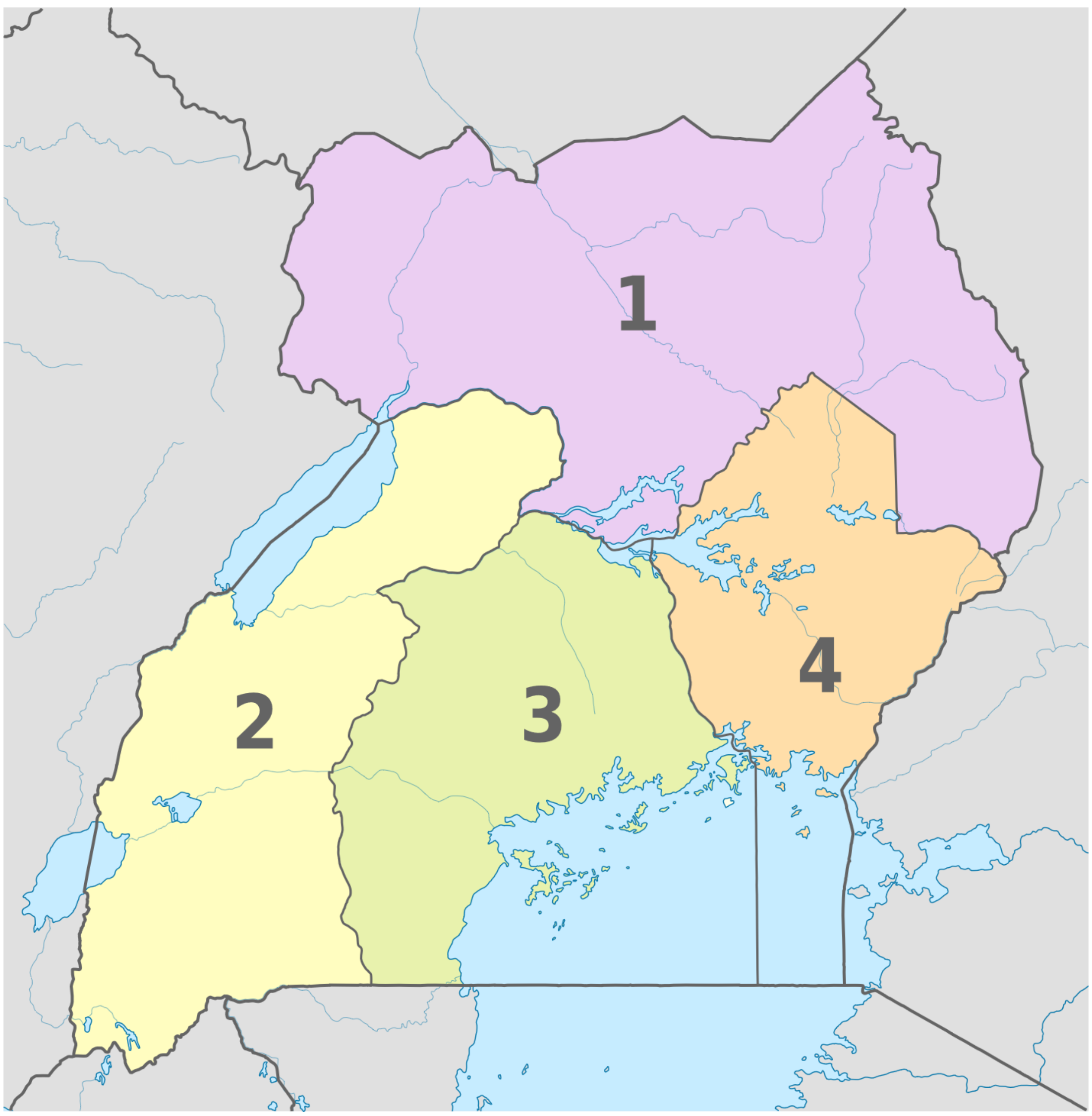

Figure 1: Administrative map of Uganda showing Northern region (1), Western region (2), Central region (3) and Eastern region (4) (TUBS, 2012).

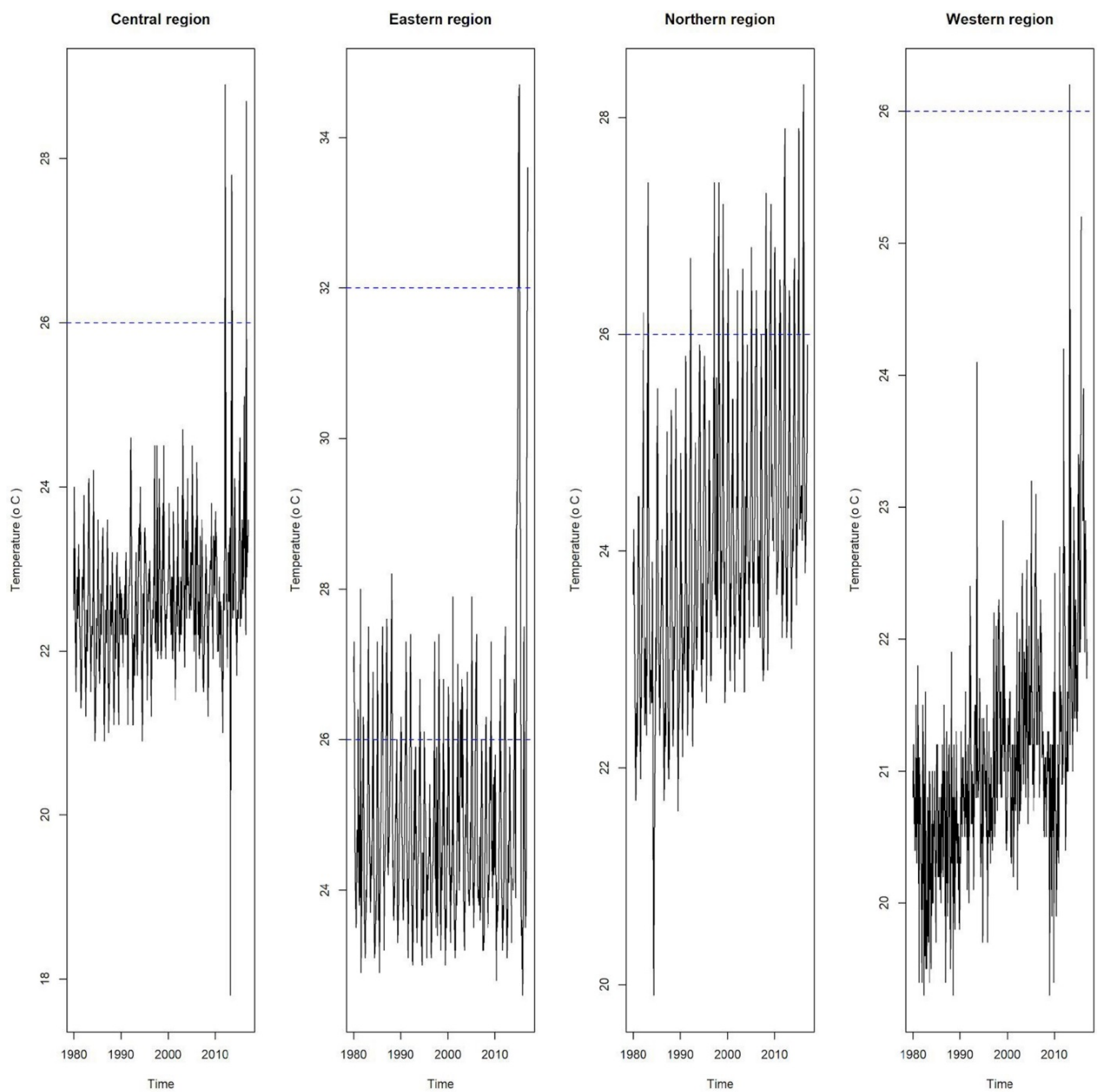

Figure 2: Mean Temperature for different regions for period 1980-2016.

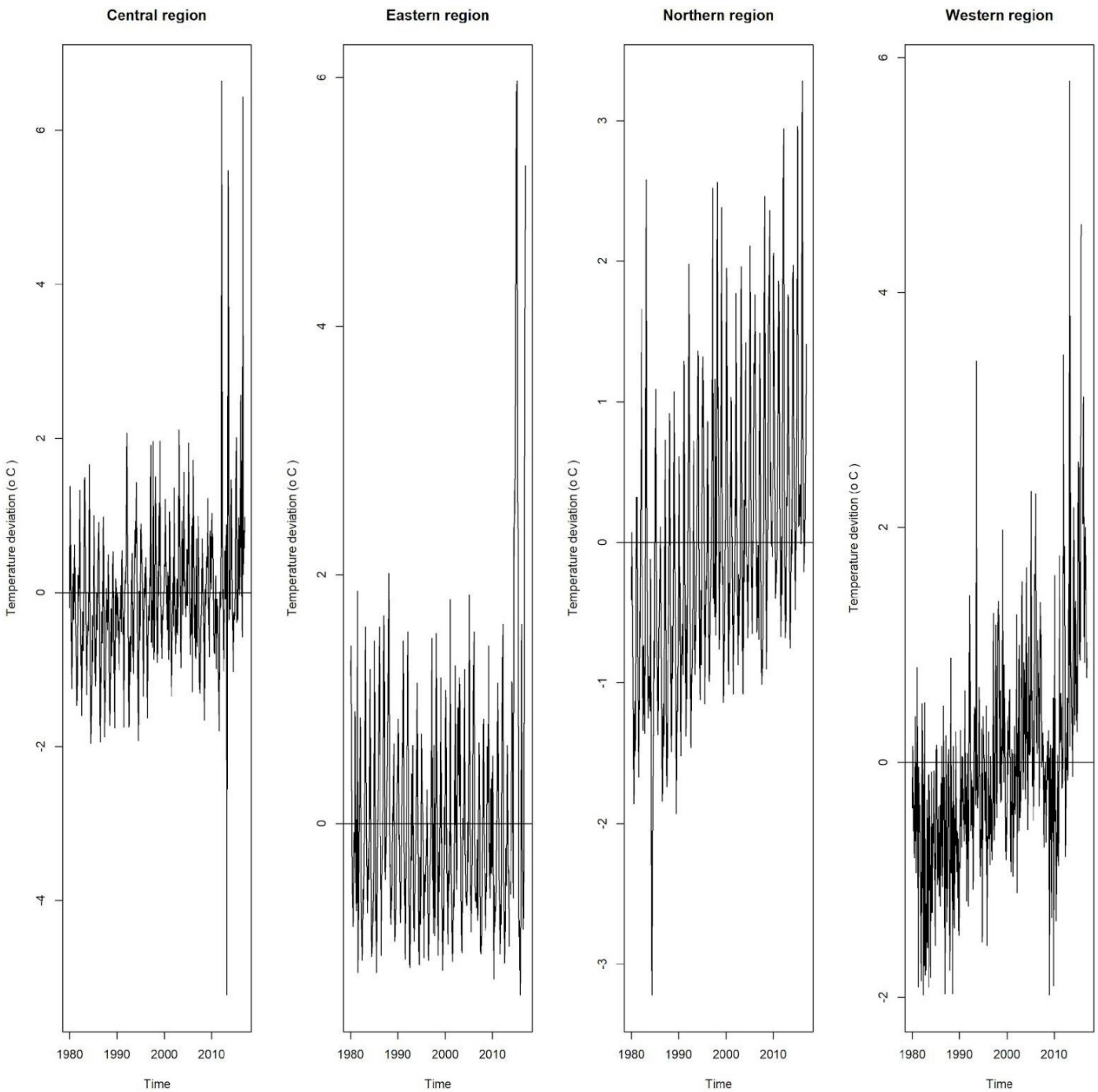

Figure 3: Temperature deviations from the long term mean for the different regions for a period 1980-2016.

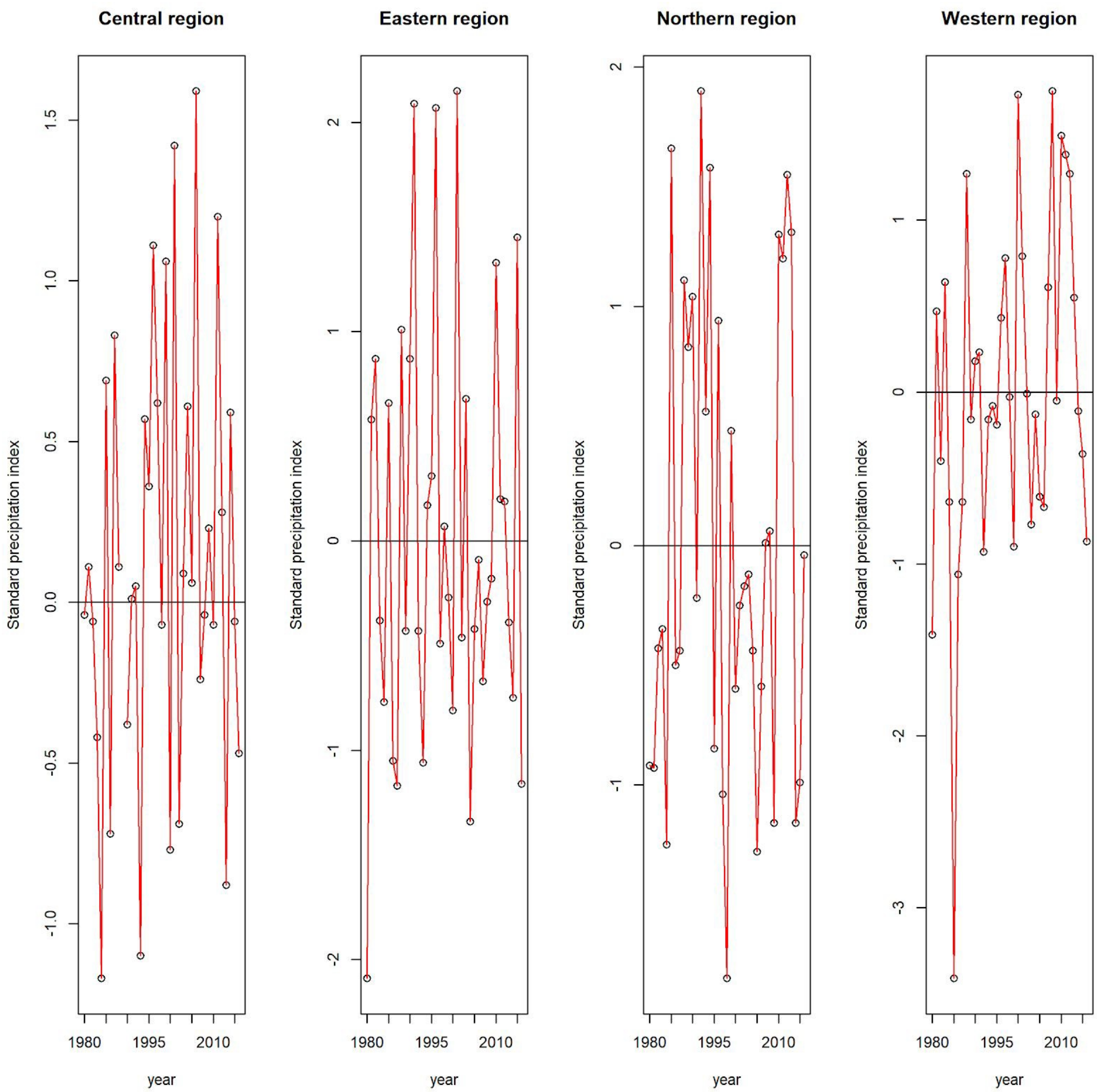

Figure 4: 12-month Standard precipitation index for the different regions for a period of 1980- 2016.

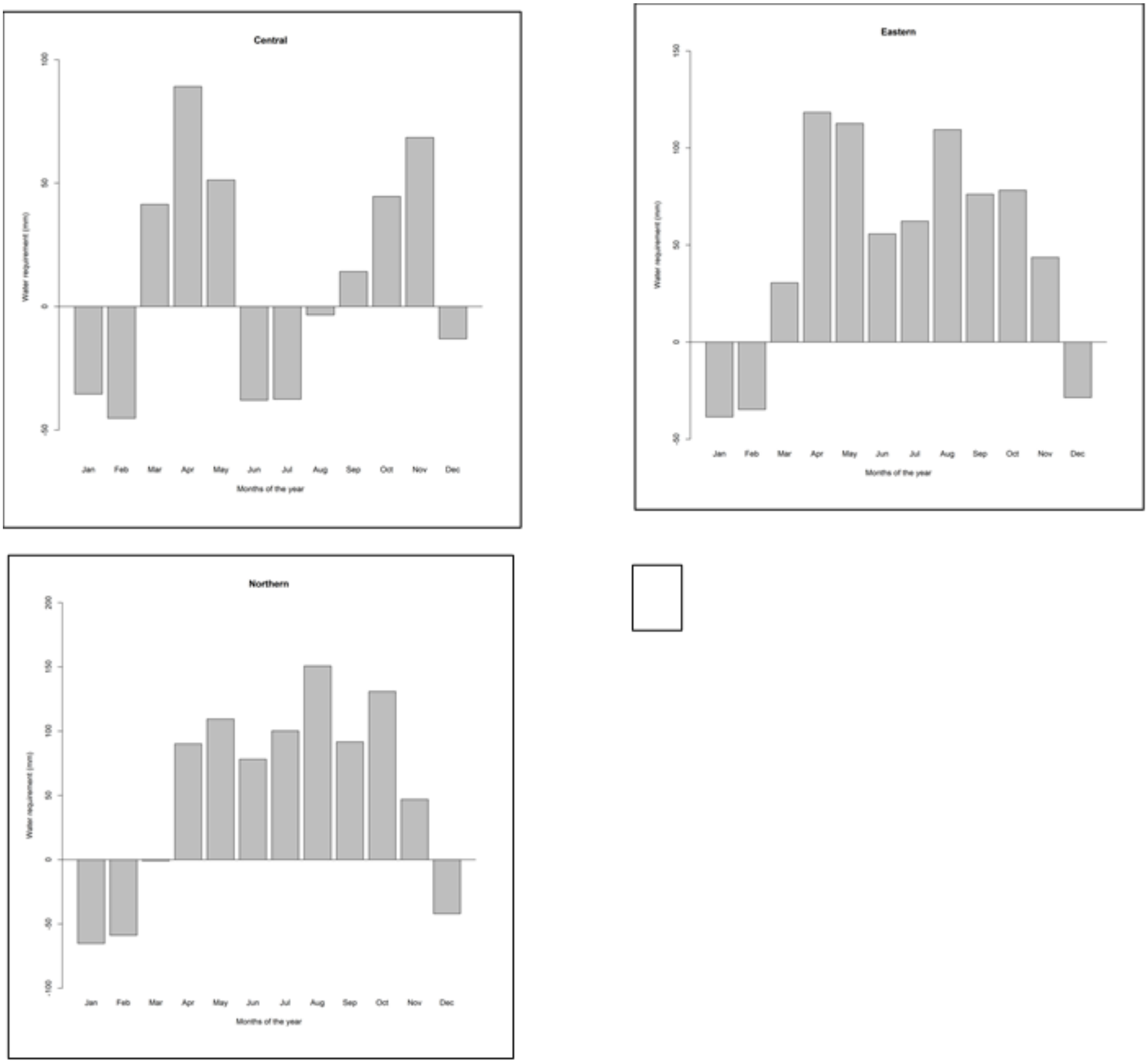

Figure 5: Monthly water requirement for the different regions

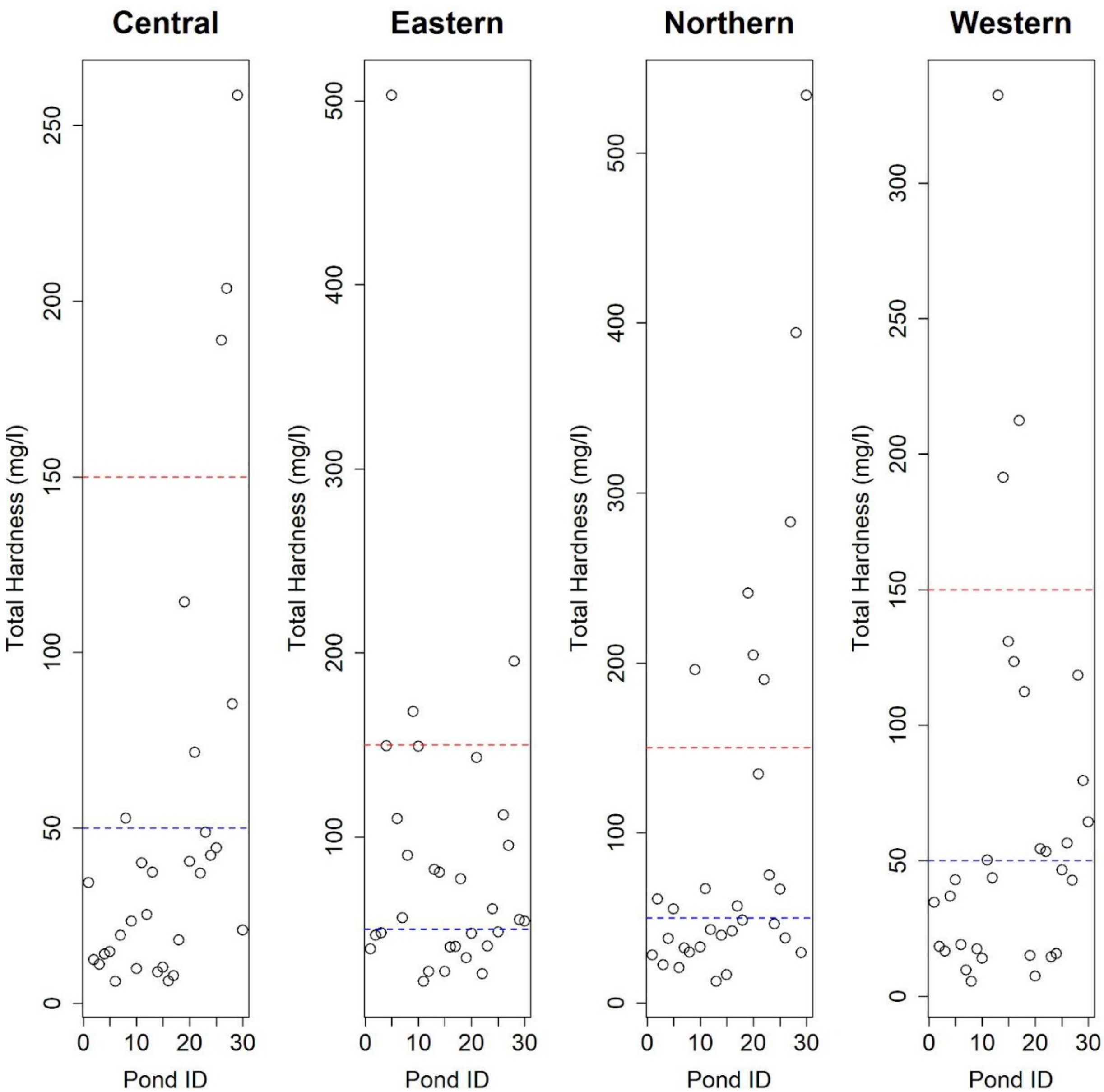

Figure 6: Frequency distribution of different pond water sources for total hardness concentration.

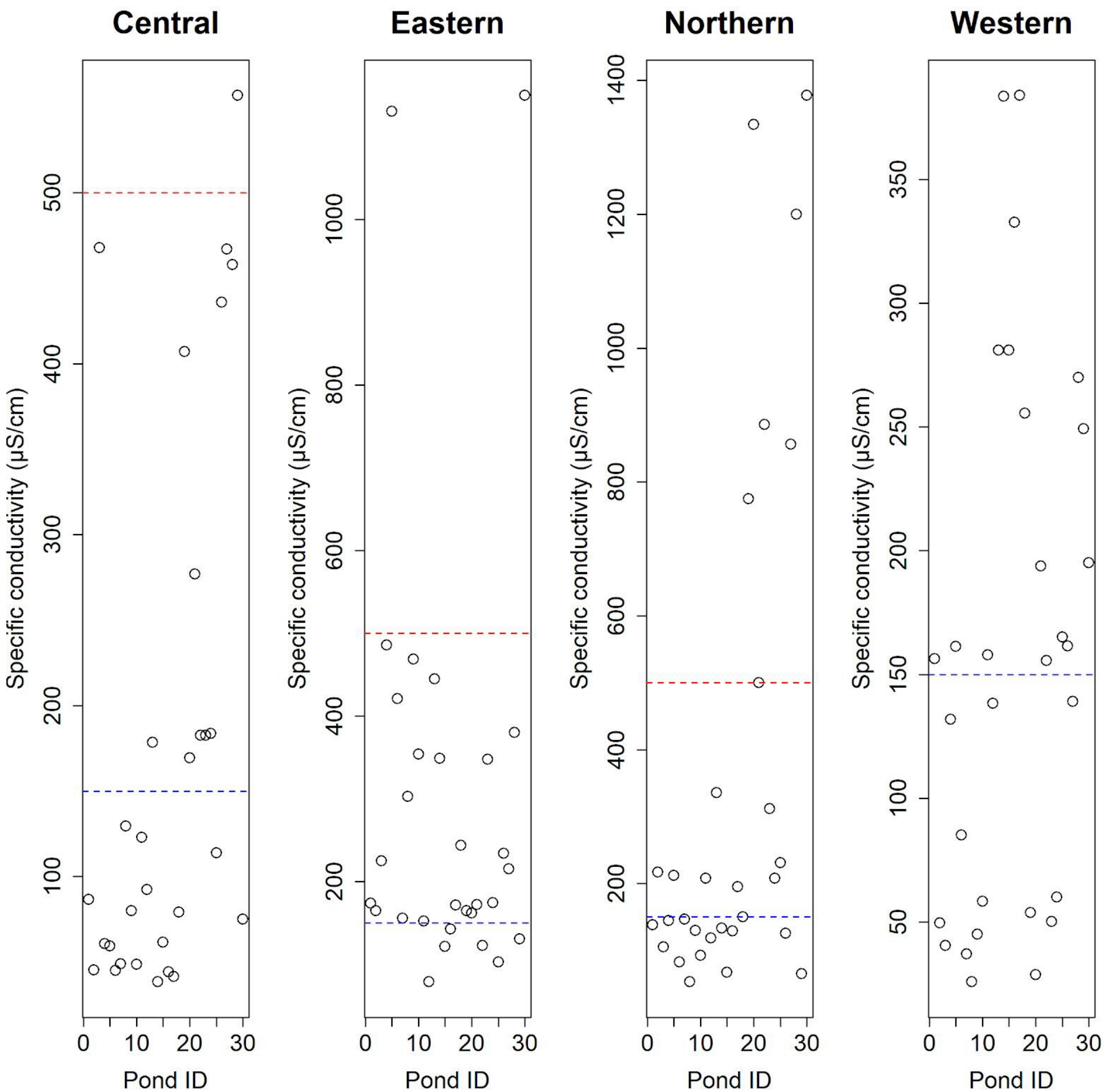

Figure 7: Frequency distribution of different pond water sources for specific conductivity concentration.

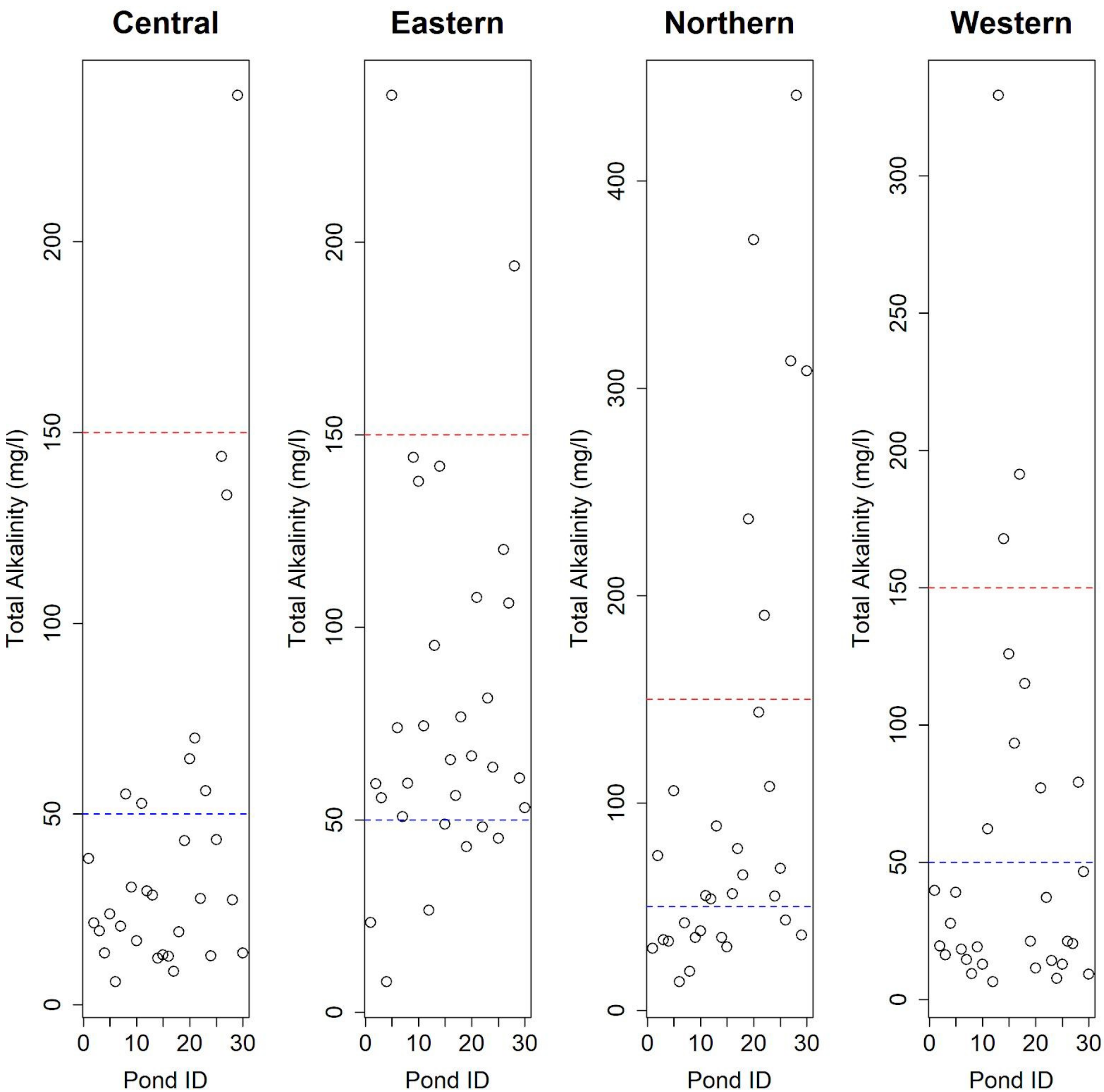

Figure 8: Frequency distribution of different pond water sources for total alkalinity concentration.

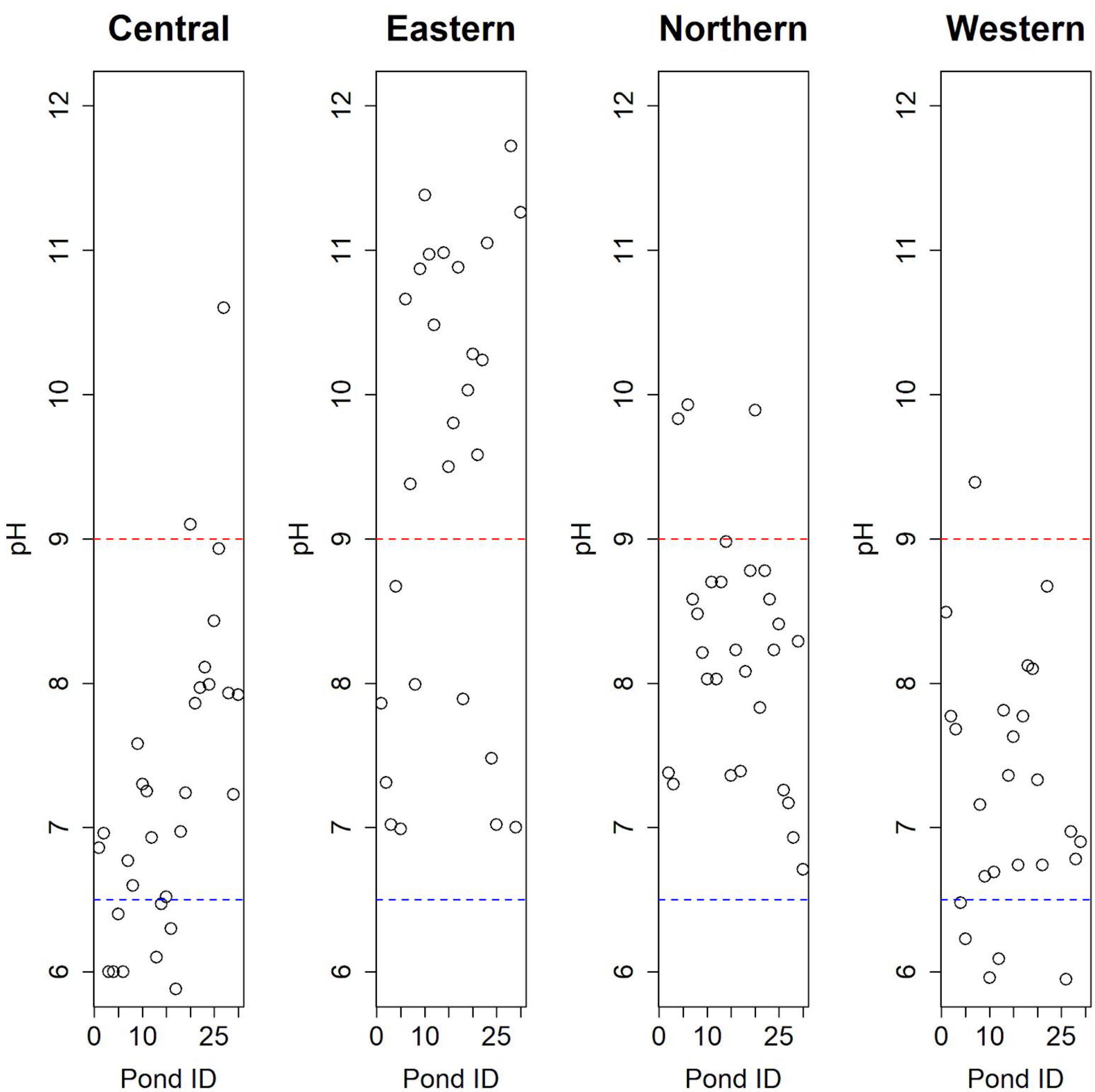

Figure 9: Frequency distribution of different pond water sources for pH concentration.

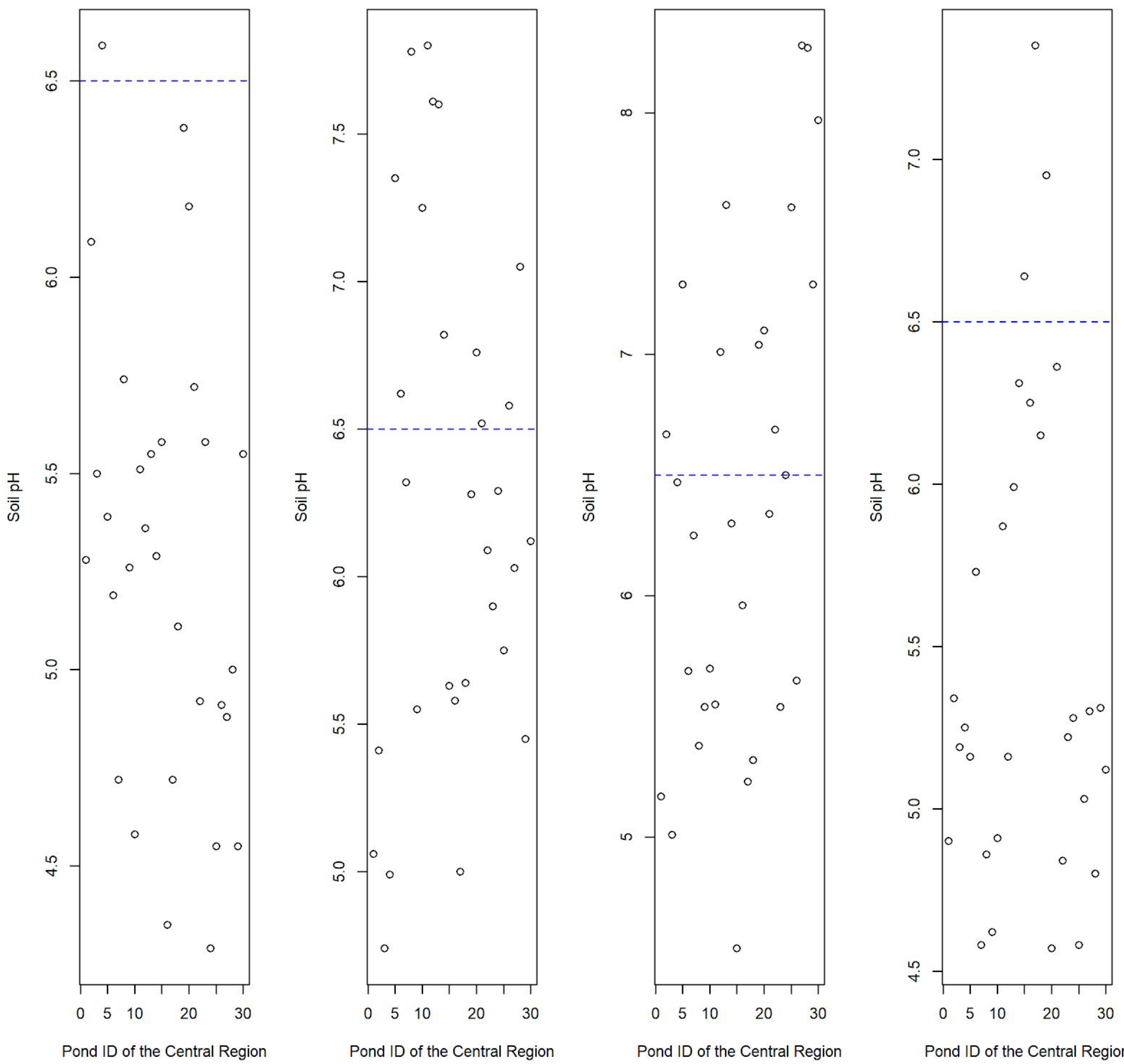

Figure 10: Frequency distribution of different pond water sources for soil pH.

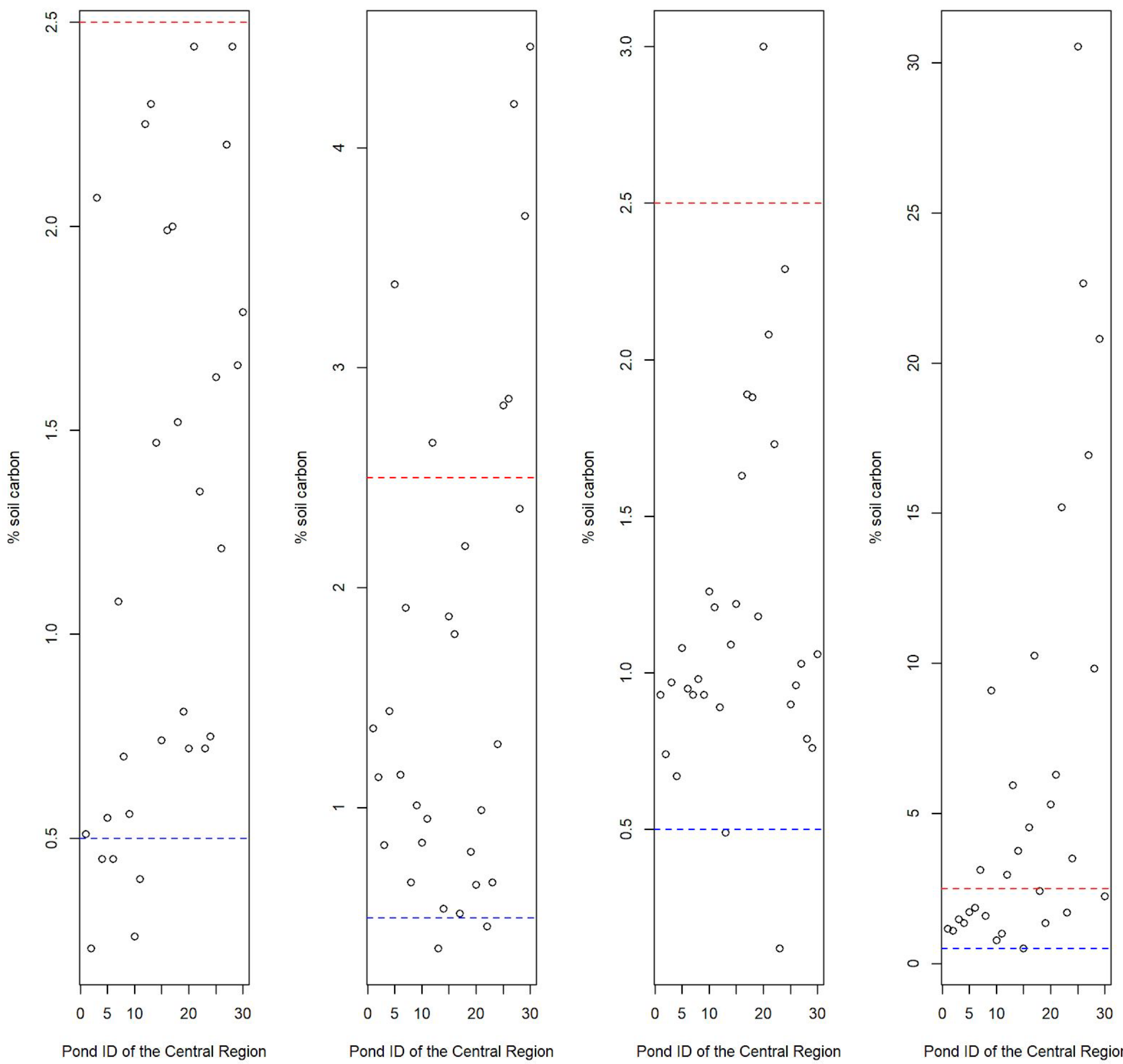

Figure 11: Frequency distribution of different pond water sources for total carbon.

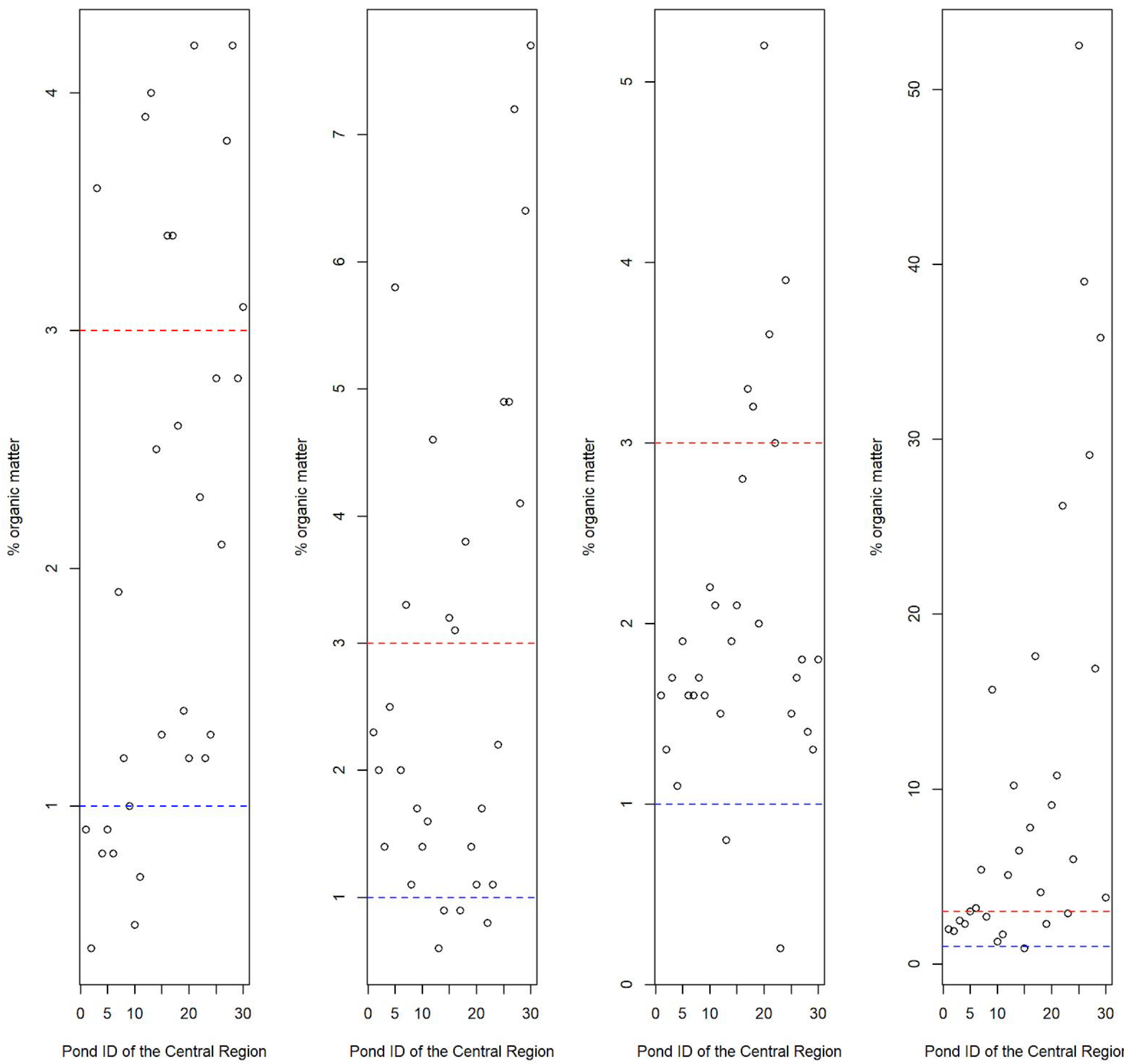

Figure 12: Frequency distribution of different pond water sources for organic matter.

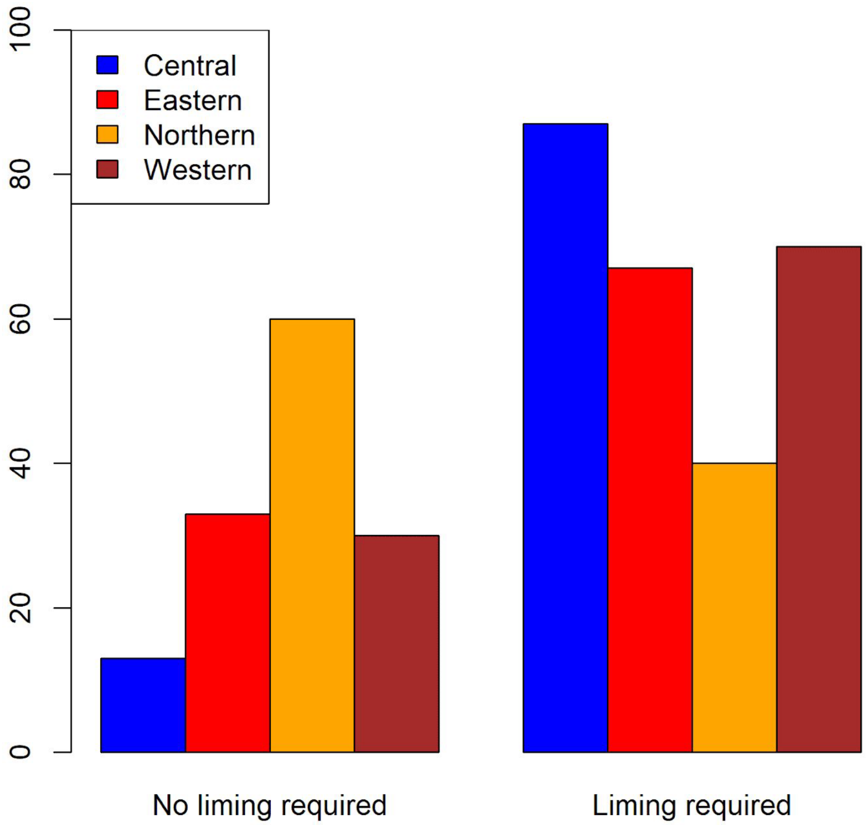

Figure 13: Percentage frequency of the ponds that needed liming and those that did not in the different regions.

ADDITIONAL INFORMATION

Water Quality Management Recommendations for Tilapia and African Catfish Culture in Uganda-A list of water quality management procedures for use in pond culture of tilapia and African catfish are provided below:

Tilapia

1. The water source for the pond such as a well or stream or water from the pond that is filled by runoff should be analyzed. The minimum analysis would include; pH, total alkalinity, and electric conductivity. A complete analysis including trace elements would be desirable for a better understanding of the water quality. However, a survey of water sources and ponds suggested that low pH and alkalinity were the usual problems.
2. The area around the water source and watershed of the pond should be examined for sources of erosion that could create turbidity in the ponds or for pollution that could be harmful to fish. Highly polluted sites should be neglected for building new ponds. Erosion on watersheds usually can be prevented by establishing grass cover.
3. Many ponds in Uganda have acidic bottom soils and lower alkalinity than necessary for good fish production. Although this limitation is easily corrected by liming, there does not seem to be a source of good quality liming material. The best product located (Neelkanth Ltd hydrated lime) had an effective neutralizing value of only 50% of best quality agricultural limestone.
4. Hydrated lime at applications above 100 kg/ha of high quality product will raise pond pH enough to sometimes kill fish. Thus, the hydrated lime product would have to be applied to the pond bottom between crops when there are no fish in the pond. The pond should be allowed to stand after refilling until the pH is below 8.5. This usually will take about 2-3 weeks, but if the pond owner has a pH meter or kit, the pH can be measured and possibly allow less fallow time.

5. The recommended rates for the use of the Neelkanth Ltd hydrated lime for ponds of different alkalinities follow:

Alkalinity (mg/L)	Neelkanth Ltd hydrated lime (kg/ha)
Below 10	8,000
10-20	6,000
20-40	4,000
Above 40	0

6. Farmers should urge the government to either establish some standards for liming materials or import liming materials of better quality than the domestic products. Note: Possibly there are other sources of liming materials of better quality that were overlooked in the study.
7. If pH is below 4.5 in pond water, there will be no alkalinity. The best option usually is to abandon such sites. But, if desired, high rates of liming can be tried.
8. Liming material should be spread uniformly over ponds. It should be applied at least 2 weeks before phosphate fertilizer is applied to ponds. Liming material can be applied before, at the same time, or soon after the first application of organic fertilizer.
9. Alkalinity should be measured annually in ponds and liming materials re-applied in accordance with measured alkalinity (see #5).
10. In ponds where feed will not be applied, fertilizers are necessary to increase fish production. Organic fertilizers such as fresh-cut grass, leaves, livestock manure, or chicken manure may be used. Alternatively, chemical fertilizers such as urea and triple superphosphate may be used to fertilize ponds.
11. It is difficult to establish the maximum safe amount of organic fertilizers for a pond, because organic fertilizers vary in water and nutrient content. The maximum rate probably should not exceed 200 kg/ha/day for grasses, hay and leaves or 100 kg/ha/day for animal manure. Of course, organic fertilizers may be applied daily, every other day, three times weekly, or even weekly. But, organic matter uses oxygen as it decomposes. Warning: Excessive organic fertilizer application can lead to dissolved oxygen depletion and fish kills may result.
12. Chemical fertilizers have a known nutrient content making the application rate easier to determine. The most common chemical fertilizers used in ponds are urea and triple super phosphate. Satisfactory application rates usually are 15 – 20 kg/ha triple superphosphate.
13. Fertilizers should be applied at 1- 2 weeks' intervals until a good phytoplankton bloom is established. Afterwards, fertilizers should be applied as necessary to maintain the phytoplankton bloom.
14. The abundance of phytoplankton typically is gauged by water clarity. In a properly fertilized pond for tilapia, underwater visibility usually will be around 30 – 40 cm.
15. The underwater visibility can be checked with a ruler or other measuring stick to which a white object attached at the end. The measuring device is extended vertically downward into the water until it first disappears from sight. The depth of underwater visibility is read from the ruler at the water surface. Note: It is possible to purchase a Secchi disk for measuring water clarity. This device is a weighted 20-cm diameter disk with calibrated line attached. It is lowered into the water and the depth at which it disappears is recorded.
16. Fertilizers should be re-applied when the underwater visibility is less than 45 cm. Do not wait until the water clears more before making another fertilizer application. A high abundance of phytoplankton must be maintained to support fish production.
17. Another reason for maintaining a good phytoplankton bloom is for underwater weed control. In clean ponds, dense infestations of underwater plants that are undesirable in fish ponds may grow profusely.
18. The fertilizers for applying in a pond should be weighed and placed in a large pail. The pail should be filled with water and 15 – 30 minutes allowed for fertilizers to dissolve. The water and fertilizer should be stirred vigorously for 2 – 3 minutes after which the mixture should be splashed over the pond surface.
19. Dense phytoplankton bloom (underwater visibility less than 10 – 15 cm) should be avoided because too much phytoplankton may result in nighttime dissolved oxygen depletion and fish mortality.
20. Farmers may choose to feed tilapia in ponds rather than to fertilize ponds to increase tilapia production.

21. In ponds with feeding, it still is desirable to apply agricultural limestone to ponds with low alkalinity water.
22. Pelleted feed should be applied one or two times daily. Usually, it is more effective to fish growth the daily feed allowance is offered in two applications rather than a single application.
23. The feed application rate should be gradually increased as the fish grows. Usually, early in the grow-out period, feed is applied at 3- 4% of the estimated weight of fish in the pond. Later, the feeding rate may be reduced to 2.5% or even 2 % of fish weight in ponds.
24. Water from feeding enrich ponds with nutrients leading to phytoplankton blooms. Too much phytoplankton can cause dissolved oxygen depletion especially at night.
25. Tilapia are hardy and withstand low dissolved oxygen concentration well. But, low dissolved oxygen concentration can kill them.
26. In order to minimize the possibility of fish kills from oxygen depletion, daily feed input probably should not exceed 75 kg/ha/day, but to be safe, a limit of 50 kg/ha/day is prudent.
27. Ammonia can be toxic to fish, but if dissolved oxygen concentration is adequate in ponds with feeding, ammonia toxicity to tilapia is seldom seen.
28. Some fish farmers apply bacterial products (usually living cultures of bacteria) often called probiotics to ponds for removing ammonia and improving other aspects of water quality. There is no evidence from research that probiotics are effective.
29. Water exchange may be used in pond with feeding to increase the dissolved oxygen supply and allow greater feed input and fish production. Rates of water exchange from 25% to several hundred percentage of pond volume per day have been used, but there is no reliable method for determining the acceptable feeding rate at a water exchange rate other than by monitoring the dissolved oxygen concentration.
30. Another way to increase fish production in ponds with feeding is to apply mechanical aeration. The relationship between aeration rate and fish production is well established.
31. Several kinds of aerators are available, but paddlewheel aerators are most commonly used in fish ponds. Both electric and diesel-powered devices are available.
32. The general “rule of thumb” for aeration is to install one horse power (hp) of aeration for 500 kg of fish above 2,000 kg/ha. For example, to produce 5,000 kg/ha of fish, the calculation of aeration requirement follows;
33. 5,000 kg fish/ha - 2,000 kg fish/ha = 3000 kg fish/ha
34. 3,000 kg fish/ha/500 kg fish/ha/hp = 6 hp aerators/ha
35. Aerators should be placed in water of 0.75 m or more in depth. When multiple aerators are installed in a pond, they usually are positioned to cause a circular water flow pattern.
36. Ponds usually have high dissolved oxygen concentration during the day, and aerators can be turned off. The critical period for aeration in fish ponds typically is at night.
37. Ammonia often accumulates in pond with feeding and aeration because of large feed input. Ammonia is toxic to fish, but tilapia are quite tolerant to ammonia. Unless total ammonia nitrogen concentrations consistently are 5 – 10 mg/l, ammonia stress or toxicity would not be expected unless pH in pond water was above 9. Test kits can be purchased for measuring pH and ammonia, but ammonia and pH monitoring in tilapia ponds is not usually necessary.
38. The only effective way of reducing ammonia concentrations in ponds (aside from lowering feed inputs which is not desirable and does not provide immediate ammonia reduction) is to flush water through ponds.

African Catfish

39. This air-breathing species is very tolerant to low dissolved oxygen and poor water quality conditions. As a result, little water quality management is necessary.
40. The only recommendation is to apply liming materials to acidic, low alkalinity ponds. The instructions for liming tilapia ponds may be followed.