Assessing land-use impacts on a 5th-order tropical river using multiple environmental indicators

Impactos de uso da terra em um rio tropical de 5^a ordem determinados por meio de múltiplos indicadores ambientais

Iola Gonçalves Boëchat
Professora do Programa de Pós-Graduação em Geografia
Universidade Federal de São João del-Rei, MG, Brazil
iboechat@ufsj.edu.br

Mario Brauns
Department River Ecology
Helmholtz Centre for Environmental Research, Magdeburg, Germany
mario.brauns@ufz.de

Ana Paula Campos de Carvalho Laboratório de Limnologia Aplicada Universidade Federal de São João del-Rei, MG, Brazil anapaula.fields@hotmail.com

Aparecida Beatriz das Mercês de Paiva-Magela Laboratório de Limnologia Aplicada Universidade Federal de São João del-Rei, MG, Brazil beatrizpaiva12@hotmail.com

Ronaldo César Chaves Laboratório de Limnologia Aplicada Universidade Federal de São João del-Rei, MG, Brazil ronaldocchaves@yahoo.com.br

Sandra Hille
Department People and Culture
Helmholtz Centre for Environmental Research, Magdeburg, Germany
sandra.hille@ufz.de

Björn Gücker Professor do Programa de Pós-Graduação em Geografia Universidade Federal de São João del-Rei, MG, Brazil guecker@ufsi.edu.br

Resumo

Usos da terra, tais como expansão e a intensificação da agricultura e a urbanização, afetam a saúde de ecossistemas riverinos e ameaçam sua diversidade biológica de uma maneira multifatorial e interativa. Neste estudo nós realizamos uma compilação de resultados provenientes de diversos trabalhos realizados em um rio tropical de 5ª ordem – o Rio das Mortes, na bacia do alto Rio Grande (Sudeste brasileiro) – a fim de analisarmos se a combinação de diferentes indicadores ambientais fornece uma forma mais completa e complementar de análise dos impactos de uso da terra, desde a nascente até a foz do rio, em comparação a indicadores individuais. Foram analisados dados da

qualidade da água, estrutura do sedimento, a integridade estrutural de habitats, a bioquímica da matéria orgânica em suspensão e a composição e distribuição da comunidade de macroinvertebrados bentônicos. A qualidade da água exibiu mudanças ao longo do percurso do rio, especialmente durante a estação seca, que corresponderam ao padrão de urbanização na bacia, com considerável efeito deste uso da terra na parte superior da bacia e vários centros de urbanização ao longo do curso do rio. A predominância de ácidos graxos saturados e típicos de bactérias na matéria orgânica em suspensão na água de segmentos mais urbanizados da bacia mostraram que esse importante recurso alimentar da comunidade riverina funciona como um indicador sensível da urbanização na bacia. Por outro lado, a estrutura do sedimento riverino e a integridade estrutural de habitats foram eficientes em indicar impactos locais, primariamente em trechos intermediários e urbanizados do rio, inclusive apontando efeitos positivos de esforcos locais de preservação e de diferencas naturais sobre a estrutura do sedimento. Chironomidae e Oligochaeta foram os grupos dominantes na comunidade de macroinvertebrados. Sua distribuição espacial foi determinada pela estrutura do sedimento e pela integridade estrutural de habitats e, portanto, por impactos locais na estrutura do rio. Nós argumentamos que a abordagem integrativa a impactos de uso da terra, combinando características estruturais locais, de habitat e da comunidade, com padrões de uso da terra e de qualidade da água em escala espacial mais ampla, é raramente aplicada a grandes rios tropicais, mas extremamente importante para compreendermos e manejarmos estressores de uso da terra nestes sistemas.

Palavras-chave: acesso integrado, integridade ecológica, urbanização, rios tropicais

Abstract

Land-use change, such as agricultural expansion and intensification, and urbanisation, affects river ecosystem health and threatens riverine biological communities in a multifactorial and interactive way. In this study, we compiled the results of several studies carried out in a 5th-order tropical river, the Rio das Mortes in the upper Rio Grande basin (Southeast Brazil). We analysed if a combination of different environmental indicators, such as river water quality, sediment structure, habitat structural integrity, biochemistry of suspended organic matter, and the composition and distribution of the benthic invertebrate community, provides a complementary and more complete assessment of landuse impacts from headwaters to the river mouth than single indicators. Water quality exhibited longitudinal changes along the studied river, especially during the dry season, corresponding to the urbanisation pattern in the river catchment with considerable urbanisation already in the upper catchment, and several urban centres along the river's course. The predominance of saturated fatty acids and bacterial fatty acids in the river water's suspended organic matter at urbanised river segments showed that the biochemistry of suspended organic matter, an important resource for the river's biological community, was a sensitive indicator of catchment urbanisation. In contrast, river sediment structure and habitat integrity showed local impacts, primarily in mid-catchment urbanised river segments, with notable positive effects of local conservation efforts and natural differences in sediment structure. Chironomidae and Oligochaeta were the dominant groups in the river's macroinvertebrate community. Their spatial distribution was mainly determined by sediment structure and river habitat integrity, and thereby, by local impacts on river structure. We argue that integrated assessment approaches rarely applied to larger tropical rivers, combining local structural, habitat and community characteristics with large-scale land use and water quality patterns, are important to understand and manage land-use stress in these systems.

Keywords: integrated assessment, ecological integrity, urbanization, tropical rivers.

1. INTRODUCTION

Human impacts on lotic ecosystems are perceptible on different spatial scales and in different compartments of stream and river systems. They affect water quality, hydrology, and structural diversity of micro- and macrohabitats, resulting in changes in biodiversity and biological processes (VITOUSEK et al., 1997; KARATAYEV et al., 2005). Urbanisation and the expansion and intensification of agricultural land use lead to increased exports of inorganic nutrients from catchments and is thus responsible for the global eutrophication of streams and rivers, including those in the Brazilian Southeast (SMITH et al., 2006; GÜCKER et al., 2009; GÜCKER et al., 2016). Erosion and subsequent sedimentation or transport of fine sediments in river channels are common in agricultural catchments. Riparian deforestation and homogenisation of river hydromorphology are general characteristics of land use, diminishing the diversity and availability of natural allochthonous resources (CARPENTER et al., 1998; SILVEIRA et al., 2005; SPÄNHOFF et al., 2007; GÜCKER et al., 2009). Further, pesticide, microplastic, heavy metal, and industrial and pharmaceutical residue pollution are common in urbanised and agricultural catchments (YONKOS et al., 2014; ALLINSON et al., 2015; YOU et al., 2015). In conclusion, eutrophication, xenobiotic pollution, habitat loss, low availability of natural allochthonous matter and low biodiversity are effects of unsustainable growth of human populations and land use on freshwater ecosystems worldwide (DODDS, 2006; SCHINDLER, 2006; SMITH et al., 2006).

Due to the multifactorial nature of land-use impacts (ALLAN, 2004; BIRK et al., 2020)—i.e., the effects of multiple, often interacting, stressors—efforts should be directed at identifying both the dominant stressors and their interactions, to manage and mitigate land-use impacts on lotic ecosystems. Monitoring and assessment programs of aquatic systems may include variables of water quality, multiple biological indicators, such as invertebrates, macrophytes, and diatoms, as well as functional characteristics (SOLIMINI et al., 2009). Water quality assessments in developing countries are typically limited to the determination of inorganic nutrient concentrations for inferring trophic state, physical characteristics, such as temperature, electric conductance and water transparency, as well as pH value, and concentrations of suspended sediment and dissolved oxygen (SILVEIRA et al., 2005).

The use of biological indicators of human impact is well established for aquatic ecosystems and mainly related to assessing responses in community diversity and structure, especially densities of impact sensitive and tolerant species, and functional groups of species (e.g., CUMMINS AND KLUG, 1979; REYNOLDS, 2002). In lotic tropical ecosystems, both approaches have been used based on the benthic invertebrate community (e.g., CUMMINS *et al.* 2005; CALLISTO *et al.*, 2005; Buss and Vitorino, 2010), mainly to assess changes in water quality (RIZO-PATRÓN et al.,

2013) or without distinguishing between effects of water and physical habitat quality (CALLISTO et al., 2005; HEPP AND SANTOS, 2009; BUSS AND VITORINO, 2010). However, benthic invertebrate community structure may be primarily associated with local habitat structure (CALLISTO et al., 2001; NESSIMIAN et al., 2008), and may more strongly respond to sediment structure, habitat diversity and hydrodynamic features than to water quality impacts. Thus, when investigating a large river surrounded by different types of riparian vegetation and land-use activities, it is crucial to identify the primary disturbance sources to assure the most appropriate and efficient management strategies. Thus, a multiple stressor approach, considering a multitude of environmental indicators and response variables, such as different variables of water quality, habitat quality and sediment structure, catchment land cover, and integrity of the riparian vegetation, as well as biotic community structure is indicated (ALLAN, 2004; WALSH et al., 2005). However, such integrative assessment approaches have rarely been adopted for larger tropical rivers (RAMIREZ et al., 2008).

In the present study, we applied an integrated assessment approach based on new and previously published data (BOËCHAT et al., 2013, 2014; AGUIAR et al., 2015), combining local structural, habitat and invertebrate community characteristics with large-scale land use and water quality patterns. We aimed to assess major stressors of ecosystem integrity along a 5th-order tropical river affected by catchment urbanisation and agriculture. By combining indicators and variables that respond differently to local habitat and large-scale landscape impacts, we intended to understand in a more complementary way as to how land-use patterns affect the abiotic and biotic integrity of a larger tropical river. Specifically, we tested the hypotheses that (i) longitudinal changes in water quality and biochemistry will be more strongly related to the proximity and size, as well as the population density of urban centres and agricultural areas in the river catchment than benthic invertebrate variables; and (ii) spatial changes in sediment structure and habitat integrity will be related to alterations in benthic invertebrate density and community composition along the river. In other words, water quality and biochemistry should respond more efficiently to landscape alterations in the river catchment, whereas benthic invertebrate variables and habitat integrity should be better indicators of local habitat perturbation. Moreover, we expected the responses of water quality and invertebrate variables to differ between the dry and the rainy season, as an effect of altered hydrodynamic patterns and temperature.

2. METHODS

2.1. Study sites

The study was carried out in the Rio das Mortes (Figure 1), a fifth-order tributary to the Rio Grande in the upper Rio Paraná basin. The Rio das Mortes catchment is located in the Vertentes

region in the federal state of Minas Gerais (Brazil), which is divided into 27 municipalities (IBGE, 2007; see figure 1 for urban centres in the catchment) and covers an area of approximately 6.619 km² (IGAM, 2005). The major impacts in the Rio das Mortes catchment are related to agriculture, and include riparian clear-cutting, channelisation, erosion, and sedimentation, besides contamination with fertilisers and herbicides. Additionally, the river receives raw sewage discharge from several urban centres located close to the river, which accommodate 85% of the catchment's total population (about 550,000 habitants: IGAM, 2005). In five seasonal sampling campaigns covering the dry and rainy seasons 2010 and 2011 (May and August 2010, March, June and December 2011), water quality, sediment and habitat structure, as well as benthic macroinvertebrate community assessments were performed. Water, sediment and invertebrate samples were taken in triplicate at 11 stations along the river, from its headwaters to its mouth (Figure 1), covering areas upstream and downstream of urban centres, farmland and pasture areas.

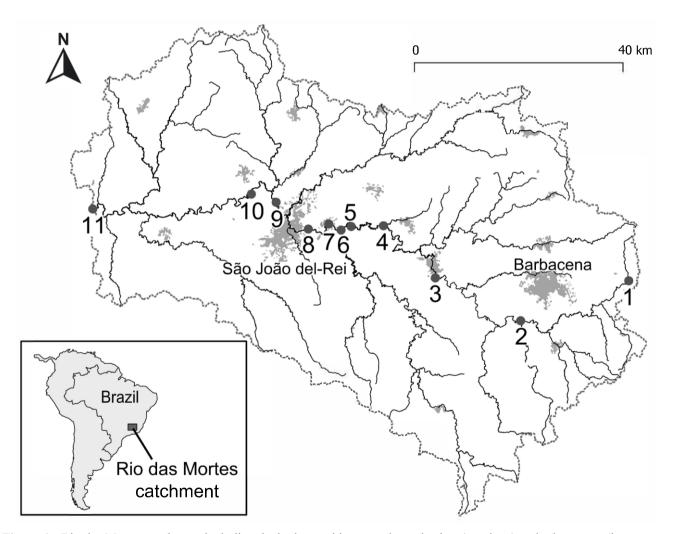


Figure 1 - Rio das Mortes catchment including the hydrographic network, study sites (numbers) and urban areas (in grey).

2.2. River water quality, sediment structure and habitat structural integrity

River water pH, temperature (T, °C), dissolved oxygen (DO, mg L⁻¹) and specific conductance (SC, µS cm⁻¹) were measured in situ with a multiparameter probe (556MPS, Yellow Springs Instruments, OH, USA) equipped with automatic temperature and barometric pressure compensation and calibrated directly before sampling. Water samples for nutrient analysis were collected with a 5L Van Dorn bottle (Limnotec, Brazil) at three different locations per sampling station and transported on ice to the laboratory. Water samples were filtered onto pre-combusted glass fibre filters (Whatman GF/F, 0.7 μm pore size) and stored at -20°C until further analysis. Filters were dried at 60°C for 6 hours and then incinerated at 550°C for four hours for particulate organic matter (POM) determination (APHA, 2003). The concentration of ammonium-nitrogen (NH₄-N), nitrate+nitrite-nitrogen (NO₃+NO₂-N), and soluble reactive phosphorus (SRP) were measured by flow injection analysis (FIALab 2500, FIALab, Bellevue, WA, USA) according to standard analytical procedures (APHA, 2003), after filtering samples through pre-flushed fibreglass filters (Whatman GF/F, 0.7 um nominal pore size). River seston fatty acid profiles, which have been increasingly used as markers for urban impacts and changes in aquatic ecosystem processes, were investigated at the same sampling stations in a previous study (BOËCHAT et al., 2014) and discussed together with the data presented in this study.

Sediment samples were taken using an Ekman bottom grab sampler (15 cm² sampled surface area). In the laboratory, sediment samples were dried, and the percentages of silt, sand and pebbles were quantified by granulometric analysis following dry sieving (GRADISTAT, v. 8, UK; BOËCHAT *et al.*, 2013). River habitat structural integrity was determined in a previous study (Boëchat et al., 2013) for each study site by applying the German river habitat on-site survey methodology (KAMP *et al.*, 2007). In this methodology, each sampling station received a score representing the level of structural integrity of the riverbed, banks and a 100 m-wide floodplain corridor upstream of each sampling station. The evaluation takes six main parameters into account (e.g., longitudinal profile, bank structures, etc.) defined by 14 functional units (including sinuosity, presence of constructions, etc.). The final survey score value varies from 1 (undisturbed condition) to 7 (totally disturbed).

2.3. Benthic macroinvertebrate analysis

Macroinvertebrates were collected either with a Surber sampler (30 cm², 250μm mesh size) or an Ekman bottom grab sampler (15 cm²), depending on sediment type. In the field, animals were manually separated from sediment and preserved in 70% ethanol. In the laboratory, organisms were identified to the lowest feasible taxonomic level, usually family, using appropriate identification keys

(FLINT, 1983; MERRITT AND CUMMINS, 1996; PES *et al.*, 2005; DOMÍNGUEZ *et al.*, 2006; PASSOS *et al.*, 2007; PIMPÃO AND MANSUR, 2009; MUGNAI *et al.*, 2010). Average population density (individuals m⁻²) was calculated for each sampling station (based on triplicate sampling) and campaign. We chose the most abundant taxa, i.e., Chironomidae, Oligochaeta, Simuliidae, and the pollution sensitive groups Ephemeroptera, Plecoptera and Trichoptera (EPT) to be included in statistical analysis.

2.4. Land cover analysis

Land cover analyses were performed based on Landsat images from 2010 (SILVA-JUNIOR et al., 2014). Sixteen land-use categories were distinguished in the Rio das Mortes catchment and grouped into three main land cover types: natural land cover (primary and secondary forest, Cerrado, Campo Rupestre, Campo Limpo and rock outcrops, and surface waters), agricultural land cover (pasture, crop plantation, open soil, eucalyptus plantation and burnt areas) and urban/industrial land cover (urban area, roads, railways, and mining). Riparian buffer zones of 60, 120, 180, 240, and 300 m width upstream of each sampling site were delimited based on hypsometric maps using QGIS 2.0 (QUANTUM GIS DEVELOPMENT TEAM, 2013). Subsequently, land cover distributions for subcatchments upstream of each sampling station and the riparian buffer zones were calculated from the previously compiled land cover map. As the relative contributions of each land cover type in riparian buffer zones of different width were highly correlated with each other, and with whole-catchment land cover (all R²>0.99), only whole-catchment land cover data were used in further analyses.

2.5. Statistical analyses

Two-way ANOVAs, followed by Tukey's HSD-tests, were used to test for differences in river water quality, sediment structure and habitat structural integrity variables, as well as benthic macroinvertebrate density among sampling stations and seasons. Benthic macroinvertebrate densities were log(x+1) transformed, and all variables were subsequently scaled to equal ranges (min. 0, max. 1) before analysis. The percentage of land cover was correlated to water chemistry, sediment structure and habitat structural integrity, and benthic invertebrate density using Spearman Rank Correlation, by pooling data from the same seasons. To evaluate response patterns of water quality, river habitat structural integrity, and macroinvertebrate density to the land cover gradient along the Rio das Mortes course, we carried out two Principal Component Analyses, separately for each season. All statistical procedures were conducted in Statistica for Windows (v. 10.0, Statsoft, USA).

3. RESULTS AND DISCUSSION

3.1. Land-use, sediment structure, river structural integrity, and water quality

Natural areas (41.6 to 53.7%) and agriculture (41.3 to 56.9%) were the prevalent types of land cover in the Rio das Mortes catchment, followed by urban areas (1.5 to 5.6%; table 1). In general, the percentage of natural and urban land cover increased, and agricultural cover decreased from the headwaters towards the middle sections of the river (table 1). From the middle to the lower sections of the river, percentage urban cover slightly decreased, and agricultural cover increased again (table 1). Sediment structure was consistently homogeneous along the riverbed, with sand dominating the sediment in all sampling sections of the river, except for the headwater and the TIR station, where pebble dominated the sediment structure (table 1). The headwater station also had the lowest urbanisation level and the highest structural integrity level (lowest score) (table 1, BOËCHAT et al., 2013). Intermediate stations (BPT and UT, table 1) exhibited the lowest structural integrity, followed by the upstream and downstream sections BAR, TIR and ER. They were thus classified as the most impacted stations in our study. Sampling stations towards the river mouth (RIT and IBI) showed better structural integrity than intermediate stations of the river. None of the investigated sampling stations received scores 1 or 2, suggesting that the entire river was submitted to some degree of structural degradation, even in the most pristine and protected sections studied (BOËCHAT et al., 2013). Interestingly, the only abiotic variables in our dataset significantly correlated with the river structural integrity score were sediment structure (Spearman-Rank correlation, positively with silt, r=0.56, and negatively with pebbles, r=-0.42, both p<0.05), suggesting that local impacts may be more perceptible in the sediment structure than, e.g., in the water quality of the studied tropical river (see next paragraph).

Water temperature was higher in the rainy season than in the dry season (ANOVA, p<0.05) (tables 2 and 3). Concentrations of SRP, NH₄-N and NO₃+NO₂-N, as well as DIN, were lower at the rainy season than in the dry season (ANOVA, p<0.05) (tables 2 and 3), possibly caused by a dilution effect due to higher runoffs during the rainy season. Except for the headwater, no significant differences were found for water chemistry variables among sampling stations along the Rio das Mortes, suggesting that water quality was compromised along the entire river. The headwater station had lower nutrient concentrations, especially NO₃+NO₂-N, than all other stations in both seasons (ANOVA, followed by Tukey HSD-test, p<0.05; tables 2 and 3).

Table 1: Relative land-use distribution (%) in the catchment, sediment structure, and river structural integrity for each sampling station in the Rio das Mortes.

	Land-use	characteristics of	f the watershed		Sediment structure			
Sampling Station	% Natural	% Urban	% Agricultural	% Sand	% Silt	% Pebble	Structural Integrity Score	
1 (Headwater)	41.6	1.5	56.9	32.2	0.4	67.4	3	
2 (CAM)	49	4.7	46.3	97.9	1.8	0.3	4	
3 (BAR)	52.6	5.6	41.8	85.3	14.2	0.5	6	
4 (PR)	53.5	5.1	41.3	81	19	0	5	
5 (BPT)	53.6	5.0	41.4	81	19	0	7	
6 (UT)	53.6	5.0	41.4	69	31	0	7	
7 (TIR)	53.7	5.0	41.3	0	0	100	6	
8 (ER)	53.7	4.1	42.2	62.2	37.7	0.1	6	
9 (FLONA)	52.5	4.5	42.9	87	9	4	4	
10 (RIT)	52.6	4.4	43	83.5	16.5	0	5	
11 (IBIT)	53.4	3.8	42.8	93.5	6.4	0.1	5	

Table 2: Longitudinal distribution of water chemistry variables (median values) along 11 sampling stations in the Rio das Mortes during the dry season. Different uppercase letters indicate significant differences (ANOVA, p<0.05, followed by the Tukey HSD Test, p<0.05).

Sampling station	T (°C)	рН	SC (µS cm ⁻¹)	DO (mg L ⁻¹)	DO sat.	SRP (µg L- ¹)	NH4-N (μg L ⁻¹)	NO ₃ +NO ₂ -N (μg L ⁻¹)	DIN (μg L ⁻¹)
1	14.3 ^A	6.5	18 ^A	8.6	86	6.7 ^A	123.1 ^A	108.9 ^A	408.4 ^A
2	14.8^{B}	6.6	40^{B}	8.4	87	14.6^{B}	328.7^{B}	362.2^{B}	$686.4^{\rm B}$
3	16.8 ^B	7.3	43^{B}	9.2	86	13.8^{B}	366.2^{B}	440.4^{B}	717.9^{B}
4	17.4 ^B	7.4	46^{B}	8.5	89	10.2^{B}	206.0^{B}	469.2 ^B	$705.2^{\rm B}$
5	17.4 ^B	7.5	48^{B}	8.3	89	12.3 ^B	220.4^{B}	533.1 ^B	753.5^{B}
6	18.5 ^B	7.5	50^{B}	8.3	88	9.8^{B}	246.8^{B}	421.9 ^B	668.7^{B}
7	16.7 ^B	7.3	56^{B}	8.6	97	12.3^{B}	288.0^{B}	464.3 ^B	752.3^{B}
8	16.7 ^B	7.4	49^{B}	8.5	88	13.1^{B}	117.7 ^B	358.7^{B}	521.5 ^B
9	16.1 ^B	7.5	48^{B}	8.2	88	15.9 ^B	260.8^{B}	338^{B}	690.1 ^B
10	16.5 ^B	7.6	45^{B}	8.6	92	13.3^{B}	218.0^{B}	432.6^{B}	594.9 ^B
11	17.6 ^B	6.9	42 ^B	8.3	93	12.3 ^B	79.3 ^A	414.5 ^B	531.7 ^B

Table 3: Longitudinal distribution of water chemistry variables (median values) along 11 sampling stations in the Rio das Mortes during the rainy season. Different uppercase letters indicate significant differences (ANOVA, p<0.05, followed by the Tukey HSD Test, p<0.05).

Sampling station	T (°C)	рН	SC (µS cm ⁻¹)	DO (mg L ⁻¹)	DO sat.	SRP (µg L- ¹)	NH4-N (μg L ⁻¹)	NO ₃ +NO ₂ -N (μg L ⁻¹)	DIN (μg L ⁻¹)
1	19.3 ^A	6.5 ^A	17 ^A	7.5	82	1.3 ^A	29.3 ^A	45.8 ^A	1036.9 ^A
2	20.2^{B}	7.2^{B}	38^{B}	6.7	74	7.1^{B}	36.7^{B}	211.9 ^B	1167.5 ^B
3	21.4^{B}	7.7^{B}	7.9 ^A	7.9	90	1.4 ^A	123.2^{B}	512.9 ^B	1258.1 ^B
4	21.1 ^B	7.5^{B}	50^{B}	7.3	82	3.2^{B}	70.1^{B}	317.2^{B}	1194 ^B
5	21.7^{B}	7.9^{B}	47^{B}	7.2	81	3.9^{B}	87.1 ^B	439.2^{B}	1135.5 ^B
6	21.2^{B}	7.7^{B}	48^{B}	7.3	84	4.3^{B}	117.7^{B}	342.6^{B}	1611.5 ^B
7	22.2^{B}	7.1^{B}	47^{B}	7.4	83	3.8^{B}	204.8^{B}	362.1 ^B	1276.2 ^B
8	21^{B}	7.7^{B}	42^{B}	7.3	84	4^{B}	135.4 ^B	251.5^{B}	1614.5 ^B
9	18.3 ^B	7.5^{B}	37^{B}	7.5	84	2.6^{B}	116.2 ^B	222.8^{B}	1252.7 ^B
10	21^{B}	6.8^{B}	35^{B}	7.9	89	5.3 ^B	79.5^{B}	214.8 ^B	1279.4 ^B
11	21.9 ^B	7.8^{B}	37^{B}	7.5	86	4.3 ^B	38.1^{B}	256.1 ^B	1287.3 ^B

Agricultural cover, the most important land-use type in the river catchment, was positively correlated to the percentage of pebbles (Spearman-Rank correlation, r=0.57, p<0.05) and negatively with the percentage of silt (Spearman-Rank correlation, r=-0.61) in the sediment. Accordingly, agricultural land use in the river catchment may affect sediment structure in the main channel, probably due to margin erosion and clear-cutting of riparian zones for plantation purposes (WALLING, 1999). However, agricultural land use had no measurable effects on nutrient concentrations in the water. No significant correlations were detected between agricultural land use and nitrogen forms of nutrients, suggesting that nutrient export to the main channel from agricultural areas in Rio das Mortes catchment were negligible. Nutrient export from agricultural areas to the main river was probably regulated by the river catchment's buffering capacity, as already observed for sediment exports (WALLING, 1999).

Despite its small contribution to whole-catchment land cover, urban land use, rather than agriculture, was correlated to DIN concentrations (Spearman-Rank correlation, r=0.59, p<0.05), suggesting that urbanisation may have more severe effects on nitrogen availability than agriculture in the studied catchment. Urbanisation was also the most critical stressor in previous studies regarding water chemistry and river saprobity level (SPONSELLER et al., 2001; GÜCKER et al., 2016). Fatty acid analysis of the suspended particulate organic matter of the Rio das Mortes revealed a predominance of human faecal material and kitchen oils in the water, especially in segments near larger urban centres (BOËCHAT et al., 2014). Therefore, it appears that, despite the large areas occupied by pasture and agriculture in Brazil, urbanisation is more deleterious than other land use types for water quality and ecosystem functioning of similar Brazilian river systems (OMETO et al., 2000). Urbanisation also increased dissolved organic nitrogen (DON) concentrations more strongly in highly urbanised Neotropical catchments than in urbanised temperate catchments, due to the absence of efficient wastewater treatment in many tropical regions and the widespread implementation of tertiary wastewater treatment in temperate regions (GÜCKER et al., 2016). In our study, urbanisation was also the only land-use type positively correlated to the river integrity score (Spearman-Rank correlation, r=0.51, p<0.05), confirming a direct relationship between catchment urbanisation and in-stream structural degradation, already reported by other studies (LENAT AND CRAWFORD, 1994; SPONSELLER et al., 2001).

3.2. Temporal and spatial changes in the benthic invertebrate community

Despite differences in its spatial distribution, described later in this section, the benthic invertebrate community showed a similar *taxa* composition in both sampling seasons. In the dry season, the identified benthic invertebrates were distributed into 33 *taxa*, whereas 32 *taxa* were

identified during the rainy season, from which 26 taxa were also found during the dry season. Significant differences were found for benthic macroinvertebrate densities between seasons and among sampling stations within seasons (ANOVA, p<0.05). In the dry season, higher total density values were observed for all macroinvertebrate variables than in the rainy season (ANOVA, p<0.05; Figure 2). In the dry season, total macroinvertebrate density and Chironomidae density were higher at the upstream stations than at middle sections (3-6), and again higher at station 7 than at middle and downstream stations (8-11; ANOVA and Tukey HSD-test, p<0.05; Figure 2a). Oligochaeta density was higher at station 2 than at all other stations, except for station 9 (ANOVA and Tukey HSD-test, p<0.05; Figure 2a). Station 2 was the first truly urbanised station in our dataset, and Oligochaeta are frequently reported to be abundant in urban streams (LENAT AND CRAWFORD, 1994). No significant differences were found for EPT densities among sampling stations (ANOVA, p>0.05; Figure 2a). In general, less significant differences among stations were observed during the rainy season, possibly due to hydrodynamic disturbance due to frequent stormflow events that also resulted in overall low invertebrate densities. During the rainy season, total density and density of Oligochaeta did not differ among stations (ANOVA and Tukey HSD-test, p>0.05; Figure 2b). Chironomidae densities were higher at headwater stations 1 and 2, and station 9 than at all other stations (ANOVA and Tukey HSD-test, p<0.05; Figure 2b). Densities of EPT were also higher at station 9 than at all other stations (ANOVA and Tukey HSD-test, p<0.05; Figure 2b).

As Chironomidae were the dominant group in the river benthic community (Figure 2), from headwater to river mouth, significant changes in total invertebrate density were mostly associated with changes in Chironomidae densities, in both seasons. Rather similar microhabitat conditions along the river could be the reason for the dominance of Chironomidae, as sandy sediments dominated substrate structure at all stations except for the headwater and TIR stations. This pattern has already been demonstrated in a previous study, in which the response of benthic invertebrate density, biomass and secondary production among sampling stations along the Rio das Mortes were compared in a single year (AGUIAR *et al.*, 2015). Whenever present, longitudinal changes in the invertebrate community were mainly associated with the relative contribution of sandy sediment. This pattern may be pervasive in the erosion-prone, mainly sand-bottomed river systems in the Brazilian Cerrado savannah and Atlantic forest.

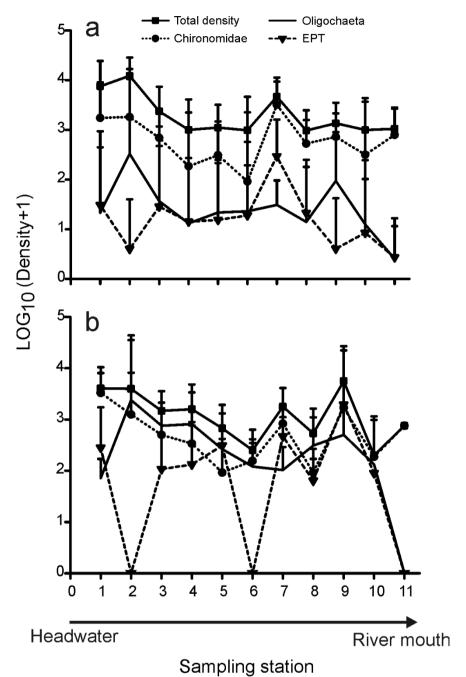


Figure 2: Longitudinal changes (mean ± 1 SD) in total density of benthic invertebrates during (a) the dry and (b) the rainy season in the Rio das Mortes.

3.3. Longitudinal changes in water quality, sediment structure, river structural integrity and benthic macroinvertebrates – landscape versus habitat effects

The PCAs run separately for the dry and the rainy seasons (Figure 3, table 4) showed on the first axis that headwater segments of the river (stations 1 and 2) were different from all other river segments when all investigated variables were analysed together. These stations had the highest total macroinvertebrate density (during the dry season), the highest Chironomid density (in both seasons), and the highest structural integrity (i.e., the lowest river integrity scores) among all stations. The first

axis separated middle-segment stations from headwater stations. These stations had high nitrogen levels and the lowest river integrity among all stations and high proportions of urban land use compared to the river's headwater and final segments (table 1). Therefore, intermediate sampling stations were plotted together in the PCAs, suggesting that urbanisation may be strongly associated to water quality variables and the river structural integrity, and supporting the view that urbanisation is currently a major stressor to river integrity in South-eastern and Central Brazil (OMETO *et al.*, 2000; GÜCKER *et al.*, 2016).

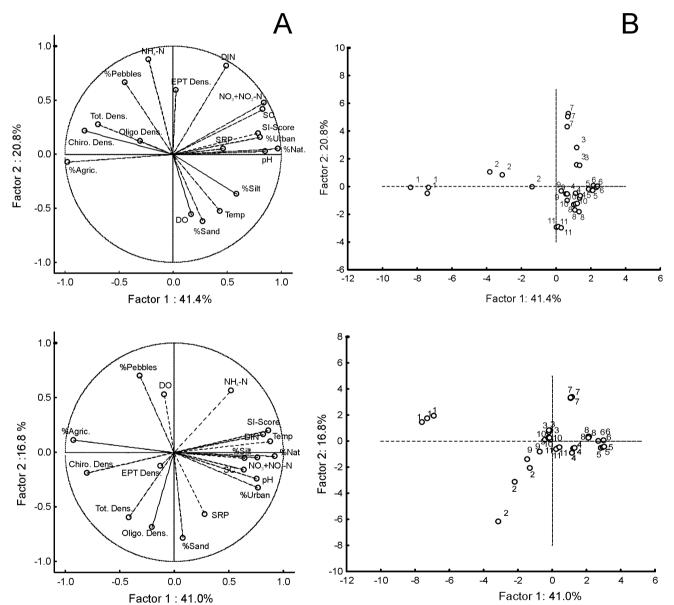


Figure 3: PCAs for water quality, sediment structure, river structural integrity, and macroinvertebrate variables in the Rio das Mortes during the dry (upper panels) and the rainy (lower panels) season. (A) variable tendencies along each axis extracted by the PCAs. (B) Longitudinal gradients of the 11 sampling stations.

Table 4:. Statistical parameters of the PCAs run separately for the dry and the rainy season.

	Dry season		Rainy season			
	1st axis	2 nd axis	1st axis	2 nd axis		
Variables contribution	Total density (-0.69)	EPT density (0.60)	Chironomidae density (-0.79)	Total density (-0.60)		
(scores-correlation	Chironomidae density (-0.81)	%Sand (-0.62)	Temp (0.88)	Oligochaeta density (-0.69)		
matrix)	%Silt (0.60)	%Pebbles (0.66)	NO_3+NO_2-N (0.76)	%Sand (-0.79)		
	SC (0.83)	NH ₄ -N (0.87)	DIN (0.86)	% Pebbles (0.69)		
	NO ₃ +NO ₂ -N (0.84)	DIN (0.82)	River integrity score (0.86)	NH ₄ -N (0.56)		
	River integrity score (0.79)		%Urban (0.76)			
	%Urban (0.81)		%Agric (-0.92)			
	%Agric (-0.97)					
Eigenvalue	7.87	3.95	7.79	3.19		
Extracted variation (%)	41.4	20.8	41.0	16.8		
Cumulative extracted	41.4	62.2	41.0	57.8		
variation (%)						

While this general pattern of land-use impact was expected, stations that did not entirely fit the presented pattern in the ordination (stations 2, 7, and 9) provided interesting information on the role of local habitat heterogeneity. Headwater station 2 showed high structural integrity and invertebrate densities, but in contrast to headwater station 1, sandy sediments and high densities of Oligochaeta (table 1) and was thus found at an intermediate position in axis 1 (Figure 3). Midstream station 7 (TIR) was isolated from the other stations in the ordinations. This urbanised station had high DIN concentrations and low structural integrity but was dominated by pebbled sediment and showed high EPT densities. Moreover, during the rainy season, benthic invertebrate densities were also high at station 9, especially those of the dominant Chironomids, but also EPT. Station 9 was the only station located in a protected area in the National Forest Park of Ritápolis (FLONA), which was the reason for the best structural integrity attributed to this station among lower river section stations. However, the fact that station 9 was located in a protected area had no considerable effect on nutrient concentrations or sediment structure (tables 1-3), placing station 9 together with other intermediate stations in the PCA plot. Nevertheless, intact margin conditions and the presence of a larger and nearnatural riparian zone at station 9, may have been responsible for the high densities of Chironomidae and EPT, a group considered sensitive to environmental impacts (CORTES et al., 2013).

These exceptions from the general land-use pattern—i.e., mainly urbanisation-related effects on river water quality and biochemistry, as well as structural integrity—we found, suggest that local, small-scale differences in river structural integrity and sediment structure must be considered, and may even be a more critical factor for the benthic invertebrate community than general water quality or catchment land-use patterns (SPONSELLER et al., 2001) in this and other tropical rivers. Thus, our results support the idea that local restoration of hydromorphology, habitat heterogeneity and riparian vegetation may already lead to considerable improvements in nearby reaches of impacted rivers. Regarding monitoring practices, water quality and biochemistry seemed to be a better indicator of urbanisation in the river catchment. In contrast, invertebrate variables were better indicators of local microhabitat structural changes, directly or indirectly caused by agricultural land-use practices in the river catchment, including deforestation of the riparian zone and margin erosion, with consequent increases of sandy sediments (MONTEIRO et al., 2016). Albeit rarely performed by responsible water management agencies in tropical regions, complementary assessments of landscape-wide and local impacts on river ecosystems, appear to be justified to devise effective and realistic strategies for mitigating land-use impacts on tropical rivers.

ACKNOWLEDGMENTS

The authors thank numerous undergraduate and graduate for their help with sampling. This study was supported by the Fundação de Amparo à Pesquisa no Estado de Minas Gerais (FAPEMIG; project number APQ-01619-09) and by a CNPq fellowship to A.P.M.V. Mattos (PIBIC-CNPq-UFSJ). I. G. Boëchat and B. Gücker were supported through productivity grants by the Brazilian National Council for Scientific and Technological Development (CNPq 302280/2015-4 and 302492/2015-1).

REFERENCES

AGUIAR, A. C. F.; GÜCKER, B.; BRAUNS, M.; HILLE, S.; BOËCHAT, I. G. Benthic invertebrate density, biomass, and instantaneous secondary production along a fifth-order human-impacted tropical river. **Environmental Science and Pollution Research**, v. 22, p. 9864–9876, 2015.

ALLAN, J. D. Landscapes and Riverscapes: The Influence of Land Use on Stream Ecosystems. **Annual Review in Ecology, Evolution and Systematics**, v. 35, p. 257–284, 2004.

ALLINSON, G.; ZHANG, P.; BUI, A.; ALLINSON, M.; ROSE, G.; MARSHALL, S.; PETTIGROVE, V. Pesticide and trace metal occurrence and aquatic benchmark exceedances in surface waters and sediments of urban wetlands and retention ponds in Melbourne, Australia. **Environmental Science and Pollution Research,** v. 22, p. 10214–10226, 2015.

APHA. Standard Methods for the Examination of Water and Wastewater. American Public Health Association, American Waterworks Association, and Water Environment Association, Washington, 1995.

BIRK, S.; CHAPMAN, D.; CARVALHO, L., *et al.* Impacts of multiple stressors on freshwater biota across spatial scales and ecosystems. **Nature Ecology and Evolution**, v. 4, p. 1060–1068, 2020.

BOËCHAT, I. G.; PAIVA, A. B. M.; HILLE, S.; GÜCKER, B. Land-use effects on river habitat quality and sediment granulometry along a 4th-order tropical river. **Ambiente e Água**, v. 8, p. 54–64, 2013.

BOËCHAT, I. G.; KRÜGER, A.; CHAVES, R. C.; GRAEBER, D.; GÜCKER, B. Land-use impacts on fatty acid profiles of suspended particulate organic matter along a larger tropical river. **Science of the Total Environment**, v. 482-483, p. 62–70, 2014.

BUSS, D. F.; VITORINO, A. S. Rapid Bioassessment Protocols using benthic macroinvertebrates in Brazil: evaluation of taxonomic sufficiency. **Journal of the North American Benthological Society**, v. 29, p. 562–571, 2010.

CALLISTO, M.; MORENO, P.; BARBOSA, F. A. R. Habitat diversity and benthic functional trophic groups at Serra do Cipó, Southeast Brazil. **Brazilian Journal of Biology**, v. 61, p. 259–266, 2001.

CALLISTO, M.; GOULART, M.; MEDEIROS, A. O.; MORENO, P.; ROSA, C. A. Diversity assessment of benthic macroinvertebrates, yeasts, and microbiological indicators along a longitudinal gradient in Serra do Cipó, Brazil. **Brazilian Journal of Biology**, v. 64, p. 743–755, 2005.

CARPENTER, S. R.; CARACO, N. F.; CORRELL, D. L.; HOWARTH, R. W.; SHARPLEY, A. N.; SMITH, V. H. Nonpoint pollution of surface waters with phosphorus and nitrogen. **Ecological Applications**, v. 8, p. 559–569, 1998.

CORTES, R. M. V.; HUGHES, S. J.; PEREIRA, V. R.; VARANDAS, S. G. P. Tools for bioindicator assessment in rivers: The importance of spatial scale, land use patterns and biotic integration. **Ecological Indicators**, v. 34, p. 460-477, 2013.

CUMMINS, K. W.; KLUG, M. J. Feeding ecology of stream invertebrates. **Annual Review in Ecology and Systematics**, v. 10, p. 147–172, 1979.

CUMMINS, K. W.; MERRITT, R. W.; ANDRADE, P. C. N. The use of invertebrate functional groups to characterize ecosystem attributes in selected streams and rivers in south Brazil. **Studies on Neotropical Fauna and Environment**, v. 40, p. 69–89, 2005.

DODDS, W. Eutrophication and trophic state in streams and rivers. **Limnology and Oceanography**, v. 51, p. 671–680, 2006.

DOMÍNGUEZ, E.; MOLINERI, C.; PESCADOR, M.; HUBBARD, M. D.; NIETO, C. **Ephemeroptera of South America**. Pensoft, Bulgaria, 2006. 646p.

FLINT, JR. O. S. Studies of Neotropical caddisflies, XXXIII: new species from austral South America (Trichoptera). **Smithsonian Contributions in Zoology**, v. 377, p. 1–100, 1983.

GRAEBER, D.; BOËCHAT, I. G.; ENCINA-MONTOYA, F.; ESSE, C.; GELBRECHT, J.; GOYENOLA, G.; GÜCKER, B.; HEINZ, M.; KRONVANG, B.; MEERHOFF, M.; NIMPTSCH, J.; PUSCH, M. T.; SILVA, R. C. S.; VON SCHILLER, D.; ZWIRNMANN, E. Global effects of agriculture on fluvial dissolved organic matter. **Scientific Report**, v. 5, p. 16328, 2015.

GÜCKER, B.; BOËCHAT, I. G.; GIANI, A. Impacts of agricultural land use on ecosystem structure and whole-stream metabolism of tropical Cerrado streams. **Freshwater Biology**, v. 54, p. 2069–2085, 2009.

GÜCKER, B.; SILVA, R. C. S.; GRAEBER, D.; MONTEIRO, J. A. F.; BROOKSHIRE, E. N. J.; CHAVES, R. C.; BOËCHAT, I. G. Dissolved nutrient exports from natural and human-impacted Neotropical catchments. **Global Ecology and Biogeography**, v. 25, p. 378–390, 2016.

HEPP, L. U.; SANTOS, S. Benthic communities of streams related to different land uses in a hydrographic basin in southern Brazil. **Environmental Monitoring Assessment,** v. 157, p. 305–318, 2009.

IBGE – INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA. Contagem da **População**. Ministério do Planejamento, Orçamento e Gestão, Governo Brasileiro, 2007.

IGAM – INSTITUTO MINEIRO DE GESTÃO DE ÁGUAS. Relatório: monitoramento das águas superficiais na bacia do Rio Grande em 2005. Projeto Águas de Minas, Belo Horizonte, 2005.

KAMP, U.; BINDER, W.; HÖLZL, K. River habitat monitoring and assessment in Germany. **Environmental Monitoring Assessment**, v. 127, p. 209–226, 2007.

- KARATAYEV, A. Y.; BURLAKOVA, L. E.; DODSON, S. I. Community analysis of Belarusian lakes: relationship of species diversity to morphology, hydrology and land use. **Journal of Plankton Research**, v. 27, p. 1045–1053, 2005.
- LENAT, D. R.; CRAWFORD, J. K. Effects of land use on water quality and aquatic biota of three North Carolina Piedmont streams. **Hydrobiologia**, v. 294, p. 185–199, 1994.
- MERRIT, R. W.; CUMMINS, K. W. An introduction to the aquatic insects of North America. Iowa: Kendall/Hunt Publishing Company, 1996. 1498p.
- MONTEIRO, J. A. F.; KAMALI, B.; SRINIVASAN, R.; ABBASPOUR, K.; GÜCKER, B. Modelling the effect of riparian vegetation restoration on sediment transport in a human-impacted Brazilian catchment. **Ecohydrology**, v. 9, n. 7, p. 1289-1303, 2016.
- MUGNAI, R.; NESSIMIAN, J. L.; BAPTISTA, D. F. Manual de identificação de macroinvertebrados aquáticos do estado do Rio de Janeiro. Rio de Janeiro: Technical Books Ed., 2010. 174p.
- NESSIMIAN, J. L.; VENTICINQUE, E. M.; ZUANON, J.; DE MARCO JR, P.; GORDO, M.; FIDELIS, L.; BATISTA, J. D'ARC; JUEN, L. Land use, habitat integrity and aquatic insect assemblages in central Amazonian streams. **Hydrobiologia**, v. 614, p. 117–131, 2008.
- OMETO, J. P. H. B.; MARTINELLI, L. A.; BALLESTER, M. V.; GESSNER, A.; KRUSCHE, A. V.; VICTORIA, R. L.; WILLIAMS, M. Effects of land use on water chemistry and macroinvertebrates in two streams of the Piracicaba river basin, south-east Brazil. **Freshwater Biology**, v. 44, p. 327–337, 2000.
- PASSOS, M. I. S.; NESSIMIAN, J. L.; FERREIRA, JR. N. Chaves para identificação dos gêneros de Elmidae (Coleoptera) ocorrentes no estado do Rio de Janeiro. **Revista Brasileira de Entomologia**, v. 51, p. 42–53, 2007.
- PES, A. M. O.; HAMADA, N.; NESSIMIAN, J. L. Chaves de identificação de larvas para famílias e gêneros de Trichoptera (Insecta) da Amazônia Central, Brasil. **Revista Brasileira de Entomologia**, v. 49, p. 181–204, 2005.
- PIMPÃO, D. M.; MANSUR, M. C. D. Chave pictórica para identificação dos bivalves do baixo Rio Aripuanã, Amazonas, Brasil (Sphaeriidae, Hyriidae e Mycetopodidae). **Biota Neotropica**, v. 9, p. 377–384, 2009.
- QUANTUM GIS DEVELOPMENT TEAM. Quantum GIS Geographic Information System. Open Source Geospatial Foundation Project, 2013. Available: http://qgis.osgeo.org.
- RAMIREZ, A.; PRINGLE, C.; WANTZEN, M. K. Tropical stream conservation. In: Dudgeon, D. (ed.) **Tropical stream ecology**. Academic Press, p. 285–305, 2008.
- REYNOLDS, C. S.; HUSZAR, V.; KRUBK, C.; NASELLI-FLORES, L.; MELO, S. Towards a functional classification of the freshwater phytoplankton. **Journal of Plankton Research**, v. 2, p. 417–428, 2002.
- RIZO-PATRÓN, F. V.; KUMAR, A.; COLTON, M. B. M. C. C.; SPRINGER, M.; TRAMA, F. A. Macroinvertebrate communities as bioindicators of water quality in conventional and organic irrigated rice fields in Guanacaste, Costa Rica. **Ecological Indicators**, v. 29, p. 68–78, 2013.

SCHINDLER, D. W. Recent advances in the understanding and management of eutrophication. Limnology and Oceanography, v. 51, p. 356–363, 2006.

SILVA-JUNIOR, E. F.; MOULTON, T. P.; BOËCHAT, I. G.; GÜCKER, B. Leaf decomposition and ecosystem metabolism as functional indicators of land use impacts on tropical streams. **Ecological Indicators**, v. 36, p. 195–204, 2014.

SILVEIRA, M. P.; BAPTISTA, D. F.; BUSS, D. F.; NESSIMIAN, J. L.; EGLER, M. Application of biological measures for stream integrity assessment in south-east Brazil. **Environmental Monitoring Assessment**, v. 101, p. 117–128, 2005.

SMITH, V. H.; JOYE, S. B.; HOWARTH, R. W. Eutrophication of freshwater and marine ecosystems. Limnology and Oceanography, v. 51, p. 351–355, 2006.

SOLIMINI, A. G.; PTACNIK, R.; CARDOSO, A. C. Towards holistic assessment of the functioning of ecosystems under the Water Framework Directive. **TRAC Trends in Analytical Chemistry**, v. 28, p. 143-149, 2009.

SPÄNHOFF, B.; BISCHOF, R.; BÖHME, A.; LORENZ, S.; NEUMEISTER, K.; NÖTHLICH, A.; & KÜSEL, A. Assessing the impact of effluents from a modern wastewater treatment plant on breakdown of coarse particulate organic matter and benthic macroinvertebrates in a lowland river. **Water, Air, and Soil Pollution**, v. 180, p. 119–129, 2007.

SPONSELLER, R. A.; BENFIELD, E. F.; VALETT, H. M. Relationships between land use, spatial scale and stream macroinvertebrate communities. **Freshwater Biology**, v. 46, p. 1409–1424, 2001.

VITOUSEK P. M.; ABER J. D.; HOWARTH R. W.; LIKENS G. E.; MATSON P. A.; SCHINDLER D. W.; SCHLESINGER W. H.; & TILMAN D. G. Human alteration of the global nitrogen cycle: sources and consequences. **Ecological Applications**, v. 7, p. 737–750, 1997.

WALLING, D. E. Linking land use, erosion and sediment yields in river basins. **Developments in Hydrobiology**, v. 146, p. 223–240, 1999.

WALSH, C. J.; ROY, A. H.; FEMINELLA, J. W.; COTTINGHAM, P. D.; GROFFMAN, P. M.; MORGAN II, R. P. The urban stream syndrome: current knowledge and the search for a cure. **Journal of the North American Benthological Society**, v. 24, p. 706–723, 2005.

YONKOS, L. T.; FRIEDEL, E. A.; PEREZ-REYES, A. C.; GHOSAL, S.; ARTHUR, C. D. Microplastics in four estuarine rivers in the Chesapeake Bay, U.S.A. **Environmental Science and Technology**, v. 48, p. 14195–14202, 2014.

YOU, L.; NGUYEN, V. T.; PAL, A.; CHEN, H.; HE, Y.; REINHARD, M.; GIN, K. Y. H. Investigation of pharmaceuticals, personal care products and endocrine disrupting chemicals in a tropical urban catchment and the influence of environmental factors. **Science of the Total Environment**, v. 536, p. 955–963, 2015.