

Stormwater impact on water quality of rivers subjected to point sources and urbanization – the case of Addis Ababa, Ethiopia

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Abstract

Urbanization of a catchment often causes degeneration of rivers. We studied the water quality of three rivers in Addis Ababa based on the impact of stormwater and non-point sources, and urbanization. Along these rivers several point sources were registered, with direct discharge of industrial and domestic wastes into them. To distinguish the impact of these year-round point-sources from stormwater, we analysed physicochemical parameters, nutrients and heavy metals sampled from upstream to downstream sections of each river in the dry and wet season. Dissolved oxygen (DO), NO₂-N, NH₄-N, PO₄-P, (Cr(VI) and Cu) exceeded international standards, pointing to a generally poor water quality of the rivers in both seasons. NO₃-N, Mn and Zn were problematic in dry season only. Although stormwater improved DO, conductivity, PO₄-P, Cr(VI) and Zn, the levels were still critical, pointing to construction sites, agriculture and pit latrines, somewhat offsetting the effect of stormwater dilution. No clear impact of urbanization pressure was found.

Introduction

Rivers are often at the centre of urban development due to the many services they provide (Cohn 1998). As a city grows bigger, the environmental pressure on its local rivers increases, especially if the city does not have the resources to manage solid waste and wastewater adequately. This is often the case in cities in developing countries, where wastewater from industries and households may be discharged in untreated form to rivers, and where solid waste may accumulate at the course of the rivers (Strandberg, 1971). In addition, stormwater is a major cause of urban river water pollution in both developed and developing countries (Karbassi *et al.* 2007; Nazafpour *et al.* 2008). As it moves on, stormwater picks up contaminants that have accumulated on the various surfaces in the antecedent dry period, and carries the load of contaminants to the river. The concentration of contaminants in stormwater entering a river is a result of both the strength of the non-point sources passed on the way, and the volume of stormwater.

The capital city of Ethiopia, Addis Ababa is experiencing rapid urbanization and may be one of the fastest growing cities in Africa (Mazhindu *et al.* 2010). The current population is 3.434 million (CSA, 2013), corresponding to

a population density of approximately 6,359 persons per square kilometer. The city has evolved around a number of rivers, all starting in the mountainous areas within the boundary of the city. Despite a mean annual rainfall of 1058 mm, most of the rivers are ephemeral due the rain being concentrated in a four months period from June to September (NMA, 2016). The elevation of the city presents significant slopes from 3,000 meters in the north to 2,100 meters in the south over 30 km (GPS measurement 2016).

Whilst the rivers of Addis Ababa are crucial for the water supply of the city, they are also being used for discharge of wastewater and dumping of solid waste. The level of river water pollution in Addis Ababa has increased as urbanization intensified and the economic development remained at a low level (Alemayehu *et al.* 2003). According to the City of Addis Ababa Bureau of Finance and Economic Development (2013), about 14.3% of the total population practices open defecation, whilst the remaining uses pit and flush latrines. The extent of wastewater collection coverage of the city is 44.3% distributed on 7.3% by sewer lines and 37% by vacuum trucks (AAWSA 2011). Concerning solid waste, 25% is not collected but disposed off, frequently by dumping into rivers or drains or onto open spaces (Regassa *et al.* 2011). The

existing stormwater management systems are fragmentary and mainly serving major roads with rivers being the final receiving system (Belete, 2011). Stormwater generation is increasing with the growing area of impervious surfaces as the city expands and densifies (Butler and Davies, 2004).

Addis Ababa is subdivided into two major river catchments, namely Little Akaki and Big Akaki. For rivers in Little Akaki catchment, the following water quality parameters have been found by various authors: dissolved oxygen, DO 0.1–7.12 mg/L (Beyene *et al.* 2009), electrical conductivity, EC 576–1790 $\mu\text{S}/\text{cm}$ (Tolla 2006; Beyene *et al.* 2009; Temesgen 2009), pH 6.59–7.8 (Tolla, 2006; Temesgen, 2009), $\text{NO}_3\text{-N}$ 0.48–39.78 mg/l (Beyene *et al.* 2009; Temesgen 2009), Cu 0.02 mg/L, Zn 0.023–0.192 mg/L (Tolla, 2006), and Mn 0.64 mg/L (Temesgen, 2009).

Studies conducted in South Korea (Chang, 2005), Nepal (Kannel *et al.* 2007) and Bulgaria (Astel *et al.* 2007) found that the water quality of urban rivers deteriorated downstream due to cumulative effects coupled with wastewater discharges into rivers. Furthermore, studies conducted in China by Ho and Hui (2001) and Ding *et al.* (2015) on rivers passing through both forest and urbanized areas showed that urban areas are the major contributors of nutrients (N, P) during both the dry and wet season which could be attributed to point and non-point source pollution such as municipal and industrial wastewaters. Another study conducted for two urban rivers in Japan found that the pollutant types and levels varied inconsistently from upstream to downstream locations showing pollutant concentration of $\text{NO}_3\text{-N}$ in one river increased by 50% moving downstream, whilst in the other river a downstream reduction was ascribed to purification provided by riverine wetlands and dilution (Woli *et al.* 2004).

Understanding the contribution of year round point sources and stormwater-activated non-point sources to the pollution of running waters will help urban planners and city decision-makers to effectively prioritize responsive strategies. Taking Addis Ababa as case, the present study was conducted to:

- observe the water quality of three rivers and compare findings with Ethiopian and international standards,
- investigate the impact of stormwater runoff on river water quality by comparing dry and wet seasons, and
- establish any relations between river water quality and the level of urbanization.

Materials and Methods

Study area

To document the water quality of rivers in Addis Ababa, we selected three rivers, namely, Shegole, Little Akaki and Jemo, which are all located in the Little Akaki River catchment in the western part of the city (Fig. 1). This catchment drains into the main Akaki River, which is a tributary of Awash River, draining the central and eastern part of Ethiopia into an endorheic basin near the border of Djibouti. Their headwaters originate north of Addis Ababa. Shegole passes through the oldest, most congested and densely built-up parts of the city, close to the urban core, Little Akaki passes through a moderately urbanized areas, and Jemo passes through relatively less and recently urbanized parts nearer the periphery of the city.

Thus, at large scale, the three rivers represent an urbanization gradient with a population density per square kilometre of 19,294 in Shegole catchment, 8,793 in Little Akaki catchment and 6,490 in Jemo River catchment, as

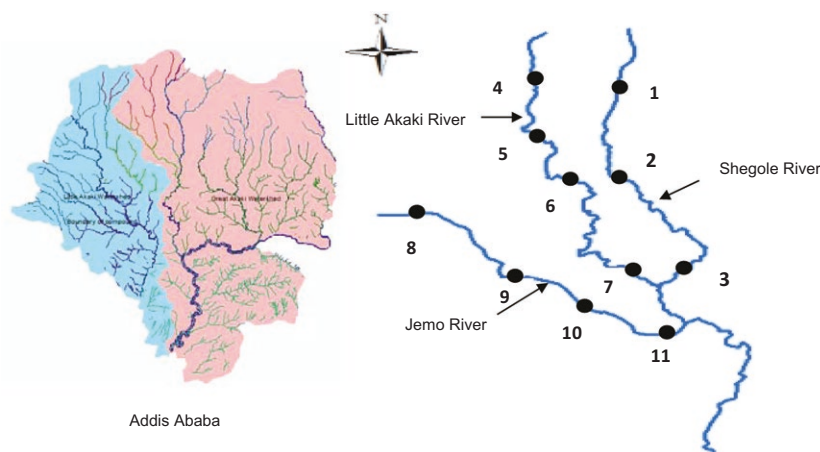


Fig. 1. Left: Addis Ababa city with Little Akaki catchment shaded in blue. Right: The sampled rivers with the sampling points indicated with number and black dots. [Colour figure can be viewed at wileyonlinelibrary.com]

calculated from population numbers (CSA, 2013) and area of rivers' catchment was delineated with ArcGIS (version 10.3.1). Within each river, attempts were made to represent the urbanization gradient by placing sampling sites in upstream, midstream, and downstream parts, with upstream sites representing less urbanized areas compared to mid- and downstream sites.

In total, 11 sites were sampled, distributed on the three rivers as shown in Fig. 1 and Table 1. To document the difference between seasons, water samples were collected twice in each season of 2015. Dry season samples were obtained from March 10–12 (i.e. replication 1) and May

15–17 (i.e. replication 2); and wet season samples on July 18 (i.e. replication 1) after rainfall of 7.4 mm, and August 18 (i.e. replication 2) after rainfall of 12.3 mm.

Water samples were grabbed by lowering a polyethylene bottle, rinsed in distilled water, into the river. Samples were stored in a dark refrigerated system for a maximum of two days until analysis.

Physicochemical parameters analysis

To describe physicochemical conditions dissolved oxygen (DO), electrical conductivity (EC) and pH were measured

Table 1 Names and coordinates of the sampling sites, and observed main point sources

Rivers and site codes	Site descriptions	UTM-coordinate and elevations above sea level (m)	Point sources (expected corresponding pollutants are footnoted)
Shegole	1 Nuna gamo Plc	09°03.517'N 38°42.762'E 2544 m	Tannery ^a Toilet and showers (services) ^b Garages ^c , recreation ^d
	2 EiABC	09°00.695'N 38°43.274'E, 2344 m	Liquor and soft drink factories ^e Public college with dormitories ^f
	3 Opposite Mekanisa liquor factory	09°58.564'N 38°44.101'E, 2234 m	Abattoir ^g Urban agriculture ^h
	4 Bero	09°03.016'N 38°41.063'E, 2470 m	Urban agriculture ^h Toilet & showers (settlement) ^b
	5 Kolfe High School	09°02.012'N 38°42.125'E, 2374 m	Tannery ^a , fodder processing ⁱ Animal production ^j , urban agriculture ^h
	6 Zenebe work/Alert	08°59.39'N, 38°42.573'E, 2268 m	Toilet and showers (settlement) ^b
	7 Mekanisa liquor factory	08°58.504'N 38°43.949'E 2334 m	Liquor factory ^a Urban agriculture ^h Seedling nursery ^k
Little Akaki	8 Ayer Tena	08°58.936'N 38°41.553'E, 2274 m	Garage ^c Toilets (recreation facility) ^b
	9 China camp	08°58.418'N 38°42.322'E, 2229 m	Animal production ^j Gravel quarrying ^l
	10 Yetebaberut fuel station	08°57.76'N 38°43.107'E 2232 m	Large auto-workshop ^c , fuel station ^m Urban agriculture ^h Solid waste dumping site ⁿ
	11 Lebu	08°57.217'N 38°43.877'E 2216 m	Urban agriculture ^j Public sanitary facilities ^b Demolition waste ^o
Jemo			

^aHeavy metals, organic micropollutants (e.g. polychlorinated biphenyls (PCBs), formaldehyde resins, pesticides (UNEP 1994; Mwinyihija 2010)

^bNutrients, detergents (Schmoll 2006)

^cHeavy metals, sulphuric acid, aliphatic hydrocarbons (used oil, petroleum), organic micropollutants (automotive paints)

^dNutrients, suspendable solids

^eNutrients, suspendable solids (Eremektar *et al.* 1995)

^fNutrients, organic micropollutants (cleansing agents), aliphatic hydrocarbons (used oil and grease)

^gNutrients, suspendable solids, NaCl (Sangodoyin and Agbawhe 1992)

^hNutrients, pesticides, suspendable solids

ⁱNutrients, suspendable solids

^jNutrients, NaCl, suspendable solids (Williams 1995)

^kNutrients, pesticides, suspendable solids

^lHeavy metals, suspendable solids, aliphatic hydrocarbons (used oil, grease, petroleum) (WHO 2003)

^mAliphatic hydrocarbons (oil, grease, petroleum leaks), heavy metals (Raad *et al.* 2012)

ⁿHeavy metals, organic micropollutants, (e.g. cleansing agents, PCB, formaldehyde, resins and pesticides), total solids

^oHeavy metals, suspendable solids

Table 2 Observed river water quality parameters and allowable environmental standards of Ethiopia, US, Europe and Australia-New Zealand

Pollutant	Ethiopian standard	International standards	Dry season observations – average values for river:			Wet season observations – average values for river:		
			Shegole	Little Akaki	Jemo	Shegole	Little Akaki	Jemo
DO (mg/L)	No data	4.50 ^a	0.18	3.16	2.49	5.43	7.29	5.16
pH	6.5 – 9	6.5–9 ^a	7.76	7.94	8.01	8.18	8.27	8.47
Turbidity (NTU)	No data	No data	239	35	54	376	661	302
Total NO ₂ -N (mg/L)	No data	0.10 ^b	0.90	2.74	2.62	5.37	10.26	11.00
Total NO ₃ -N (mg/L)	20	3.0 ^b	2.39	1.31	1.46	1.88	2.05	2.36
Total NH ₄ -N (mg/L)	No data	1.0 ^b	2.56	2.24	3.16	0.97	0.75	1.76
Total PO ₄ -P (mg/l)	5.0	0.20 ^c	45.55	20.97	41.46	14.77	8.92	16.55
Dissolved Cr(VI) (mg/L)	0.05	0.0034 ^d	0.021	0.075	0.063	0.010	0.055	0.060
Dissolved Mn (mg/L)	0.5	0.150 ^d	0.370	0.320	0.590	0.040	0.043	0.058
Dissolved Cu (mg/L)	2.0	0.0049 ^d	0.070	0.010	0.020	0.060	0.003	0.010
Dissolved Zn (mg/L)	5.0	0.0078 ^d	0.320	0.090	0.100	0.110	0.050	0.070

^aUSA^bAustralia-New Zealand^cEU^dEU, Denmark

on-site using a portable multi-parameter digital metre (HACH, HQ40d) equipped with probes (DO-probe LDO 10105, EC-probe CDC 40105, and pH-probe USPAT 6912050) and turbidity was measured with portable turbidity-metre (OAKTON T-100).

Nutrients analysis

Water samples were filtered through a 0.42 µm filter (Whatman). Nutrients including phosphate (PO₄-P), nitrate (NO₃-N), nitrite (NO₂-N), and ammonium (NH₃-N) were analysed in a laboratory using a spectrophotometer (JENWAY 6405UV/Vis) following standard methods in APHA (2005).

Heavy metals analysis

Water samples from the three rivers were filtered using a 0.42 µm filter (Whatman) to analyse heavy metals including Cr(VI), Cu, Mn and Zn. The analyses were conducted in a laboratory with HACH reagents and a DR200 HACH spectrophotometer, using diphenylcarbohydrazide for Cr(VI), bicinchoninate (copper reagent) for Cu, periodate oxidation for Mn, and zincon for Zn methods, respectively.

To the extent possible, the observed water quality of the three rivers in Addis Ababa was compared with the

Ethiopian environmental standard set by the Ethiopian EPA and UNIDO (2003) and with freshwater requirements or acceptable levels for US (USEPA, 1986, updated on-line 2015), Europe (EU, 2013), and Australia-New Zealand (ANZECC 2000), referred to as international standards, as summarized in Table 2 in Results.

Regarding turbidity no requirements exist. For nutrients, the US and EU standards state that the acceptable levels depend on local ecoregions, and accordingly should always be adjusted hereafter. The higher Ethiopian limit for NO₃-N compared to Australia-New Zealand standard may reflect such differences in ecoregions. Based on a comparative study by Claussen *et al.* (2012) on the national requirements used by 17 EU member states when implementing the EU Water Frame Directive it was possible to retrieve insight on the PO₄-P levels employed. From this study, it is seen that 11 of the 17 member states require a total PO₄-level not exceeding 0.2 mg/L for good river water quality to be obtained, whilst up to 1 mg total PO₄-P is the maximum allowed by one member state.

Again, the higher Ethiopian limit for PO₄-P may reflect differences in ecoregions. It should be noted that nutrient standards, both Ethiopian and international concern total concentrations, so when we compare with our observations for dissolved concentrations it is a conservative

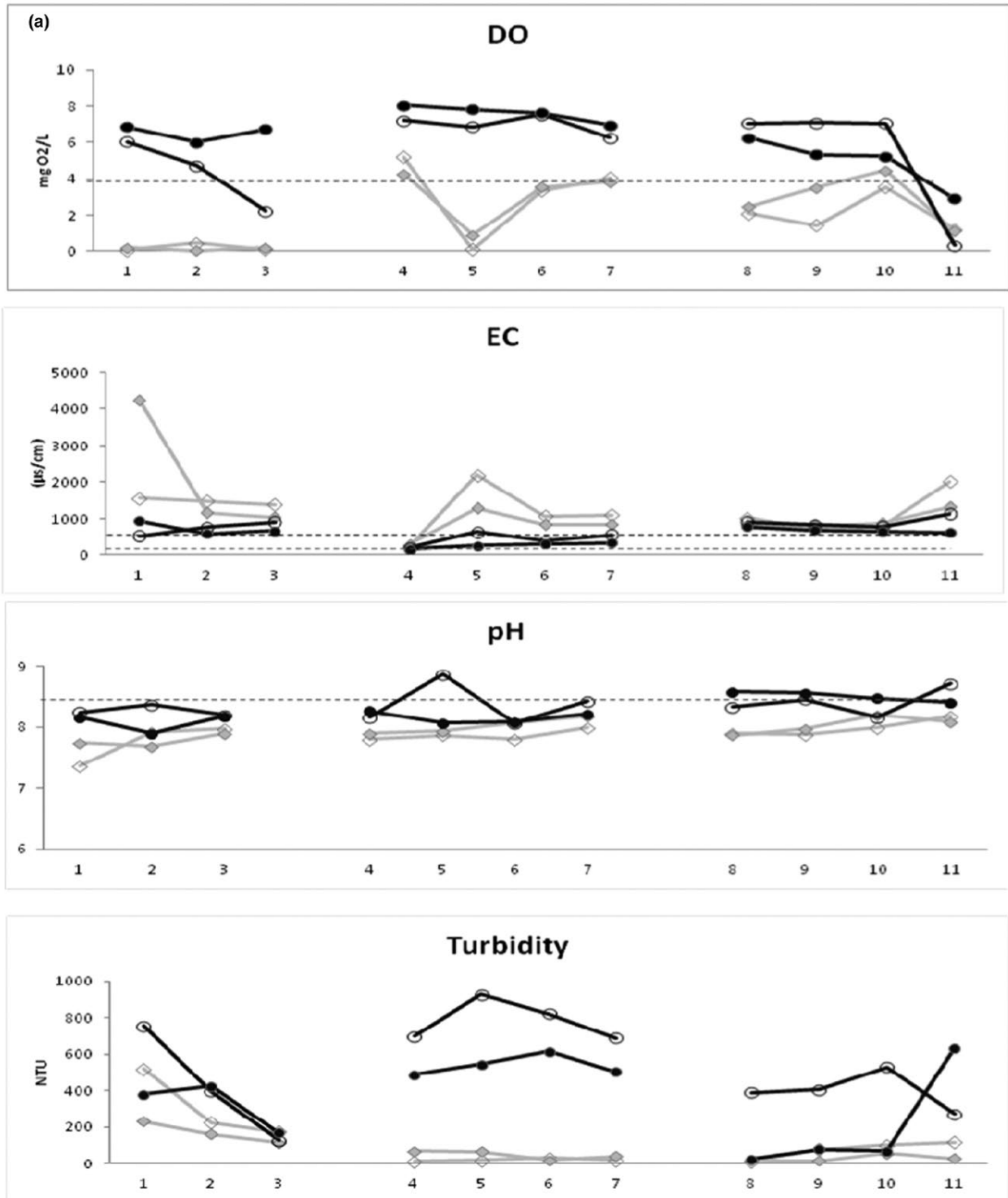


Fig. 2. Water quality as observed in wet and dry seasons expressed as DO, EC, pH, turbidity (a) , and dissolved concentrations of $\text{PO}_4^{2-}\text{-P}$, $\text{NO}_3^-\text{-N}$, $\text{NO}_2^-\text{-N}$, and $\text{NH}_4^+\text{-P}$ (b) and Cr (VI), Cu, Mn, Zn (c) of three rivers in Addis Ababa.

Sampling points 1, 2, and 3 represent Shegole, 4, 5, 6 and 7 represent Little Akaki, and 8, 9, 10 and 11 represent Jemo. This order reflects an urbanization gradient within the catchment, from highest (Shegole) to lowest (Jemo). The numbering of sampling points for each river goes from upstream to downstream, which also reflects an urbanization gradient along each river. Black lines with circles = wet season, Grey lines with diamonds = dry season, Non-filled symbols = sampling replication 1, Filled symbols = sampling replication 2.

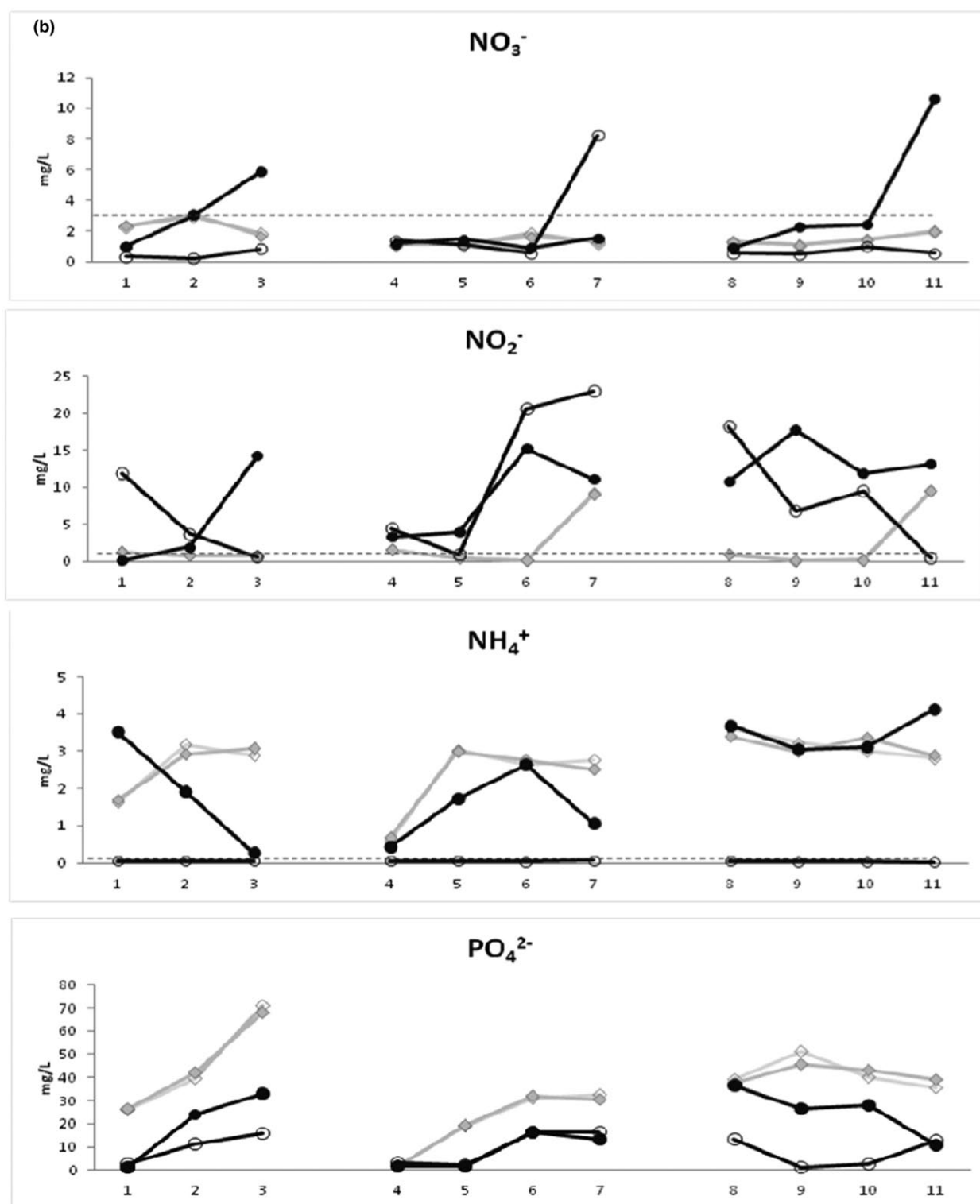


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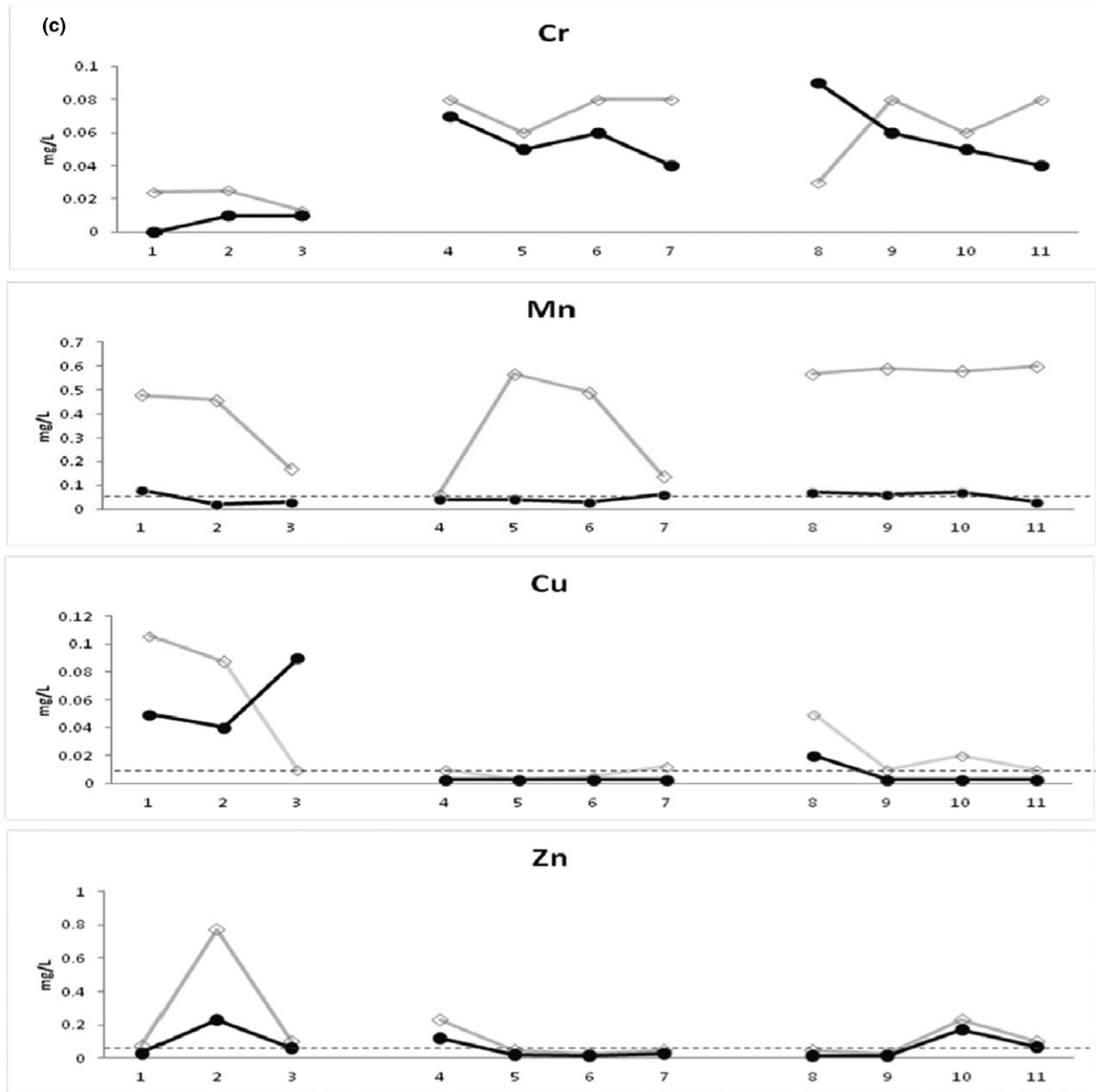


Fig. 2. (continued)

comparison. Regarding Cr(VI), Cu, Mn and Zn both the Ethiopian limits and the Danish long-term threshold values for implementation of the EU Water Frame Directive (Ministry of Environment and Food of Denmark 2015) were used. According to the EU Water Frame Directive, the threshold levels for Mn and Zn must take the natural background concentrations into account, which are unknown for the studied rivers in Addis Ababa, but may explain the higher limits for these to metals in the Ethiopian limit. The reason for higher levels for Cr(VI) and Cu in the Ethiopian limits compared to the Danish is unknown.

Results

The observed water quality in the three investigated rivers of Addis Ababa is presented in Fig. 2. Moreover, the average values of the dry and wet season observations in parallel with the Ethiopian and international standards are presented in Table 2.

Sampling points 1, 2 and 3 represent Shegole; 4, 5, 6 and 7 represent Little Akaki; and 8, 9, 10 and 11 represent Jemo. This order reflects an urbanization gradient within the catchment, from highest (Shegole) to lowest (Jemo).

The numbering of sampling points for each river goes from upstream to downstream, which also reflects an urbanization gradient along each river. Black lines with circles = wet season, Grey lines with diamonds = dry season, Non-filled symbols = sampling replication 1, Filled symbols = sampling replication 2.

Despite limited number of samples, the observed levels and patterns of the general parameters DO, EC, pH and turbidity from replication 1 are to a large extent repeated in replication 2 for both seasons. This indicates that the employed sampling strategy was capable of capturing the main factors controlling the river water quality.

When the observed river water quality is compared with the available Ethiopian standards (Table 2), pH was within the standard range, although with a tendency to reaching too alkaline levels. $\text{NO}_3\text{-N}$, Mn, Cu and Zn were well below the standard, except Mn for Jemo river in the dry season. In both seasons, the average values of Cr(VI) were higher in Little Akaki and Jemo rivers, whilst in Shegole river it was below the Ethiopian limit. Average $\text{PO}_4\text{-P}$ was strongly exceeding the limits (Table 2), although a few samples from both dry and wet season were below the limit (Fig. 2b). The actual exceedances for $\text{PO}_4\text{-P}$ are assumed to be significantly higher because we only measured dissolved $\text{PO}_4\text{-P}$.

If the observed water quality is compared with international standards it is seen that the dry season samples generally did not meet the standards, whilst the wet season samples for some parameters met the standards whilst in other cases not, or were even worse (Table 2). For DO, the international standard of a minimum concentration of 4.5 mg $\text{O}_2\text{/L}$ was observed in most of the wet seasons' samples but not in the dry seasons, where the oxygenation of the water in some samples was close to zero (Fig. 2a).

Regarding nutrients, it is seen that although nitrate was in most measurements below the 3 mg/L level, the associated and more toxic N-forms of nitrite and ammonium severely exceeded the international standards. Likewise, phosphate surpassed the international standards of 0.2 mg P/L by several orders of magnitude.

When it comes to the four measured metals it is seen that Cr(VI) exceeds the international standard in extreme degree in both the wet and dry seasons, and that this is also the case for Cu regarding Shegole, whilst Cu is around the international standard in Little Akaki and exceeds the international standard slightly in the dry season but not in the wet season in case of Jemo. Because the natural background level should be added to the international standard for Zn it is not possible to conclude whether Zn met the standard. It is noted that Zn shows a pattern similar to Cu. Although the international standard for Mn should also take the natural background concentration,

it can be concluded that in the wet season the Mn is below the international standard of 0.15 mg/L. The dry season samples showed higher levels, exceeding this level, because no background level information is available this level may still be within the international standard.

The influence of stormwater runoff on river water quality can be revealed by comparing dry and wet season samples. Based on DO, EC, $\text{NH}_4\text{-N}$, $\text{PO}_4\text{-P}$, Cr, Mn, Cu and Zn there may be a tendency for improved river water quality in the wet season, corresponding to stormwater having a diluting effect on the contaminants in the river in wet season. Thus, considering samples from same site it is seen that the DO was up to 86-folds higher, EC was up to 5-folds lower, both $\text{PO}_4\text{-P}$ and Mn were up to 20 folds lower, and Cr(VI) up to 6-folds lower in the wet season compared to the dry season. Regarding $\text{NH}_4\text{-N}$ and the other metals no clear differences were observed. $\text{NO}_3\text{-N}$ and $\text{NO}_2\text{-N}$ tended to be highest in the wet season, indicating strong non-point sources being present.

The anticipated urbanization gradient was only reflected to some extent. This is the case when the three rivers are compared, where the expected order of contaminant level would be Shegole, Little Akaki and Jemo, and when the less urbanized upstream samples of individual rivers are compared with more urbanized downstream samples of the same river. Whilst dry season DO was clearly at the lowest level in the Shegole river compared to Little Akaki and Jemo, this river was not outstanding otherwise. Thus, nutrients, Mn and Zn were at similar levels in all three rivers, and although Cu was highest in samples from Shegole, the opposite was the case regarding Cr, where Little Akaki and Jemo presented highest concentrations.

Regarding the within-river comparison, only nutrients expressed a tendency for increasing loads when moving from upstream to downstream, although there were quite some exceptions. Similar patterns were not seen for other parameters. This suggests the direct discharge of wastewaters into rivers from the nearby industries, toilet facilities and institutions to have stronger impacts on the river water quality than the level of urbanization.

Discussion

Comparison of observed water quality levels with Ethiopian and International standards

As revealed from the three rivers studied, the observed nutrients and heavy metals were below the Ethiopian standards, except phosphate, Cr (VI) and Mn which exceeded the standard in both the dry and wet weather in almost all measurements. If the observed water quality is compared to international standards, it is extremely high in the dry season and despite some improvement for most parameters in the wet season, the levels are

still exceeded. For $\text{PO}_4\text{-P}$, $\text{NO}_2\text{-N}$, $\text{NH}_3\text{-N}$, Cr and Cu, the exceedance is measured in decades.

This comparison is therefore quite important to ensure local standards gradually become compatible with international ones. Because improvement of standards and regulations are iterative processes, environmental water quality standards are tighten based on progress achieved and compliance with general social and economic development of the area. Putting in place environmental standards alone doesn't result in effective water resources protection. Therefore, regulators, environmental engineers and scientists should monitor and evaluate the effectiveness of the set standards through continuous pollution level observation and compare with best international standards.

Impact of stormwater runoff on river water quality by comparing dry and wet seasons

If the contaminant levels observed in this study are compared with findings by other authors (e.g. Beyene *et al.*, 2009), it is seen that the DO-range in our study reached higher to around 8 mg/L in wet season measurements in two of the three rivers, but also that EC set record high levels in single dry season measurements of all three rivers exceeding 2000 $\mu\text{S}/\text{cm}$, as did pH, reaching levels above 8 in all wet season measurements.

For $\text{NO}_3\text{-N}$ and Mn, our observations are in similar range as reported by Alemayehu (2001) and Temesgen (2009), as is the case for Cu and Zn concerning the rivers Little Akaki and Jemo, whilst Shegole River exceeds previous reporting several folds. For the other parameters, we found no previous reporting for comparison.

The higher values of the observed river water quality parameters signifying poor quality can be attributed to year-round direct discharge of untreated industrial effluent and domestic wastewater. Here, the tanneries, which were found at the headwater of two of the three rivers, may cause permanently high concentrations of Cr and Cu, whilst the constant discharge of municipal wastewater from toilets, showers and other domestic sources, including open defecation causes a continuous high load of nutrients. In support of this, it is estimated that 56 % of municipal wastewater is connected illegally through pipes and drains to the rivers (AAWSA, 2011).

The fact that stormwater runoff only reduced the contaminant levels to a minor extent indicates that additional contaminant sources become active in wet weather. Here, the many stretches of agricultural practices along the river may provide a source of nutrients, especially P, which may be leached from soil enriched with inorganic fertilizers. Agricultural practices may also explain the increased levels of nitrite and ammonia in wet season, which is in

agreement with the study conducted by Carpenter *et al.* (1998). Another likely source of nutrients activated during wet weather is the remaining municipal wastewater, of which a fraction is assumed to end up in pit latrines which may overflow during rain.

The reason for the high pH levels observed in the wet season is unknown, but one plausible explanation may be the rapid urbanization rate and corresponding high number of construction sites, where concrete is being used. The many building activities may also be the reason for high Cr during wet weather because Cr is found in concrete (Kayhanian *et al.* 2009).

The up to fivefold higher turbidity of river water in the wet season compared to the dry season is a clear indication of the significant contribution of stormwater runoff in the wet season. Turbidity is assumed to increase during storm events due to soil erosion from agricultural practices, and wash-off solids from demolished materials from construction sites and unmanaged solid wastes (Regassa *et al.* 2011).

The improvement of DO in the wet season might be attributed by turbulence of running water, combined with lower content of organic matter in the stormwater runoff, as also suggested in rivers in India and Argentina (Pesce and Wunderlin 2000; Joshi *et al.* 2009). The low oxygenation of the river water during dry season, in some samples approaching zero, is ascribed to the organic loads from direct discharge of domestic and industrial wastewater, as also pointed out by Awoke *et al.* (2016) comparing river water quality in four river basins in Ethiopia, and Alemayehu (2001) ascribing low DO in rivers of Addis Ababa from solid waste dumping and wastewater discharge. Furthermore, our finding is consistent with study conducted by Karn and Harada (2001) who reported that the dry season contributed significant impact on river pollution in three urban territories of Nepal, India, and Bangladesh due to year round pollutants flow into the rivers and reduced river water discharge.

Generally, the increase in mean flow rate from 1.16 m^3/s in June to 19.73 m^3/s in August and then, the decrease of the flow rate from 0.95 m^3/s in October to 0.21 m^3/s in May of the rivers in the study area is an indication to the decrease in concentration and wash off pollutants during the rainy season.

Therefore, understanding of the pollution status of rivers both in the dry and wet season is central to evidentially identifying the contribution of point sources and non-point sources, as stormwater in the wet season is known to degenerate river water quality in urban settings. Stormwater, an urbanization problem, is commonly polluted by sediments, heavy metals, untreated domestic and municipal wastes and is mainly discharged directly into rivers. Thus, to prevent river water pollution from

point and non-point sources, establishing clear water management measures need to be integrated with waste management practices.

Impact of urbanization on river water quality

The fact that only weak indications of impact of urbanization on the observed rivers water quality suggests point sources distributed along the rivers, like direct discharge of industrial wastewater and leaching from municipal waste dumps in the river to overrule the impact of building density and its correlated activities including direct discharge of domestic wastewater, open defecation, and overflow of pit latrines. This observation differs from studies conducted in China by Deng *et al.* (2015) that reported the quality of rivers decrease with urbanization gradient, suggesting river pollution in our study is dominated by specific point sources. Another explanation may be that the urbanization gradients in the Chinese studies were larger than in this study, where the catchments in all cases were to some extent urbanized.

Thus, identifying the relation between river water quality and level of urbanization is key to formulate appropriate environmental management tools related to water and the environment that accommodates the continuous and fast rates of urbanization in developing countries. This is a roadmap for environmentalists to consider land-use patterns, domestic and industrial pollution loads, agricultural practices, population density, hydrological aspects and level of urbanization when studying river water quality which may help to realize the need for preventive measures.

According to UNEP (1997), water quality problems have attracted increasing attention especially in developing countries where environmental protection are now becoming a major obstacle for sustainable development. Consequently, water pollution control is clearly one of the most critical issues that need urgent and informed action to prevent the already stressed water resources from contamination.

For example, studies conducted in UK by Groffman *et al.* (2002) and in USA by Neal and Robson (2000) report that vegetated river banks reduced the reach of pollutants into rivers. Conversely, due to encroachment of river banks, this buffer mechanism is likely to have been offset in the case of the three rivers studied in Addis Ababa.

The present study highlights the need to address point source pollution like industries, garages, and animal production sites, preferably with decentralized treatment systems to prevent direct discharge to rivers (Massoud *et al.* 2009). Regarding the non-point sources originating from households without controlled emptying latrines, or practicing open defecation, improved sanitation should be prioritized. Here, separation of greywater and latrine

would be recommended, e.g. using composting toilets (Zavala *et al.* 2005) because flush-based toilets put pressure on water resources and pollutes the receiving water body as already witnessed today in Addis Ababa.

For the non-point pollution sources, which mainly reach the rivers with the stormwater runoff, less focus is needed if greywater and latrine could be managed in closed systems, as most of the expected nutrient load will then be removed. Buffer zones, also along agricultural land, would be an additional recommended measure (Anbumozhi *et al.* 2005). The apparent load of heavy metals, especially Cr, could be reduced if a greening programme could be realized, ensuring vegetation cover of bare soil (Wise, 2008; Barbosa *et al.* 2012).

The practical way forward concerning the application of the present study is to inform water and environmental managers through designing cleanup plans, and help arrest the main pollutant sources. Observing the state of water quality in rivers and identifying the degree of water pollution helps to understand the current situation and help reduce public health, environmental and economic impacts of water pollution. Subsequently, it enables environmentalists to establish appropriate management approaches towards achieving sustainable water resources protection. This can be achieved through reduction of the proportion of water pollution originating from diffuse sources (e.g. agricultural use of fertilizers, stormwater) which cannot be controlled by the end-of-pipe approaches. The knowledge of the source, concentration and type of pollutants help identify the need for pollution control measures, assist environmental regulators in targeting the most significant problems and to assess the necessity for making changes to legislative provisions. Informed and enforceable water pollution control standard is fundamental for its effectiveness.

Conclusion

Based on wet and dry season sampling of water from three rivers in the Little Akaki catchment of Addis Ababa, we conclude that the rivers have a poor water status when compared to international standards. This includes low oxygenation, too high salt concentrations and tendency to too alkaline pH, high nutrient status of both N and especially P, and severe heavy metal contamination with Cr and Cu. Even when compared to the less strict Ethiopian standards phosphate is still problematic, and in two of the three rivers also Cr and Mn. When comparing with the available data from other studies conducted previously in Addis Ababa similar ranges were found for most parameters, although some were much higher like EC and Zn.

Direct discharge of untreated industrial wastewater from a number of industries stretched along the rivers,

including tanneries, breweries and garages, supplemented with direct discharge of untreated municipal wastewater serving 56% of the households are assumed to constitute the main year-round contamination sources. Open defecation and leaching of solid waste dumped directly in the rivers is also considered significant. During the wet season the river water quality is slightly improved, but still often exceeding the international standards and in case of P, Cr and Mn also exceeded the Ethiopian limit.

Although stormwater dilutes the contaminants and brings more oxygen, there seems to be a number of additional non-point sources activated during rain. We point to pit latrines overflowing and leaching from agriculture along river banks contributing nutrients, and construction sites in the growing city contributing heavy metals, especially Cr.

No strong correlation with urbanization gradients on the level of pollutant for rivers passing through densely, moderately and relatively less urbanized parts of the city could be found, and no strong correlation when comparing upstream and downstream sections of same river. This might be due to point-sources being located along the full stretch of all three rivers and the fact that all catchments show some degree of urbanization.

It is recommended to target industrial wastewater with decentralized treatment systems, municipal wastewater with a treatment plant, and to implement improved sanitation for all households not connected to a sewage pipe. Re-introduction of vegetated riverbanks is also recommended as buffer zones. We also recommend the Ethiopian standard to be revised as there are huge gaps with the international standards considered from the US, EU and Australia-New Zealand.

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