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Macroinvertebrate Structural Composition as Indicators of Water Quality in Headwater Streams

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Abstract

Changes in land use from forestry to urban settlement or agriculture are of great global concern because they are associated with soil degradation, enrichment of nutrients, sedimentation, input of harmful pollutants into aquatic ecosystems and alteration of ecological communities. Benthic macroinvertebrate assemblages at eight sites along the Nzoia River headwater streams and how they correspond to different land use practises were assessed in February-March, 2020 as indicators of water quality. These sites were selected along a disturbance gradient (land use) and were grouped into reference sites (n =4; minimally disturbed sites) and disturbed sites (n =4). A number of physico-chemical parameters were determined in situ and benthic macroinvertebrates were collected and preserved in 70% alcohol before being transported to the laboratory for processing. Variables; conductivity, DO, temperature, velocity and discharge recorded significant differences between the two site categories. Total abundance, taxon richness, evenness, diversity and number of dominant taxa were determined between the two site categories. EPT and Coleoptera co-dominated the reference sites, whereas, Diptera and the other order co-dominated the disturbed sites. Families Polycentropodidae and Hydropsychidae of order Trichoptera and Hydrophilidae of order Coleoptera were restricted to the reference sites. Tolerant families such as Mesoveliidae, Notonectidae and Belostomitadae of order Hemiptera and Thiaridae, Lymnaeidae and Planorbidae of order Mollusca were only found in the disturbed sites. Significant variations displayed in macroinvertebrate assemblages were largely due to variations in water quality. As in many other studies within the region, populations of macroinvertebrates have proven themselves to be good water quality indicators and can be used as bioindicators.

Keywords: Bioindication, Macroinvertebrates, Physico-Chemical Variables, Afrotropical Streams

INTRODUCTION

In lotic systems, where variations in hydrological characteristics are challenging and complex to estimate, use of biological monitoring has proven to be valuable because of its integrating nature (Soininen & Könönen, 2004). Biological indicators such as fish, diatoms and macroinvertebrates have been relied on to provide integrated estimates of water quality (Castela *et al*., 2008) and have been established as reliable tools for tracking historical environmental changes inferred from groups preserved in sediments (Kilroy *et al*., 2006). Macroinvertebrates are organisms that do not have a backbone and are mainly seen with the naked eyes (Allan, 2004) that exist in different habitats ranging from fast flowing mountainous streams to inhabiting the lower areas of the streams and rivers below rocks (Dallas, 2007). They are useful bioindicators because they have long life-span and have low mobility hence cannot quickly move away from environmental stress (Barbour *et al.,* 1999).

Knowledge of the composition and distribution of the benthic macroinvertebrates, offers reliable and local details on recent events that have caused the observed patterns (Marques *et al*., 2003). Within the region, several researchers have encouraged the use of macroinvertebrates (both benthic and drifting) as biological indicators in the face of deteriorating water quality in streams and rivers (Adakole, 2000 Raburu, 2003; Masese *et al*., 2009; Aura *et al.*, 2010). On the Kenyan side of the Lake Victoria basin, widespread degradation of aquatic ecosystems is majorly attributed to land use/land cover change (Raburu, 2003; Okungu & Opango, 2005). Intensified farming activities in the Nzoia River Basin (GEF, 2004), which is the largest catchment in the Lake Victoria Basin section of Kenya, has led to sedimentation, an increase in the enrichment of nutrients derived from fertilizers used in the farms and livestock input when using the streams and rivers as watering grounds, contamination from pesticides (Osano *et al.*, 2003), not just to the Nzoia River and its tributaries, but also to Lake Victoria (Okungu & Opango, 2005).

The Nzoia River headwater streams serve as critical water sources for various uses and users. However, a variety of anthropogenic practices are threatening the quality of the water, such as bathing, washing, water collection for domestic purposes, swimming, irrigation, sand mining, washing motorbikes and vehicles, including discharging waste water from urban cities and factories. In that regard, there is a need to monitor the current status of water quality in these streams since the serve as in influent rivers of L. Victoria. Water quality assessment and overall deterioration within the catchment have for long focused on the assessment of physico-chemical parameters, which is a costly approach and lacks an integrative capacity to report on the influence of pollution on biodiversity and the ecological integrity of aquatic resources. There is therefore need to adopt an effective and economical (both in terms of money and time) monitoring tool. Since different taxa of macroinvertebrates respond differently to environmental pressures, such as habitat loss and degradation, pollution and siltation, an overview of the environmental conditions of that river can be predicted by quantifying the abundance and diversity of different macroinvertebrates at a given site (Rosenberg & Resh, 1996; Kilonzo *et al.*, 2014; Masese *et al.*, 2021). Therefore, this study was intended to examine the effects of changing water quality on the structural composition and distribution of macroinvertebrates in the headwaters of the Nzoia River, Knowledge that can be used to enhance river management strategies within the region. We hypothesized that the composition of macroinvertebrate assemblages would vary as a result of changes in land use, water quality and habitat characteristics.

MATERIALS AND METHODS

Study Area and Design

The Nzoia River is 257 km long that originates from Mount Elgon, Cheranganyi hill and Kaptagat forest. It flows south and then west, ultimately draining near Port Victoria into Lake Victoria. The Nzoia River is the second biggest river in Kenya by discharge with an estimated discharge of about 118 m^3s^{-1} or about 3,721 million cubic metres annually. The climate of the region is primarily tropical humid, with mean annual precipitation ranging from 900 to 2200 mm and temperatures varying greatly with elevation from 13°C to 25°C. The annual pattern of rainfall is bimodal, with long rainfall between March and June, and short rainfall between August and October. The river traverses a land use gradient of varying human population densities and pressures (Nyadawa & Mwangi, 2010). Study sites were grouped into two categories; reference and disturbed, following riparian land use and reach-scale human influences. Reference sites had a riparian zone that was >60% forest, shrublands or grasslands cover with little or no human influences. Disturbed sites had a riparian zone with >60% agriculture (crop land), human settlements and urban centres. A total of 8 sites were sampled with four (Chepkoilel River at Kaptagat, Sabor River, Kipsenganyi River and Sosiani River at Nairobi Bridge) being reference sites while another four (Sosiani River at the Market, Sosiani River at Huruma, Chepkoilel River at Turbo Bridge and Sosiani River at Turbo) regarded as disturbed sites (Figure 1).

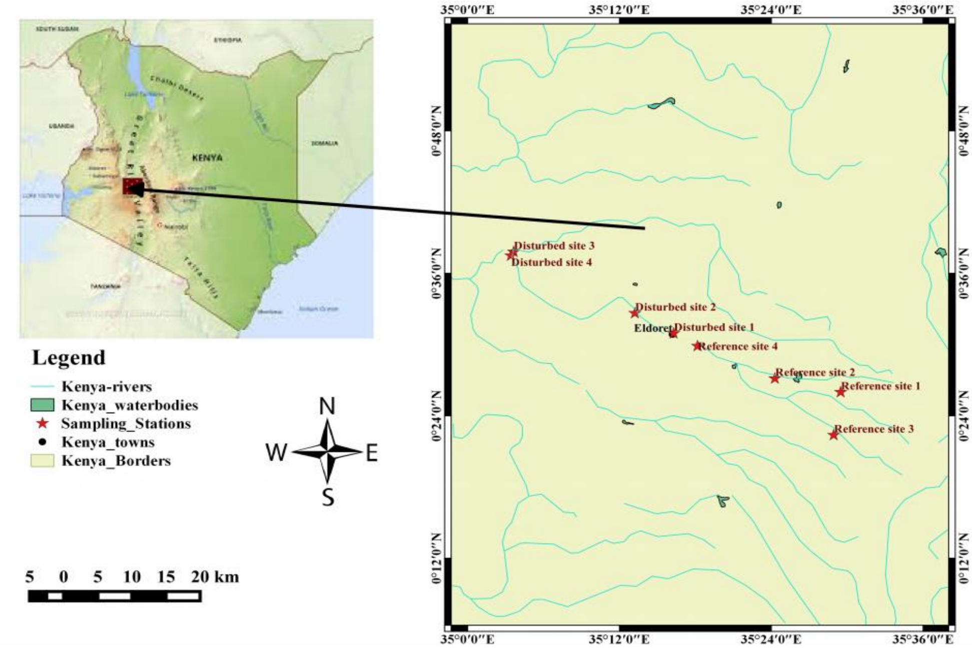

Figure 1: Location of sampling sites in headwater streams of the Nzoia River, Kenya.

Sample Collection and Processing

Physico-chemical variables

Sampling was done during the dry season (February-March 2020). Water temperature, dissolved oxygen concentration (DO), pH, salinity, total dissolved solids (TDS) and electrical conductivity (EC) were measured *in situ* at each sampling site prior to the sampling of macroinvertebrates using a YSI multi-probe water quality meter (556 MPS, Yellow Springs Instruments, Ohio, USA). At each site stream width was measured with a measuring tape on 10 transects at midpoints of 10-m intervals along the reach. The water depth was also assessed at a minimum of 5 points using a 1-m ruler. With a mechanical flow meter (General Oceanic's; 2030 Flow Meter, Miami, Florida), velocity was measured at the same points as depth. Stream discharge was estimated following the velocity–area method (Wetzel & Likens, 2000).

Macroinvertebrate sampling and processing

From each of the eight study sites and sampling occasion, three quantitative samples were taken using a kick net in riffles, runs, pools and marginal vegetation. The sampling process involved disturbing the bottom of the stream, upstream of the net (500-µm mesh size), thus, the dislodged macroinvertebrates are washed by water currents into the net. Kicking of macroinvertebrates was performed for a typical 1 minute per biotope on an area of approximately 1 m^2. The sampled macroinvertebrates were placed in plastic containers, labelled and preserved in 70% alcohol before being transported in cool boxes to the laboratory for processing. In the laboratory the samples were washed under running water through a series of sieves. Macroinvertebrates were then sorted, identified to family level with the aid of keys and schema in several guides (Day *et al*., 2002; de Moor *et al.*, 2003a, b; Merritt and Cummins, 1996) and enumerated for determination of numerical abundance, diversity and richness.

Statistical Analysis

Two-sample t-test was used to test significant variations in physico-chemical water and stream size variables between reference and disturbed site categories. Community structure was described in terms of taxon richness, relative abundance and diversity indices between site categories. The several reach-scale diversity indices calculated included Shannon's diversity index (H′) that was derived as a measure of diversity. Gamma diversity (i.e., Hill's number; Hill, 1973) and Fisher's alpha (Fisher *et al*., 1943) were calculated as extra measures of diversity. As a measure of evenness, a H′/H′max index (Pielou, 1975) was used. Species richness was derived from the reciprocal form of the Simpson index (1-Ds) (Simpson, 1949). Margalef's species richness index was calculated as an extra measure of species richness. In order to test for statistical differences in abundance and richness between the two site categories, two-sample t-tests were used. The Canonical Correspondence Analysis (CCA) was used to show relationships between of water quality variables and macroinvertebrate structural assemblages. The output was displayed as triplots in which the plotted points for macroinvertebrates and site categories could be related to physico-chemical and stream-size variables that were represented as rays. Statistical analyses were performed with PAST (version 3.21) software while figures were created in MS Office Excel (2016).

RESULTS

Water Physico-Chemical Variables

Disturbed sites had higher values of water quality and stream size variables, except pH and DO which were lower in these sites (6.5±0.7 and 6.3±0.8 mgL^{-1}), respectively (Table 1). Reference sites recorded lower values for all the water quality variables and stream size variables except for pH and DO which was 6.8±0.8 and 8.1±1.7 mgL^{-1}, respectively, which were higher in these sites than at disturbed sites. Higher discharge levels (0.26±0.1 m^3s^{-1}) were recorded in disturbed sites while references sites had much lower discharge (0.08±0.1 m^3s^{-1}). The width of the rivers was large in disturbed sites (12.2±5.4 m). Salinity levels were higher in disturbed sites (0.16±0.2 mgL^{-1}) while in reference sites salinity levels were relatively lower (0.01±0.1 mgL^{-1}). There was significant differences in temperature, conductivity, Total Dissolved Solids (TDS), width and discharge (p <0.005) (Table 1).

Table 1: Two-Sample t-test for significance of physico-chemical variables between the two site categories (Reference and Disturbed sites). physico-chemical variables expressed as mean ± SD. *p** Significant < 0.05

Water Quality & Stream Size Variables	Reference sites (n= 4)	Disturbed sites (n= 4)	t-test	
			t-value	*p*-value
Temperature (°C)	13.6±0.9	18.1±1.2	2.086	<0.001*
Conductivity (µScm^{-1})	31.1±9.7	96.9±23.2	2.093	<0.001*
TDS (mgL^{-1})	0.02±0.1	0.06±0.1	2.093	<0.001*
Salinity (mgL^{-1})	0.01±0.1	0.16±0.2	2.160	0.006*
DO (mgL^{-1})	8.1±1.7	6.3±0.8	2.228	0.012*
pH	6.8±0.8	6.5±0.7	2.131	0.331
Width (m)	4.3±1.6	12.2±5.4	2.120	<0.001*
Depth (m)	0.3±0.1	0.4±0.2	2.086	0.004*
Velocity (ms^{-1})	3.55±1.8	3.98±2.2	2.093	0.796
Discharge (m^{3}s^{-1})	0.08±0.1	0.26±0.1	2.160	<0.001*

Macroinvertebrates Structural Composition

The study recorded a total of 17,879 macroinvertebrates belonging to 14 orders and 49 families (Table 2). There was spatial variations in the macroinvertebrate families between the two site categories. Eight orders of insects namely Ephemeroptera, Plecoptera, Diptera, Trichoptera, Coleoptera, Lepidoptera, Odonata and Hemiptera, and six non-insect orders (Arachnida, Decapoda, Arhynchobdellida, Oligochaeta, Tricladida and Mollusca) were collected from the study sites. Families Polycentropodidae and Hydropsychidae of order Trichoptera and Hydrophilidae of order Coleoptera were restricted to the reference sites. These families are sensitive macroinvertebrate taxa and cannot tolerate poor water quality in the disturbed sites. Tolerant families such as Mesoveliidae, Notonectidae and Belostomitadae of order Hemiptera and Thiaridae, Lymnaeidae and Planorbidae of order Mollusca were only found in disturbed sites (Table 2).

Table 2: Presence-absence distribution of macroinvertebrates in the sampled study sites. + =presence while - =absence (Site 1 =Chepkoilel River at Kaptagat, Site 2 =Sabor River, Site 3 =Kipsenganyi River, Site 4 = Sosiani River at Nairobi Bridge, Site 5 =Sosiani River at the Market, Site 6 = Sosiani River at Huruma, Site 7 =Chepkoilel River at Turbo Bridge and Site 8 = Sosiani River at Turbo)

		Site Categories							
		Reference				Disturbed			
Order	Family	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8
Arachnida	Araneae	-	+	+	+	-	+	-	+
Arhynchobdellida	Hirudinidae	+	-	+	+	+	+	+	+
Ephemeroptera	Baetidae	+	+	+	+	+	+	+	+
	Leptophlebiidae	+	+	+	+	+	+	+	+
	Tricorythidae	+	+	-	+	+	-	+	+
	Caenidae	+	+	+	+	+	+	+	+
	Ephemerythidae	+	+	+	-	+	+	+	+
	Oligoneuridae	-	-	+	+	-	-	+	+
	Heptageniidae	+	+	+	+	+	+	+	+
Diptera	Muscidae	+	-	-	-	+	+	-	+
	Tabanidae	-	-	-	+	-	-	-	+
	Tipulidae	+	+	+	+	+	+	+	+
	Simuliidae	+	+	+	+	+	+	+	+
	Chironomidae	+	+	+	+	+	+	+	+
	Ceratopogonidae	-	+	+	-	-	-	+	-
Odonata	Corduliidae	-	+	-	+	-	-	+	+
	Gomphidae	+	+	+	+	-	-	+	+
	Lestidae	+	+	+	+	+	-	+	+
	Libellulidae	-	+	-	-	-	-	-	+
	Aeshinidae	-	+	-	-	-	-	-	+
Trichoptera	Calamoceratidae	-	+	-	+	-	-	+	-
	Polycentropodidae	-	+	-	+	-	-	-	-
	Hydropsychidae	+	+	+	+	+	+	+	+
	Lepidostomatidae	+	+	-	+	-	-	+	+
	Leptoceridae	+	+	+	+	+	-	+	+

	Hydroptilidae	-	-	+	-	-	-	-	-
	Philopotamidae	+	+	-	+	+	-	-	-
Hemiptera	Mesoveliidae	-	-	-	-	-	+	+	-
	Pleidae	-	-	-	+	-	+	+	+
	Nepidae	-	+	-	-	-	-	-	+
	Naucoridae	-	-	+	+	-	+	+	+
	Notonectidae	-	-	-	-	-	+	+	+
	Belostomitadae	-	-	-	-	-	+	-	+
	Corixidae	-	-	+	+	+	+	+	+
Tricladida	Planariidae	+	+	+	-	+	+	-	-
Coleoptera	Hydrophilidae	+	-	-	+	-	-	-	-
	Gyrinidae	+	+	+	+	-	+	-	+
	Elminae	-	+	-	+	+	-	+	+
	Larainae	-	+	-	+	-	+	+	+
	Scirtidae	+	+	+	+	-	-	+	-
Oligochaeta	Lumbruculidae	+	+	+	+	+	+	+	+
	Tubificidae	+	+	+	+	+	+	+	+
Plecoptera	Perlidae	-	+	-	-	-	-	+	+
Mollusca	Thiaridae	-	-	-	-	+	+	-	-
	Sphaeridae	+	+	+	+	+	+	+	+
	Lymnaeidae	-	-	-	-	-	+	-	-
	Planorbidae	-	-	-	-	-	+	+	+
Decapoda	Potamonautidae	+	+	+	+	-	-	+	-
Lepidoptera	Crambidae	-	-	+	+	-	-	+	-

Major orders that are usually used as indicators of pollution or poor water and habitat quality in streams and rivers were used to describe macroinvertebrates relative abundance in the study sites (Figure 2). The five (5) major orders considered were EPT (Ephemeroptera, Plecoptera and Trichoptera), Diptera, Coleoptera, Hemiptera and other orders (comprised of all the other orders that were identified in the study sites). In reference sites, the relative abundance of EPT and Coleoptera co-dominated while at disturbed sites relative abundance of the other orders was highest (Figure 2a). Order Diptera recoreded higher abundance in the disturbed sites than the reference sites. The abundance of EPT and Coleoptera reduced in disturbed sites because they are sensitive orders that cannot thrive in poor quality waters while Diptera and others (Odonata, Mollusca, Oligochaeta, Tricladida, Arachnida and Arhynchobdellida) dominated these disturbed sites (Figure 2a). In terms of taxon richness, reference sites were rich in EPT and Coleoptera taxa which have sensitive macroinvertebrates while disturbed sites were rich in Diptera, Hemiptera and the others which contain tolerant macroinvertebrate families (Figure 2b).

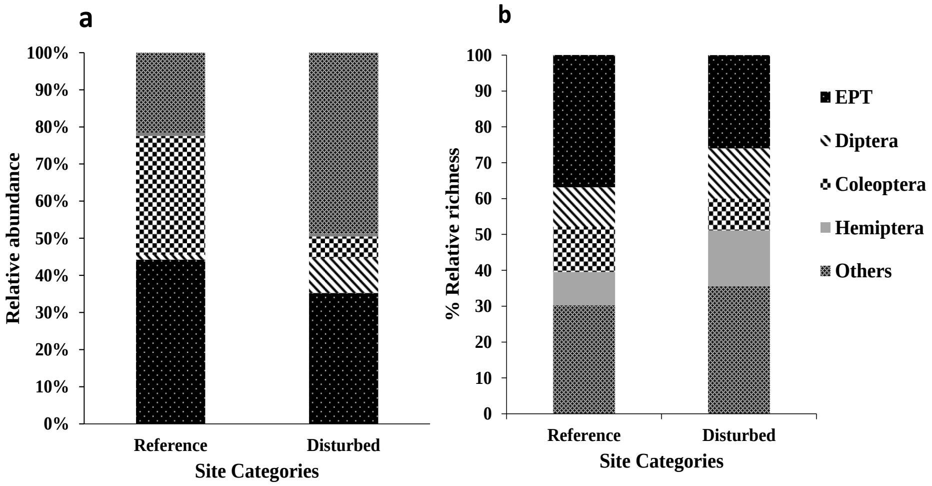

Figure 2: Relative abundance of macroinvertebrates (a) and Relative Taxa Richness of macroinvertebrates (b) in the eference and disturbed site categories of the Nzoia Headwater Streams.

Diversity indices used to measure community structure of macroinvertebrates at sites between the two categories displayed mixed results, with some showing wide ranges, such as Fisher's alpha diversity, dominance, evenness and Margalef's species richness index, while the rest showed narrow ranges (Table 3). Shannon (2.47) and Simpson (0.87) indicated that reference sites were more diverse than disturbed sites while more macroinvertebrates dominated the disturbed sites by 0.22 while reference sites dominance was 0.13 (Table 3). These reference sites still recorded higher values of Fisher alpha (6.25) and Hills number (3.05). They also had a higher number of taxa (45) as compared to the disturbed sites which had the least number of taxa (43) (Table 3).

Table 3: Macroinvertebrates diversity indices between the reference and disturbed study sites

Diversity indices	Reference (n =4)	Disturbed (n =4)
Taxa_S	45	43
Individuals	6,100	11,779
Dominance_D	0.13	0.22
Simpson_1-D	0.87	0.79
Shannon_H	2.47	1.94
Evenness_e^H/S	0.27	0.16
Margalef	4.82	4.69
Equitability_J	0.66	0.51
Fisher_alpha	6.25	5.93
Hill's_number	3.05	2.39

Relationships between Water and Stream-Size Variables and Macroinvertebrate Assemblages

Canonical Correspondence Analysis (CCA) was used to investigate the relationship between macroinvertebrates and major water quality and stream size variables in the site categories. Sensitive macroinvertebrate taxa (e.g. Philopotamodae, Hydroptilidae, Scirtidae, Leptophlebiidae, Polycentropodidae, Lepidostomatidae and Oligoneuridae) mainly of the EPT and Coleoptera orders were found in the reference sites and were associated with higher velocity and dissolved oxygen concentration (Figure 3). At the disturbed sites, tolerant macroinvertebrate taxa found there (e.g. Planaridae, Lymnaidae, Chironomidae, Lestidae, Mesoveliidae, Notonectidae, Belostomatidae and Nepidae) were associated with higher conductivity, temperature, TDS and river width (Figure 3).

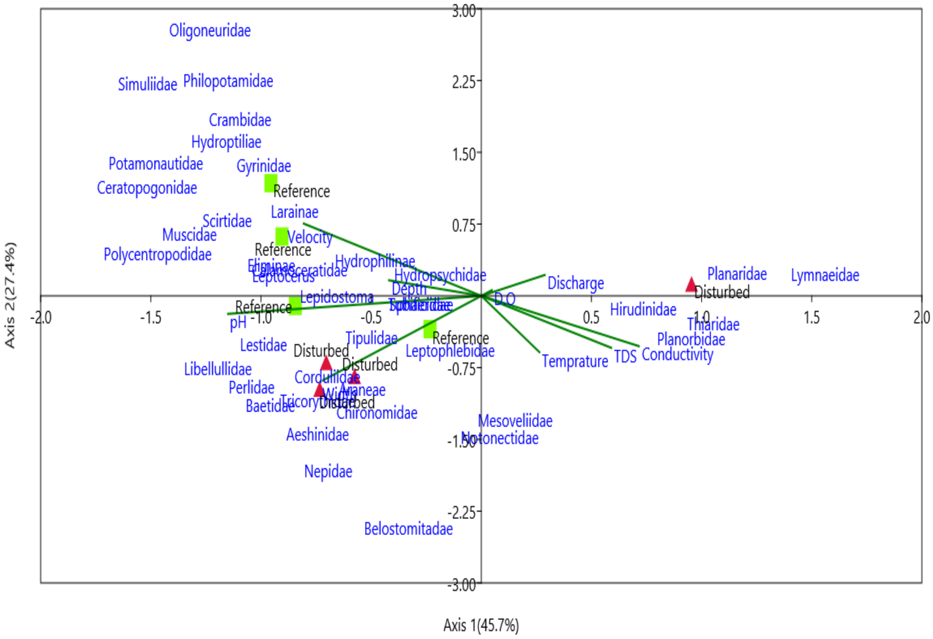

Figure 3: Canonical Correspondence analysis (CCA) triplot of macroinvertebrates taxa based on abundance data in relation to physico-chemical water and stream-size variables between the two site categories.

DISCUSSION

The physico-chemical parameters and stream-size variables showed that water conditions were significantly better in reference sites than in the disturbed sites. Changes in water quality between the two site categories was indicated by decreasing DO levels, increasing temperature, pH, conductivity, salinity and TDS levels. Marginal vegetation along the reference sites seemed to contribute significantly to the good quality of water in these streams. The increase in temperature levels in the disturbed streams than in the reference streams could be attributed to deforestation and riparian zone clearing. The increased canopy cover in the reference sites that elicited the shading of the streams may have facilitated the low temperature levels recorded in these streams (Masese *et al.*, 2014; Ontumbi *et al.*, 2015). The increase in electrical conductivity in disturbed sites could be highly attributed to the increase in anthropogenic activities around these areas (Aura *et al.*, 2010). In similar studies (Aura *et al.*, 2010; Ontumbi *et al.*, 2015), increased levels of conductivity, temperature and total suspended solids, found in river Sosiani, Kenya were ascribed to the ever-increasing anthropogenic activities in the area including conversion of lands to agriculture and urbanization. These activities have seen to the inherent alteration of water quality in immediate and surrounding river systems.

The high abundance and taxon richness recorded in the reference sites than the disturbed sites can be attributed to the good water quality as well as suitable habitat conditions in these streams. Coleoptera, Ephemeroptera, Plecoptera and Trichoptera taxa were dominant in the upstream sites (reference sites) but declined downstream. These taxa are known for their pollution-sensitive nature and their unlikelihood to persist in polluted areas, thriving only in pristine conditions. This is unlike taxa belonging to families of; Chironomidae, Simuliidae, Planariidae and Oligochaeta which were abundant in the midstream and downstream (disturbed) sites owing to their ability to withstand pollution and degraded conditions. These taxa are often found in areas associated with organic pollution caused by nutrient enrichment and sedimentation from agricultural activities in the adjacent riparian areas (Buss *et al.*, 2002).

The lower numbers of EPT taxa in the disturbed sites (occasioned by urban settlements and agricultural activities) coincided with water quality degradation. This phenomenon can therefore be used as an indication of water quality change and giving these taxa an important role as biomonitors to changes in water quality. Several studies have recognized the significant correlation between land use and macroinvertebrate assemblages, indicating that the total number of macroinvertebrate taxa and the percentage metric of groups like Ephemeroptera, Plecoptera and Trichoptera (EPT) decrease while Oligochaeta and Diptera taxa increase as the pollution and changes in the river quality increases (Masese *et al.*, 2009; Aura *et al.*, 2010; Hussain & Pandit, 2012; Masese *et al.*, 2014). The disturbed sites had high temperature, TDS, conductivity and salinity levels with several studies indicating degraded conditions favouring taxa belonging to order Diptera (mainly of Chironomidae and Tanypodinae) and Oligochaetes (Tubifiscidae and Lumbriculidae) while Ephemeroptera, Plecoptera and Trichoptera (EPT) are associated with minimally disturbed conditions (Hawkins & Vinson, 2000; Hyslop & Brown, 2012).

Reference sites had higher diversity than the disturbed sites. The higher diversity of macroinvertebrates in these areas than in the disturbed sites could be a factor of habitat diversity and complexity given that these sites are areas with little or no human disturbance with some having intact riparian zones. Streams with minimally disturbed riparian vegetation have been reported to shed leaves and large wood into these streams creating habitat complexes and produce diverse habitats that supports a high biodiversity as well as increased abundance of macroinvertebrates (Mathooko, 2001; Kaufmann & Faustini, 2012; Anyona *et al.*, 2014).

CONCLUSION AND RECOMMENDATIONS

This study demonstrates that macroinvertebrates can be utilized as bioindicators and also in biomonitoring protocols to evaluate changes in water quality in streams and rivers running through agricultural and urban landscapes. These organisms have varying responses to varying degrees of degradation and changes in river and stream structure with some being more tolerant than others. From our study, EPT & Coleoptera were associated with good water quality while Oligochaetes and Chironomids were associated with poor water and habitat conditions. These results therefore highlight the importance of macroinvertebrates in biomonitoring and in predicting degraded and un-degraded aquatic systems. The current study provides information that can be used by water resource managers and environment officers to conserve these headwater streams.

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Conflict of Interest

The authors declare that they have no conflicts of interest to disclose

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