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Urban impact on ecological integrity of nearby rivers in developing countries: the Borkena River in highland Ethiopia

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Abstract Accelerated pollution and eutrophication of rivers and streams because of human activity are a concern throughout the world and severe in Africa where Ethiopia is case in point. The objective of this study was to assess the urban impact on the ecological integrity of the Borkena River at the eastern escarpment of the central Ethiopian highlands. The water quality status and macroinvertebrate distribution and diversity of the river were assessed during the dry and wet seasons. Diversity indices revealed that a severe decline in the ecological integrity of the Borkena River downstream of Dessie and within Kombolcha towns in terms of macroinvertebrate abundance and composition. Clustering and ordination analysis clearly separated reference sites from urban impacted sites. At the urban-impacted sites, dissolved oxygen was also depleted to 0.5 mg/l and BOD_5 values were reached to a level of above 1,000 mg/l, with extremely low biological diversity of pollution-sensitive taxa. These patterns are the result of a combination of rampant dumping of untreated wastes exacerbated by geologic, topographic, climatic and land use factors.

Keywords Borkena River · Ecological integrity · Ethiopia · Faunal diversity · Macroinvertebrate · Pollution

Introduction

Accelerated pollution and eutrophication of rivers and reservoirs because of human activity are a concern throughout the world (example Burcher and Benfield 2006; Jonnalagadda and Mhere 2001) and severe in Africa (example Ndiritu et al. 2003), where Ethiopia is a case in point (Devi et al. 2008; Alemayehu 2001). However, most research on this problem has been done in industrialized countries, with little information from tropical Africa, especially Ethiopia and other countries in the Horn. Unlike developed nations where stringent regulations have been implemented to restrict the discharge of untreated wastewater into rivers and streams, existing pollution legislation in developing countries, including

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Ethiopia, is weak and generally not adequately enforced (Kumie and Kloos 2006). Ethiopian rivers and streams flowing through larger communities become heavily polluted when they are widely used for domestic, commercial, and industrial purposes (Alemayehu 2001; Hailu and Legesse 1997). The extent of ecological damage thus inflicted on any Ethiopian surface waters and public health impacts has not yet been assessed due to lack of scientific criteria to monitor water quality. Specifically, ecological assessments based on river fauna inventories have been hampered by the absence of biotic indices. The urgency of determining stream water quality and ecological integrity in Ethiopia is indicated by the heavy dependence of the rural population and many urban dwellers on surface waters and by recent studies predicting that the country will face economic water scarcity by the year 2025 (World Meteorological Organisation 1996). Moreover, increasing demands for and scarcity of this natural resource are rapidly becoming a cause of conflict between different users in both rural and urban settings (Flintan and Imeru 2002).

In addition to using the water of the Borkena River for domestic and recreational purposes, the residents and manufacturing firms of Dessie and Kombolcha towns use it also as a dumping site of domestic, commercial and industrial waste materials. The total length of the Borkena between Dessie and Kombolcha towns is approximately 23 km. These are two of the oldest towns in Ethiopia, with no appropriate sewer lines, sewage treatment plants or proper solid waste disposal sites. The 2006 population of Dessie was projected to be about 169,000 and that of Kombolcha 68,000 (Federal Democratic Republic of Ethiopia Central Statistical Authority 2004). The amounts of waste dumped into the river have not been estimated but are considerable due to the failure of enforcing anti-dumping regulations. Rubbish heaps dumped at various sites are unsightly and the source of strong odors which contrast with the scenic mountain landscape surrounding these towns. The objective of this study was to assess the urban impacts of Dessie and Kombolcha towns on the ecological integrity of the River Borkena, with a focus on physicochemical parameters and the macroinvertebrate fauna.

Materials and methods

Study area and sampling sites

The study area is located approximately 375 km northeast of Addis Ababa on one of the two main national north–south long-distance roads (Fig. 1). The 23 km stretch of the Borkena River between Dessie and Kombolcha and 1 km each upstream of Dessie and downstream of Kombolcha were included in this study (Fig. 1). The altitude of the study area ranges from 1,775 m at the lowest site near Kombolcha to 2,638 m at the highest site upstream of Dessie. The climate is of the cool, subhumid moist agro-ecological highland zone locally known as *dega* around Dessie and the warmer *woyna dega* around Kombolcha. The steep escarpment of the high plateau is highly dissected, with a dense drainage network. Mixed subsistence agriculture prevails in the study area, characterized by the cultivation of the staples teff and maize and livestock raising.

The rock outcrops around Dessie and Kombolcha consist of volcanic rocks and Aiba Basalt, with alluvial, lacustrine and marine sediments and residual soils mainly at lower elevations. Basalt is the most dominant rock type in the central part of the area and is exposed along the road cuts, hillsides, and the banks of the Borkena River. It is highly porous at the surface and its soil friable, subject to soil erosion and land slides (Ayenew and Barbieri 2005). Using a group of Geographic Information System software (ArcGIS), the local slopes in the area were found to vary from 0 to about 82% with a mean slope of 15.5%. The steep slopes, especially the deeply incised rivers and gullies of the Tossa/Azewa Gedel Mountain, experience heavy runoff and are prone to landslides during the rainy season.

The climate of the Dessie-Kombolcha area is sub-humid to humid with annual rainfall slightly above 1,000 mm, about 70% of which falls usually in heavy downpours during the main rainy season from July to September and 25% during the smaller rains from January to April. The long-term average annual temperature of Dessie varies from 12°C to 18°C and of Kombolcha from16 to 32.5°C (Federal Democratic Republic of Ethiopia Central Statistical Authority 2004). The steepness

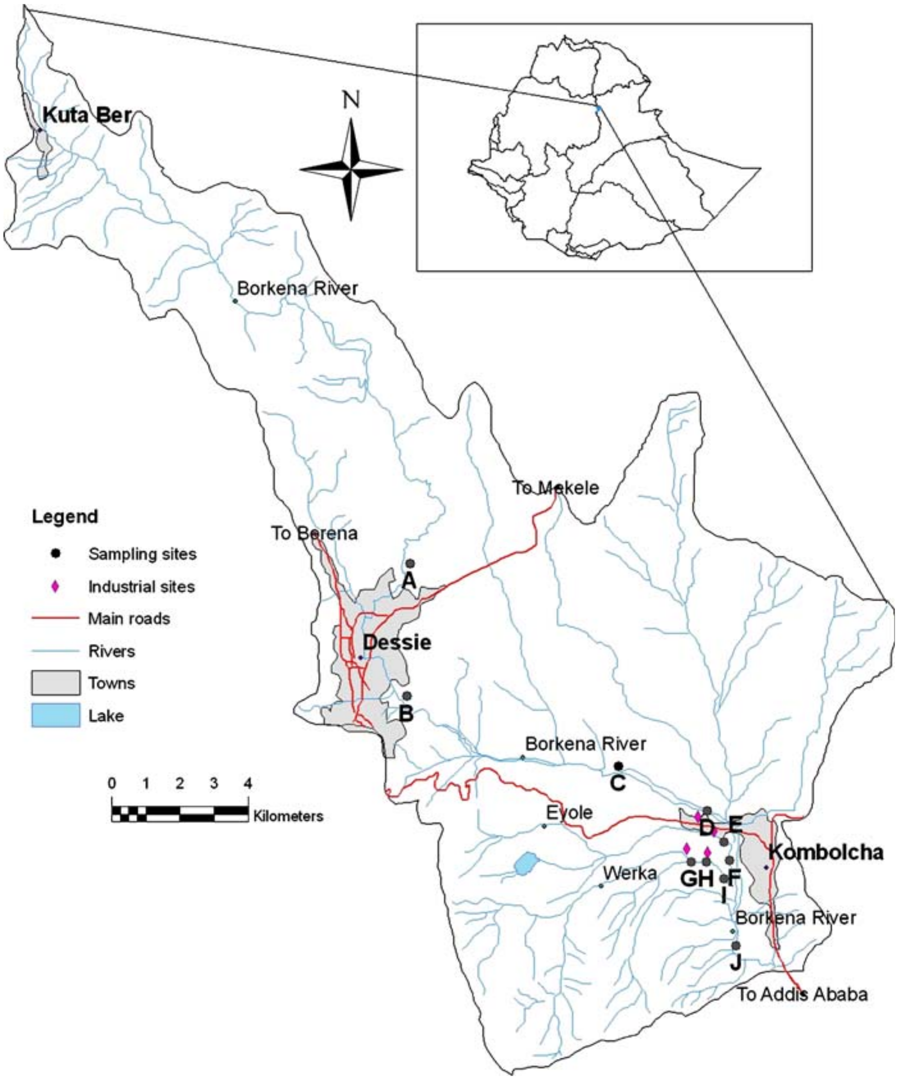


Fig. 1 Location of the study area, the Borkena basin, its rivers, towns and roads, and the 10 sampling sites

of the local topography, heavy rainfall, and availability of highly weathered and fractured rocks and unconsolidated deposits favor extensive surface runoff and frequent landslides during the wet season. Groundwater storage capacity is relatively low, as reflected in heavy runoff and flooding during the rainy season and low level stream flow during the dry season. Depth to groundwater varies from a few meters close to the banks of the Borkena River to more than 20 m in the central part of Dessie (Ayenew and Barbieri 2005).

The usual problem of selecting aquatic sampling sites in the field that are similar in all aspects and that can be divided into control and experimental groups solved by choosing adjacent sites on the same streams or rivers that permit upstream and downstream comparisons (Reynoldson et al. 1997). Based on this approach, an array of upstream site characteristics reflecting the biological conditions of the river minimally impacted by the urban environment was considered in selecting the two uppermost sites on the Borkena River. The other eight sites within 23 km were chosen based on the degree of human disturbance, physical changes of water, proximity to point source pollutants, and accessibility.

Generally, riffle communities of streams are more diverse in invertebrate forms than pools (Gerth and Herlihy 2006). Based on these findings, we selected riffle sites with a homogenous habitat for water and macroinvertebrate sampling.

The six main sampling sites along the main River Borkena were coded A, B, C, D, F and J. Another four sites E, G, H, and I along the two main tributaries (Eyole and Worka streams of the Borkena River) were included in the dry season only (due to resource limitation) to assess the impacts of industrial waste effluent in Kombolcha town. Therefore, the wet and dry season comparison is based on the six main samplings sites along the main river Borkena. The upstream site A was included to represent relatively unimpacted reach of the river. There is only one small town located on the Borkena upstream of Dessie, Kuta Ber. Because of its relatively small size (the estimated population in 2006 was 4,943) and its long distance from Dessie (30 km) appears to have little impact on Borkena River quality. Whereas downstream site C only impacted by Dessie town but far away about 21 km recovery distance and upstream of Kombolcha and (B, D, E, F, G, H, and I) are impacted due to inflow of untreated domestic and industrial wastes from the two towns. Sampling site J which is out of the Kombolcha town boundary was chosen as a potential recovery site.

Sampling technique, variables and their measurement

Chemical analysis alone is inadequate for assessment and management of river water quality and aquatic systems (Cairns 1995). Biological monitoring that integrates physicochemical analysis with faunal assemblages, channel characteristics, riparian zones and habitat structure is a sensitive approach (Fore et al. 1996). Therefore, we used this combined and robust method to examine both the distribution of macroinvertebrates as biological indicators and physicochemical variables, as well as Geographical Information System (GIS) maps and habitat surveys to investigate the urban impacts on river water quality and on the aquatic ecosystem. Sampling was done during both the dry season (in February) and at the end of the wet season (in September) of 2005.

Sampling sites on rivers should, as a general rule, be established at places where the water is sufficiently mixed for only a single sample to be required. Sampling at three to five points is usually sufficient and fewer points are needed for narrow and shallow rivers and streams (Bartram and Balance 2001). Consequently, a composite sampling technique was employed to take water samples at three sampling points across the width of the Borkena River for chemical analysis. The water samples were collected by inserting clean bottles of 2 l to a 30 cm depth in the opposite direction of the current flow of the river. The samples were transported to the laboratory within 1 to 6 h for analysis. Chemical analysis followed standard methods by APHA (1998).

Although no one sampling method will provide enough information to reflect the actual biological community which exists at the sampling site, the Kick-Net method can be used to obtain samples of the macroinvertebrate from riffle type habitat communities in shallow rivers (Davies 2001). A 100 m stretch was representative of the Borkena's sampling in riffle areas. Those areas of the stream comprising of cobble/gravel substrate with a fast current, shallow water (usually less than 8 in. in depth) and non-laminar flow were selected.

Collections of macroinvertebrates from more than one habitat type may introduce variation that can potentially mask water quality differences among sites (Ostermiller and Hawkins 2003). Therefore, to minimize this variation, all samples were collected from the same habitat types of riffle zones of streams in areas where there was the best canopy coverage and side bank macro-vegetation. Macroinvertebrates were collected and processed using a standardized method described by Ostermiller and Hawkins (2003). A rectangular frame kick net with a 250-μm net on a 50 × 33 cm frame was used for collection. The kick net was placed in the river of different depths on the opposite direction to the course of flow and the river bed was agitated continuously with the feet of the same person for 3 min to dislodge macroinvertebrates within a 10 m stretch of flow and allow the current to sweep out all dislodged organisms into the net. After 3 min the contents of the net were transferred into a collecting jar containing 90% ethanol. This procedure was repeated three times per site to calculate average values. Jars were transported to the laboratory for sorting and dissecting. In the laboratory the contents were transferred into a bowl, sufficient water was added and the supernatant was pured through a sieve (500 μm) to retain the macroinvertebrates. This was repeated until all macroinvertebrates separated from the sand and mud. They were subsequently transferred into a wheel tray in order to observe and pick them up with forceps. All macroinvertebrates were sorted and then identified using a binocular dissecting microscope and assigned their taxonomic level. Stream habitat forms are an essential component of river health that can be used to evaluate the overall integrity of a river system (Maddock 1999). The condition of local stream/river habitats, otherwise known as the habitat template, influences the structure and organization of biological communities (Downes et al. 1995). Habitats in relation to riparian vegetation, bank stability, nature of riverbed stratum, and anthropogenic impacts were checked using a pre-designed standard check list. Discharge was calculated using the midsection method as it is described by Hauer and Lamberti (2006).

Data analysis

Relationships between the environmental data and genera abundance or community metrics were assessed using canonical multivariate analysis. To explore the response of macroinvertebrates, a detrended correspondence analysis (DCA) on the abundance data were performed. Because taxa abundances exhibit unimodal responses to environmental gradients, we performed Canonical Correspondence Analysis (CCA; ter Braak and Smilauer 2002). Environmental variables and macroinvertebrate abundance data were log $(x+1)$ transformed prior to statistical analysis to normalize and stabilize the variance. Preliminary analysis of the metric data indicated that the lengths of the gradients were long (i.e., >2 standard deviations; Jongman et al. 1995). The package CANOCO software, version 4.5, the algorithm for CCA in CANOCO was used to standardize the environmental data to a mean of 0 and standard deviation of 1. This removes the effect of differences in measurement units among these variables (Jongman et al. 1995). Correlations of the environmental variables with the significant axes were calculated to determine those environmental variables that were significantly correlated with the axes (Jongman et al. 1995). The different

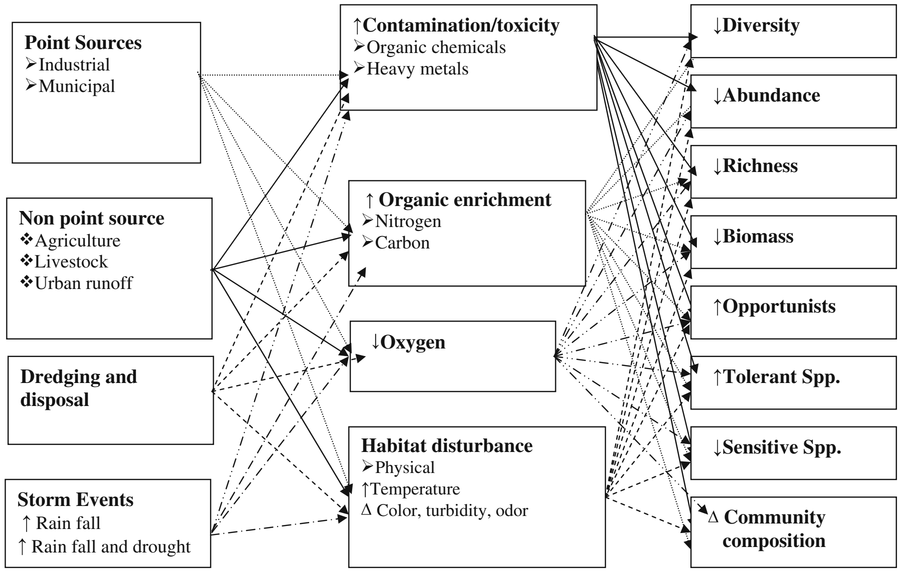


Fig. 2 Summary of a conceptual model of the indicator, showing linkages between sources of stress, types of stress, and effect on the benthic community of the Borkena River based on the field data and the model by Jackson et al. (2000)

Table 1 Mean[a] major physical and chemical characteristics of 10 sampling sites along the course of the Borkena River and its tributaries in February 2005 (dry season sampling)

Variables and units	Sampling sites									
	A	B	C	D	E	F	G	H	I	J
Temperature (°C)	23.1	23.4	24.6	24.4	26.6	25.0	22.9	23.2	29.1	20.0
Width (m)	2.3	3.6	3.9	4.6	2.5	4.1	1.3	–	1.8	4.9
Discharge (m^3/s)	0.110	0.142	0.126	0.126	0.033	0.160	0.024	0.090	0.030	0.157
Conductivity (mS/cm)	0.36	1.08*	0.38	0.52	1.23*	0.75	0.79	0.84	0.81	0.78
pH	7.40	3.6*	7.5	7.3	7.5	7.2	7.6	6.4	6.7	5.5
Turbidity (NTU)	16.61	50.00*	2.46	9.39	22.01	18.90	9.50	11.79	11.5	2.61
DO (mg/l)	7.9	0.1*	7.8	5.9	0.4*	3.0	7.0	0.2*	0.1*	5.8
BOD_5 (mg/l)	5	849*	6	55*	875*	310*	2	1185*	1245*	8
PO_4^{3-} (mg/l)	0.001	57.24*	0.48	3.21	1.97	0.48	48.10*	0.41	50.56*	0.53
NH_3–N (mg/l)	1.277	17.400*	0.101	5.275*	1.860	3.400	0.890	1.016	0.705	0.531
NO_3–N (mg/l)	0.116	1.560	0.060	0.037	0.045	0.040	0.037	0.239	0.202	0.099
Cr^{3+} (mg/l)	Trace	0.04	Trace	0. 10	1.04	0.25	Trace	Trace	0.02	Trace
Cr^{6+} (mg/l)	Trace	0.045	Trace	0.08	1.00	0.20	Trace	Trace	Trace	Trace
PO_4^{3-} (mg/l)	0.001	57.24*	0.48	3.21	1.97	0.48	48.10*	0.41	50.56*	0.53
Chloride (mg/l)	15	125*	40	56	820*	80	20	58	63	72

Trace Concentration <0.0001 mg/l; *A* upper Dessie town (reference); *B* downstream of Dessie town; *C* upper Kombolcha town boundary; *D* in the center of Kombolcha town and upper Eyole Stream; *E* Eyole Stream which carries effluents from the tannery, textile industries and meat and flour factories; *F* below the confluence of Eyole Stream and Borkena River; *G* Worka Stream which carry textile residences swimming pool and above brewery effluent; *H* brewery factory effluent; *I* Worka Stream below the confluence of brewery effluent; *J* Borkena 1 km below Kombolcha town boundary (recovery)

*Values which have p value less than 0.05 as compared to the reference (A; one-way ANOVA)

[a] The mean of the site means within each sample type

indices were calculated using BioDiversity Professional, Version 2. The significance for the mean of the different parameters within sites as compared to the reference and among them was done with one-way ANOVA (Statview 5.0).

Results

Qualitative description of habitat features, water condition and major environmental stressors

Based on the physical habitat survey result, substrate particles size varies slightly among the sites. The most dominant substrates were large stones, small stones, cobble, and sand/silt. However, embeddedness and the degree to which dominant particles are surrounded by fine inorganic sediments and organic waste particles did vary considerably among the sites. The terrestrial vegetation cover was generally sparse at all sites except at site J. Poor farming practices, overgrazing and deforestation in the study area are the major factors contributing to land degradation and are exacerbated by the impact of the natural environment in this mountainous region. We also observed human activities like car washing and sand mining at sampling sites D and F which have a direct impact on the river water quality. Residents use this river for cloth washing, bathing and even for drinking without further purification and treatment. Cattle grazing in and around the river bank was also intensive and very common. Much of the solid and liquid wastes that were generated by Dessie and Kombolcha towns were directly dumped and drained into the Borkena, particularly at sampling sites B, D, and F. Based on a model adapted from Jackson et al. (2000), the main stressors, the anticipated impact and possible linkage of indicators were summarized (Fig. 2).

Physicochemical characteristics of the river at the sampling sites

The mean concentrations of conservative and non-conservative pollutants varied greatly across the sampling sites during both dry and wet seasons. The mean concentrations of ammonia, nitrate, chloride, BOD_5, total phosphate, conductivity and turbidity were more elevated at all sites than at the upstream reference A and at the

Table 2 Mean concentration[a] of major physical and chemical characteristics of six sampling sites along the course of the Borkena River in September 2005 (wet season sampling)

Variables and units	Sampling sites					
	A	B	C	D	F	J
Temperature (°C)	13.0	18.6	14.6	18.2	18.1	20.6
Width (m)	8.5	11.2	14.9	15.4	16.0	12.9
Discharge (m^3/s)	14.2	16.5	19.7	19.9	20.1	21.8
Conductivity (mS/cm)	0.300	0.360	3.634*	0.426	0.411	0.687
TDS (mg/l)	192	209	238	258	245	3.88*
Salinity (mg/l)	0.1	0.1	0.2	0.3	0.3	0.3
pH	8.11	8.09	8.39	8.53	8.26	8.26
DO (mg/l)	8.0	2.0*	7.2	1.2*	2.0*	6.0
BOD_5 (mg/l)	3.2	632.4*	6.5	742.0*	659.1*	4.7
NO_3–N (mg/l)	0.100	1.510*	0.090	1.723*	1.695*	0.074
NH_3–N (mg/l)	1.021	12.481*	0.231	13.237*	12.764*	0.147
Chloride (mg/l)	10	110*	22	237*	246*	18
Altitude(m)	2,638	2,506	1,879	1,828	1,835	1,775

Key for sites (see Table 1)

*Values which have p value less than 0.05 as compared to the reference (A; one-way ANOVA)

[a] Mean indicates the mean of the site means within each sample type

recovery site J the furthest downstream (Fig. 1, Tables 1 and 2). The dissolved oxygen in the river was significantly depleted about eight fold for wet season and 80 fold for the dry season at site B at the downstream end of Dessie town and at sites E, H and I (Fig. 1, Tables 1 and 2) inside Kombolcha town. Eyole Stream (a tributary of the Borkena River), which carries the waste effluents of the textile, tannery and meat processing factories at sampling site E (Fig. 1) had significantly lower

Table 3 Abundance, distribution and indices of macroinvertebrates at different sites along the course of the Borkena River in February 2005 (dry season sampling)

Macroinvertebrate taxon	Taxon codes	Sampling sites					
		A	B	C	D	F	J
Baetidae	Baet	81	0	67	20	54	273
Heptagenidae	Hepta	12	0	0	0	0	6
Ephemeridae	Ephem	0	0	0	0	0	4
Caenidae	Caen	125	0	91	20	2	182
Perlidae	Perl	10	0	0	0	0	0
Limnephilidae	Limn	5	0	0	0	0	0
Hydropsychidae	Hpsy	0	0	6	0	0	278
Elminthidae	Elmin	47	19	95	1	188	0
Hydrophilidae	Hphi	0	1	0	0	0	1
Kenidae	Keni	2	0	0	0	0	0
Haliplidae	Halip	3	0	0	0	0	0
Dytiscidae	Dytis	13	0	0	0	0	1
Chironomidae	Chiron	95	278	39	6	428	31
Tipulidae	Tipul	0	0	8	18	6	0
Tabanidae	Taban	0	0	4	0	0	4
Ceratopogonidae	Cerato	3	218	8	0	8	3
Lumbricidae	Lumb	4	679	133	10	0	79
Tubificidae	Tubif	0	80	192	0	2	0
Corixidae	Corix	126	0	0	0	0	3
Gerridae	Gerri	0	0	0	0	0	1
Aphelocheiridae	Aphelo	8	0	117	0	0	2
Gomphidae	Gomph	0	0	15	11	2	5
Platycnemididae	Platyc	51	0	0	0	0	0
Aeshnidae	Aesh	0	0	0	0	0	1
Agriidae	Agrii	57	0	0	0	0	0
Valvatidae	Valva	27	0	2	0	0	0
Sphaeriidae	Spha	12	0	0	0	0	0
Limnacidae	Limnac	0	0	0	5	0	0
Physidae	Physi	12	0	0	0	0	0
Idotea	Idot	0	0	0	4	0	0
Total number of families		19	5	13	9	8	16
Abundance		693	1275	777	95	690	874
Shannon Hmax		1.28	0.78	1.11	0.95	0.90	1.28
Alpha		3.61	0.82	2.22	2.44	1.27	3.61
d %		18.18	53.26	24.71	21.05	62.03	18.18
Simpson's Diversity (D)		0.117	0.364	0.151	0.149	0.465	0.117
% PT		43.2	81.3	58.8	47.4	62.2	33.8
FBI		6.6	8.8	7.1	5.3	7.1	5.3

Key for sites (see Table 1)

d % Berger–Parker Dominance; *FBI* Family Biotic Index; % *PT* percent pollution tolerant taxa concentrations of oxygen ($p < 0.05$) and significantly higher concentrations of chloride, Cr^{3+} and Cr^{6+}, BOD_5 value (Table 1). The effluent from the brewery at the sampling site H before joining Worka Stream (another tributary of the Borkena) was characterized by low levels of dissolved oxygen and high BOD_5 values. The lowest mean pH was recorded for the sampling site B and was significantly lower ($p < 0.05$) than the reference. Smaller variations in pH values were recorded among other sites during the dry season but not during the wet season. The mean electrical conductivity also significantly increased ($p < 0.05$) at sampling site B during the dry season and at C during the wet season. Sampling site C was partially recovered, as indicated by higher dissolved

Table 4 Abundance, distribution and indices of macroinvertebrates at different sites along the course of the Borkena River in September 2005 (wet season sampling)

Macroinvertebrate taxon	Taxon codes	Sampling sites					
		A	B	C	D	F	J
Elmidae	Elmid	21	9	0	0	0	6
Elminthidae	Elminth	73	0	0	0	0	0
Gyrinidae	Gyrin	8	0	0	0	0	0
Psephenidae	Pseph	98	0	0	0	0	0
Corixidae	Corix	69	0	0	0	0	14
Perlidae	Perli	84	62	34	0	0	0
Kenidae	Keni	172	159	105	26	15	0
Heptagenidae	Hepta	218	84	51	9	14	15
Baetidae	Baet	691	203	121	97	91	92
Ephemeridae	Ephem	176	93	29	0	0	0
Hydropsychidae	Hpsy	783	398	306	295	327	136
Libellulidae	Libell	33	18	22	32	11	3
Lestide	Lest	17	0	0	0	0	0
Mollusca	Mollu	109	14	18	11	18	16
Chironomidae	Chiron	36	233	79	162	210	55
Muscidae	Musci	79	22	8	24	11	98
Tabanidae	Taban	82	36	23	65	42	93
Caenidae	Caen	101	0	98	11	6	98
Hydrophilidae	Hphi	0	0	0	0	0	11
Haliplidae	Halip	12	0	0	0	0	16
Gomphidae	Gomph	12	0	22	26	10	55
Dytiscidae	Dytis	26	0	0	0	0	12
Gerridae	Gerri	0	0	0	0	0	17
Lumbricidae	Lumb	24	126	89	22	17	79
Ceratopogonidae	Cerato	11	114	58	60	53	13
Tubificidae	Tubif	0	147	33	0	6	12
Tipulidae	Tipul	65	23	9	79	48	86
Total number of families		24	15	17	14	15	21
Abundance		3000	1741	1105	919	879	927
Shannon's Hmax		1.38	1.20	1.23	1.15	1.18	1.30
Alpha		4.29	3.33	4.14	3.52	4.24	4.05
Simpson's Diversity (D)		0.067	0.086	0.070	0.094	0.092	0.099
d %		8.61	18.32	12.50	14.60	19.01	17.83
% PT		13.4	30.9	30.7	25.9	30.5	30.1
FBI		4.5	7.2	5.2	5.2	5.4	5.5

Key for sites (see Table 1)
d % Berger–Parker Dominance; *FBI* Family Biotic Index; % *PT* percent pollution tolerant taxa

oxygen and lower ammonia, nitrate, chloride and BOD_5 levels. Sampling sites D and F, located further downstream in Kombolcha town and thus further impacted by Kombolcha town, had high pollution levels and were significantly ($p < 0.05$) different from the reference.

Benthic macroinvertebrate indices

The highest taxa richness was observed for the sampling site A (reference), followed by sampling site J (recovery; Tables 3 and 4). Simpson's Index (D), which measures the probability that two individuals randomly selected from a sample will belong to the same species (or some category other than species) accounts for both abundance and evenness of the species present. The value of D ranges between 0 and 1 and with this index, 0 represents infinite diversity and 1, no diversity (Strong 2002). This index was found to be relatively higher at the sampling sites B and F. Similarly, the Berger–Parker Dominance (d %) index and percent pollution tolerant (% PT) were also higher at these sampling states in both seasons (Tables 3 and 4). All metrics reflect the same in that sampling site A was the best in both abundance and evenness and the sampling sites which were affected by urban impact were dominated by related species and poor in diversity. The recovery site J downstream of the town boundaries had the second highest mean abundance and evenness values after the reference during the wet season.

Multivariate classification, variation partitioning of species data matrices and environmental characteristics

The multivariate classification of the sampling sites based on the biological data for the dry and wet season sampling is illustrated in Figs. 3, 4 and 5. They clearly demonstrate that the upstream reference site A with no significant urban impact was unique among sampling sites in both wet and dry seasons and that the recovery site J downstream of the two towns recovered better biologically during the wet season than the dry season.

For the dry season, the first eigenvalue is 0.460, implying that the first axis represents a strong gradient and the second axis is 0.280 whereas percent explained for both axes is 63.0%. The overall inertia, or variance in species dispersion in the data set, is 1.174. Polluted sites have more different macroinvertebrate communities of gradient from B to F, C to J to D along the second axis due to the influence of turbidity, phosphate, ammonia and DO (Fig. 5). Similarly in the wet

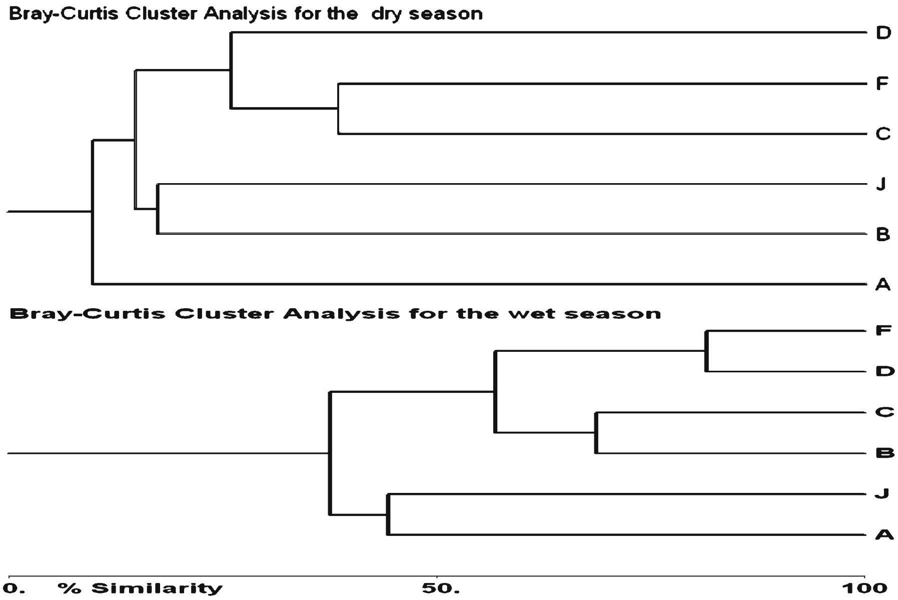


Fig. 3 Hierarchical clustering (using group average linking) of six sampling stations showing separate clustering of A in dry season and of A as well as J in wet season based on the relationship of sampling sites and the macroinvertebrate community

Fig. 4 Triplot of first and second CCA axes of the macroinvertebrate taxa, environmental variables and their corresponding sampling sites (dry season sampling). The scale in SD units is –1 to 1 for both the macroinvertebrate and environmental variable scores. The full name for the abbreviation codes of macroinvertebrate taxa are given in Table 3

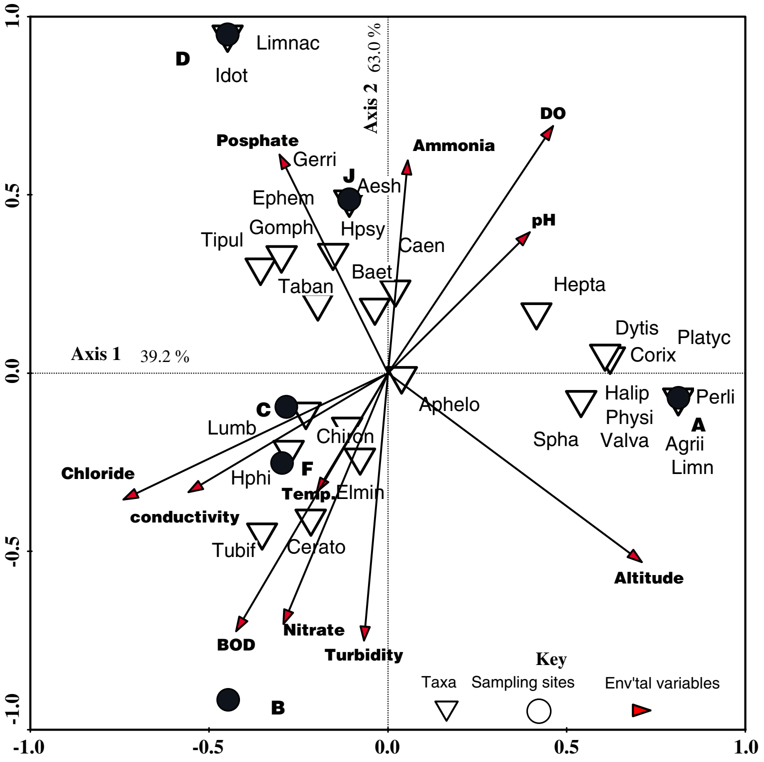
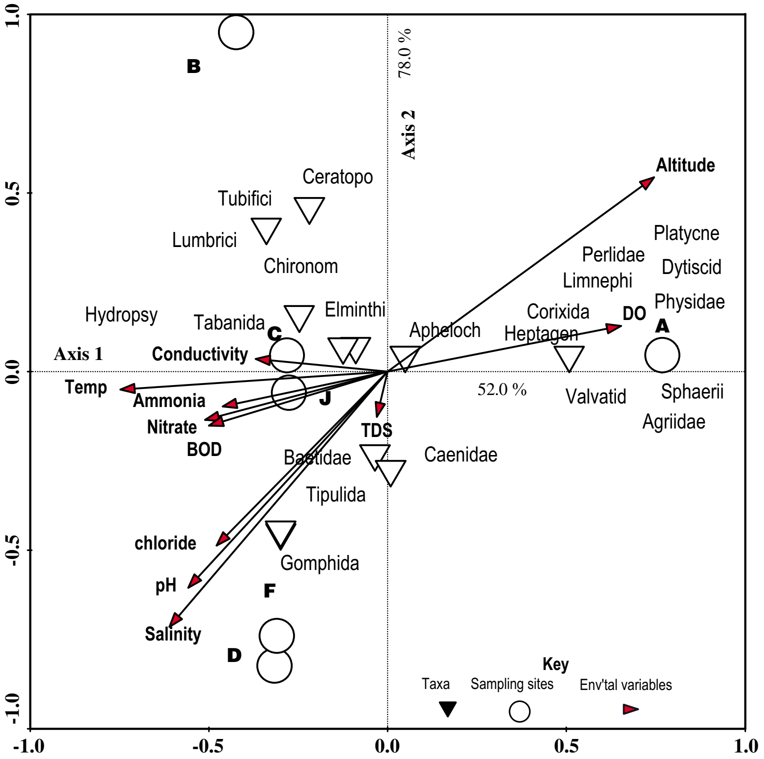


Fig. 5 Triplot of first and second CCA axes of the macroinvertebrate taxa, environmental variables and their corresponding sampling sites (wet season sampling). The scale in SD units is –1 to 1 for both the macroinvertebrate and environmental variable scores. The full name for the abbreviation codes of macroinvertebrate taxa are given in Table 4



season, the first eigenvalue is high 0.497, and the second axis is 0.249, whereas percent explained for both axes is 78.0% and the overall inertia is 0.957. Urban-impacted sites (B, D, F) are very similar in their macroinvertebrate communities and sampling sites D and F grouped together due to correlation between pollutant factors; chloride, pH and salinity. Sampling site J had low TDS and high temperature (Fig. 5), apparently influencing other tributaries and dilution down stream. Sampling site A (the reference) was highly correlated with first axes and characterized by better dissolved oxygen concentrations and lower concentrations of pollutants for both seasons.

Discussion

Applying community metrics, a drastic decline in the ecological integrity was observed in the Borkena River downstream of Dessie and within Kombolcha town in terms of macroinvertebrate abundance, composition and diversity. Clustering and ordination analysis were also clearly separated reference sites from urban impacted sites. Pollution levels and biodiversity were associated with spatial distance to these towns and point sources of pollution, reflecting human impact on the river ecology. Poor waste management (rampant dumping of domestic solid waste), discharging of industrial, commercial and household untreated solid and liquid waste into the river, intensive agricultural land use, surface runoff, landslides, and overgrazing in the Borkena catchments are the multiple-scale environmental stressors that have been reported to alter suites of environmental variables in other Ethiopian rivers and streams (Alemayehu 2001; Hailu and Legesse 1997). CCA analysis established that many of these environmental stressors were found to impact significantly on the invertebrate fauna of the Borkena River. The combination of variables might be used to identify and describe the multiple-scale stressor. The correlations of many individual environmental variables with the axes were relatively high for CCA but were not statistically significant. However, these estimated significances might be the results of other unmeasured environmental variables which could explain the remaining variation in macroinvertebrate distribution.

Dissolved Oxygen (DO) is more reactive and variable in the short-term than most chemical constituents in polluted water with organic materials (Voutsa et al. 2001). In this study DO varied considerably more spatially and seasonally among urban-impacted sites than at the upstream reference site. The seasonal variations are largely due to a dilution effect, since the discharge of the rivers increases an estimated 100 folds during the wet season and stream pollution was more intense during the dry season. This is indicated by high values of BOD_5 and its inverse relationship with DO. Chemical pollution indicators, including ammonia, nitrate and chloride, emitted mostly by municipal and industrial effluents and agricultural runoff, were found to be elevated at the urban-impacted sampling sites during both seasons.

Nitrogen, associated with algal growth and eutrophication, and concentrations of inorganic nitrogen greater than 0.3 mg/l can cause algae to grow in abundance (Nathanson 2000), also reached high levels. The mean concentration of total inorganic nitrogen (ammonia plus nitrate) at all 10 sampling sites during both seasons was equal to or greater than 0.3 mg/l the threshold set by Federal Democratic Republic of Ethiopia Ministry of Water Resources (2002). The high levels of inorganic nitrogen apparently originate from raw sewage and overflowing pit latrines during the rains, the use of fertilizers, and livestock husbandry. Organic debris, entering in to the river by surface run-off adds further pollutants to the urban waste. Mean concentrations of nitrogen were more than four times higher than the critical concentration of 0.3 mg/l at the downstream sites B, D and F, pointing to relatively greater pollution inputs from industrial and residential than agricultural sources. This was also substantiated by other chemical pollution indicators such as chloride and electrical conductivity and in agreement with studies done on the Kebena River flowing through the capital of Addis Ababa (Alemayehu 2001) and the Awetu River flowing through Jimma town in southwestern Ethiopia (Hailu and Legesse 1997).

No point source pollutants could be identified and located in Dessie town because of the many open ditches and drains that collect and empty household, commercial and industrial wastes directly into the Borkena River. However, we were able to identify major industrial point source pollutants inside Kombolcha town and associate them with a significantly higher level of BOD_5 and chromium and absence of macroinvertebrate fauna at sampling site E during the dry season. These pollutants are associated with the waste effluents of tanneries and meat and textile factories. In addition, samples of waste water from the brewery in Kombolcha, which is being discarded directly into the Worka Stream tributary at site H contained very low concentrations of dissolved oxygen (anoxic) and high levels of BOD_5.

The combined effects of these environmental variables created habitat conditions that eliminated most of the pollution-sensitive river fauna. As illustrated by the CCA and cluster analysis all were similar to indicate, the pollution gradient; relatively better water quality in the upstream river and much degraded downstream as the results of the urban sprawl and showed little recovery out of the town boundaries at the sampling site C and J. Only species that belong to families Chironomidae and Tubificidae thrived with relatively high abundance at the urban-impacted sites of B, D and F. Hence total number of taxa is limited to less of equal to nine but with abundance reaching a maximum level at these sites for the dry season sampling. This pattern is a characteristic of disturbed aquatic ecosystem. Organisms physiologically adapted to low oxygen tension exploit the excess nutrients available and thus dramatically increase in abundance. Species that belong to families such as Perlidae and Heptagenidae are clear-water fauna and disappear as pollution load increases. Beetles belonging to the family Elminthidae were recorded even among the most polluted sites, which may be due to the fact that these groups swim actively and may originate from locations other than the sampling sites and thus may not reflect habitat conditions at the actual sampling sites.

Greater macroinvertebrate abundance and diversity were observed during the wet season than the dry season. Even at B, which located downstream of Dessie town and receives the cumulative urban waste load, 15 taxa were recorded. This observation also holds true for F immediately below Kombolcha, which receives the cumulative waste load of this town. Sensitive taxa, including Perlidae and Heptagenidae were also well represented at many sites as illustrated by different indices. Family Biotic Index (FBI) indicates organic and nutrient pollution and provides an estimate of water quality for each site using established pollution tolerance values for each taxon (Hilsenhoff 1988). This index classified the sampling sites from fair quality to very poor and good to very poor for dry and wet seasons respectively. This is in agreement with the results obtained elsewhere. Mathooko and Mavuti (1992) and Harrison and Hynes (1988) also reported higher benthic abundance and diversity in the wet season than during the dry season on high latitude streams and rivers of Kenya and Ethiopia, respectively. This seasonal variation might be a response to the reduction of different environmental stresses by the rain water dilution during the rainy season. This suggests that dilution and washout effect of the rainy season somewhat restore the natural habitat conditions that favor the return of a few sensitive taxa. Therefore, even under pollution stress such as low oxygen tension and serious natural disturbances arising from the scouring action of spate and flood, the fauna can recover considerably.

A number of earlier studies have shown the effect of altitude on macroinvertebrate aquatic communities (Jacobsen et al. 1997). In our study, the reduction of the number of taxa during the dry season was more pronounced at B below Dessie (2,506 m altitude) than at sites D and F below Kombolcha (1,800 m) although the pollution status, judged from BOD_5 and DO levels, was similar. That altitude may be involved in these distributions and was also indicated by other studies, which revealed that aquatic fauna are more sensitive to low oxygen tension in streams at high altitudes than at low altitudes a (Suren 1994).

The greatest abundance for macroinvertebrates belonging to the family Chironomomidae was recorded at sites B and F, both during the dry season and following rainy season sampling. The maximum cumulative waste load of Dessie and Kombolcha towns carried by the Borkena River was recorded at B and F, respectively, and these sites were characterized by relatively high mean concentrations of chemical pollutant parameters. In addition, at sampling site F, elevated amounts of chromium both in the trivalent and hexavalent form probably originated from tanneries and textile industries. The hexavalent form of this metal is known for its high toxicity and thus might have contributed to the low faunal status of this sampling site.

Even at the upstream reference sampling site A with no measurable urban impact, the total number of taxa (19) is not considered diverse compared to high-altitude tropical rivers of Uganda and Kenya (Tumwesigye et al. 2000; Mathooko and Mavuti 1992) and other Ethiopian rivers. In the Awetu River upstream of Jimma town in western Ethiopia, for example, as many as 25 family taxa have been reported (see Hailu and Legesse 1997). The low number of taxa in the Borkena cannot be explained with available data but may be due to sparse riparian tree vegetation limiting the exogenous input of nutrients (Dudgeon 1994) and extensive land degradation and erosion due to a combination of extensive deforestation, intensive farming, and overgrazing, the effects of which are compounded by the less humid arid climate of the Dessie area.

Recovery of aquatic macroinvertebrates from the effects of pollution was documented using a ‘weight of evidence’ approach which included measures of physical, chemical and biological data (example Nelson and Roline 1996). In this study, a slight recovery of macroinvertebrates was observed during both seasons at sampling site C below Dessie town boundary and at the recovery J, although density and diversity levels remained below those recorded at the reference.

Conclusion and recommendation

The Borkena River obtains high pollution levels and its water quality deteriorated as a result of untreated domestic and industrial wastes discharged by the towns of Dessie and Kombolcha, as indicated by the decline in macroinvertebrate species distribution and chemical water parameters. These impacts are exacerbated by the rugged mountain topography of the area, which causes severe erosion and run-off of agro-chemicals which end up in the Borkena River, upsetting its aquatic biota. Both physicochemical and faunal surveys confirmed that the ecological integrity of the river was more disturbed during the dry season. Given the rapid population increase of Dessie and smaller surrounding towns and the corresponding rise of untreated domestic and industrial wastes, the Borkena River may be subject to even more pronounced effects than those described in this study, limiting its future use for domestic, recreational, agricultural and industrial purposes. Any remediation efforts will have to consider the implementation of anti-pollution measures in the form of solid waste disposal at designated sites away from water courses and slopes, establishment of community and industrial sewage treatment plants, and the development of education programs aimed at raising awareness of the pollution problem and the need for its prevention. Further studies characterizing the Borkena and other Ethiopian river systems may help to develop scientific criteria for pollution monitoring and in developing effective and feasible remedial measures.

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