Urban Ecosystems (2020) 23:133–145
https://doi.org/10.1007/s11252-019-00898-y

Concrete lined urban streams and macroinvertebrates: a Hong Kong case study

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Published online: 31 August 2019
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Abstract

In this study an urban stream network with earthen and concreted sections were studied for different seasons (wet and dry) to investigate the macroinvertebrate composition and the governing factors. The factors considered were water quality (nitrogen species, soluble reactive phosphorus etc.) and stream eco-hydraulics (velocity, wetted depth and width, vegetative indicators, number of mesoscale physical habitats, etc.). In contrast to common perception, results showed that concrete lined sites are not ecologically dead. Even though low, concrete line section had viable populations of macroinvertebrates and importantly a few native species. Interestingly, some macroinvertebrate indices of the concrete lined sites did not show a significant difference with the earthen sites. About 60% of the macroinvertebrates were grazers and filterers, and these two group populations always showed an inverse relationship. Earthen and concrete lined sites had similar diversities, but for different reasons. In general earthen sites diversity and pollution tolerance index of macroinvertebrates (PTI) was positively correlated, but no uniform correlation was observed in concrete lined sites. Some concrete lined sites with high diversity showed low PTIs (i.e. high diversity as a result of many types of pollution tolerant species) whereas in some the high diversity associated with high PTIs. Macroinvertebrate composition and the influencing factors were to a greater degree section dependent and to a lesser extent were dependent on the season. Physical heterogeneity played an important role in the macroinvertebrate responses in earthen sites. Water quality and flow rate explained comprehensively, the variations in the concrete lined sites. Results proved that nutrient levels need to be limited and instream heterogeneity needs to be improved to enhance diversity and populations of pollution intolerant species. Also, controlled vegetation harvesting is recommended in contrast to the current practice of complete removal for flow conveyance.

Keywords Concrete lined streams · Macroinvertebrates · Physical heterogeneity · Water quality

Introduction

Lotic ecosystems in the form of rivers and streams are characterized by unidirectional flow, state of continuous physical change, and spatiotemporal variation in biota in a pristine environment, and are one of the highest valued ecosystems (Costanza et al. 1997). The interaction and influence with human settlements greatly shape the characteristics of lotic waters, and rivers are being regulated since several centuries back (Decamps et al. 1988). River regulation can be in different forms such as dam construction, water extraction, gravel mining, and channel straightening (Gomes and Wai 2014). Straightening of meandered or braided channels is common in urban areas. Channel straightening could be more extremely done by burring, and/or concrete lining. Concrete lined channels convey storm water efficiently through narrow populated areas, thereby minimize flooding and erosion problems. However, such regulated streams support only a fraction of their original biodiversity and species abundance. These types of regulated streams are common in many urban areas such as Hong Kong and Singapore. In fact about one third of the second or higher order streams are concrete lined in Hong Kong. A few decades back, an economic development oriented urban society expected their streams and/or rivers to perform for flood control only. However, with enhanced education, citizens started thinking differently about regulated waterways (Nakamura et al. 2006). This led to sustainable urban stream/river designs that tried to harmonize flood control and rich biota. Such harmonization is not easy as rich biota often

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needs increased instream physical diversity and/or vegetation, which eventually increase bed friction therein by sacrificing flood safety. Nowadays, having urban waterway that has some features of a pristine stream is one of the objectives of city planners. Recent projects such as Cheonggyecheon stream rehabilitation in Korea is a good example, that governments are ready to invest heavily in such projects (Bae 2011).

In Hong Kong, attempts have been made by government departments to enhance the recreational value of concrete lined streams in recent years (Chan and Lau 2017), with the ultimate objective of working towards achieving self-sustainable channel systems. However, the ecology of concrete lined streams are less known compared with natural streams or streams that are subject to minor to moderate regulation, and is worth to in depth study. The other issues related to rehabilitation of concrete lined streams include, perception on such waters as ecologically dead, and difficulties associated in deriving baseline (reference or target) conditions. Identification of rehabilitation targets is a must in any rehabilitation program. However, most of the concrete lined streams such as the ones in Hong Kong are several decades old with no records of the pristine state before the regulation. Therefore, the target conditions either be derived based on optimum conditions from the study area itself or need to identify a stream that can be used as a reference from elsewhere.

The first objective of this 3 year study was to challenge the common perspective that concrete lined streams in Hong Kong are ecologically dead. Fully or partially due to this perception, it was observed concrete lined streams are used for expedient wastewater discharge. Therefore, only usefulness that public as well as some government departments' see of these streams is when the catchment is flood prone. Knowing life is present, would trigger the idea that it is possible and worth to rehabilitate concrete lined streams. Furthermore, studies targeting macroinvertebrates, diatoms, and similar fauna on urban water systems are scarce (Vermonden et al. 2009) and rather unfound for completely concrete lined streams which is a characteristic of many urban areas. The second objective of this study was to identify factors that corresponded with macroinvertebrate composition (irrespective whether macroinvertebrates are native or invasive, pollution tolerant or intolerant and so forth), and factors that related with acceptable or desired macroinvertebrate compositions (e.g. macroinvertebrates that are representatives of good water quality).

Materials and methods

Study area

Hong Kong is a small region, therefore do not have many large rivers. The larger rivers are mainly located in the northwest region. Shan Pui River, Shenzhen River, Kam Tin River, Sheung Yue River, and Ng Tung River are some examples of large rivers in Hong Kong (Hong Kong River net, 2017). Hong Kong has contrasting wet and dry seasons, where more than 80% of the mean annual rainfall occurs during the hot, humid wet season between May and September (Gomes and Wai 2014).

This study has been carried out in the northwest region of Hong Kong (Fig. 1). Sampling has been conducted in two (Tin Shui Wai Nullah and Shan Pui River) out of the three main drainage conduits in the study area (Kam Tin River was excluded).

Shan Pui Rivers (a total catchment of ~ 27 km^2 and drains to Deep bay) part of upper course and the entire mid-course (which is about 50% of the rivers entire length) are completely concrete lined, and referred as Yuen Long Town Nullahs. The nullahs in Yuen Long town are part of the oldest drainage systems in the territory, constructed in the early 1960's to alleviate floods (Chan and Lau 2017). Many of the nullahs are originated from natural watercourses, which over the years have been straightened and provided with concrete lined beds and banks. Upstream sections are earthen, but subject to anthropogenic disturbances such as wastewater discharges. The original stream sources no longer supply water to Shan Pui River and Tin Shui Wai nullah, due to regulation by catchwater channels and irrigation reservoirs. Lower course of the Shan Pui River was a tidal section and currently separated via an inflatable dam built near Shan Pui Chung Hau Tsuen, and no saline or brackish water comes towards upstream of the dam. Therefore, our sampling areas were strictly fresh water. The land use of middle and downstream sections were mainly residential and industrial, whereas upstream sections rural but also with a few food processing industries.

Tin Shui Wai nullah has a total catchment of about 14 km^2 and also drains to Deep Bay. Same as Shan Pui River the mid to downstream sections are concrete lined. The land use in the concrete lined sections of Tin Shui Wai nullah was similar to the concrete lined sections of Shan Pui River. The earthen sections of Tin Shui Wai nullah are subject to regulation by water structures such as weirs and dams throughout the stream course making it contrastingly different to earthen sections of Shan Pui river, therefore, did not consider in sampling.

Sampling methods

Sample locations and schedule

In total 20 reaches (sites) equally distributed between earthen and concreted sections were selected for sampling. These sites were chosen after reconnaissance surveys and based on authors' knowledge of the area such that selected sites would give a best representation of earthen or concrete lined sections. Each site was about 50–100 m long. Table 1 gives the GPS

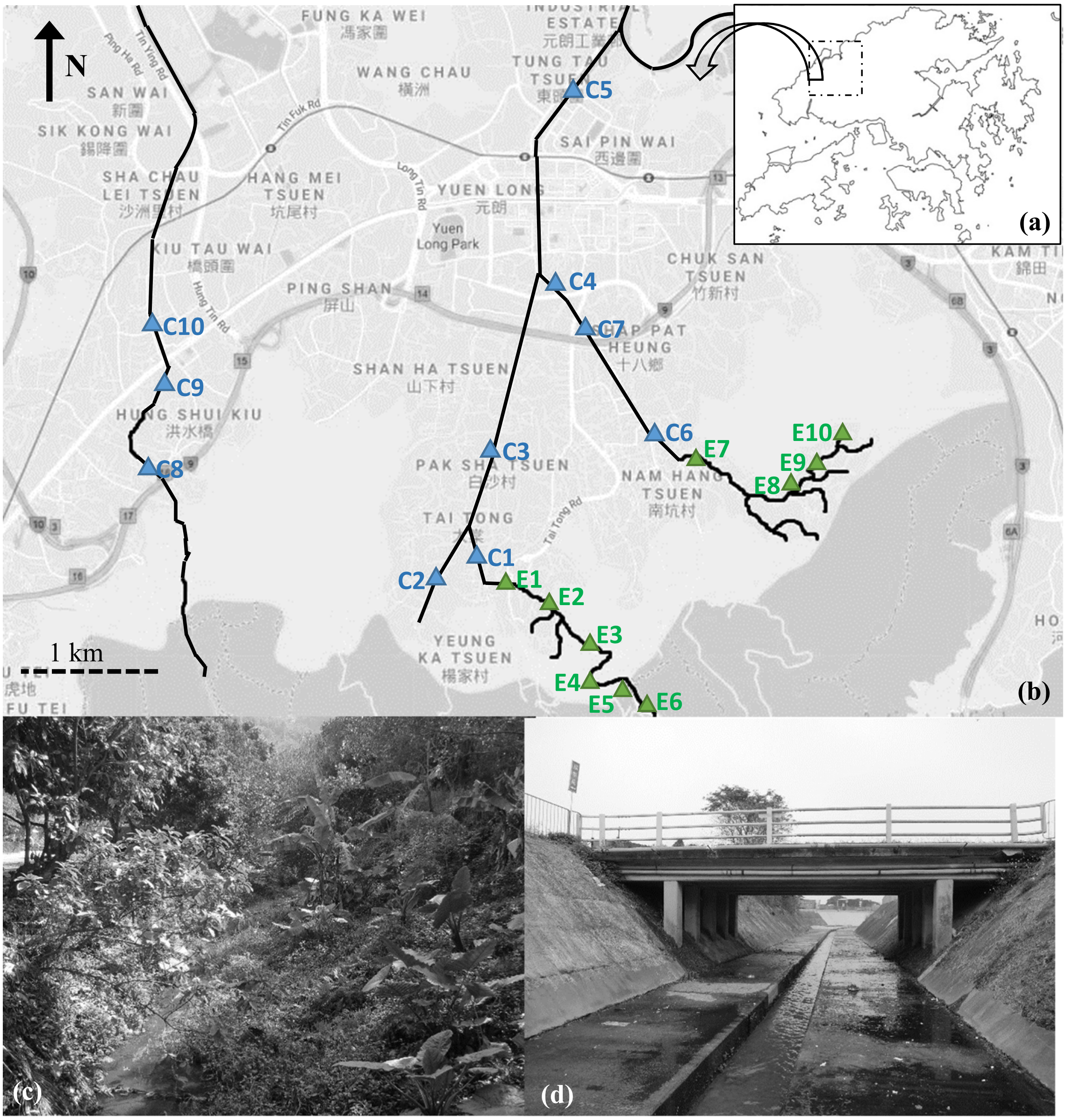

Fig. 1 Study area. **a** Map of Hong Kong; **b** Sampling locations (C and E are samples from concrete and earthen sections, respectively); **c** Sample E3; and **d** Sample C1

coordinates and eco-hydraulic descriptions of the selected sites. Sampling was carried out twice a year once each for wet and dry seasons. The first sampling was for dry season in 2014, and the last sampling was for wet season in 2016 (in total six sampling sessions). In all cases samplings days were selected to avoid extreme weather conditions and transition periods between seasons.

Macroinvertebrates sampling

Macroinvertebrates were sampled with a kick net by holding the net frame firmly against the channel bottom while disturbing the substrate upstream over a predetermined area (0.5 m × 0.5 m to 1 m × 1 m) by feet or a brush. The disturbed depth was about 0–5 cm (concrete lined sites in many cases were without soil/sediments). Before kicking, rocks (cobble size or larger) were picked and brushed all sides to the sampling tray to collect macroinvertebrates presented on them. In each site two places were sampled. These two locations were selected to cover the two major surface flow patterns (this was judged based on air-water interface area). As an example, if a site consisted of a pool and a riffle (which is the case for some earthen reaches), samples were taken from both of these locations. Macroinvertebrates were identified at least up to the respective taxonomic (genus) level, and whenever possible up to the species level. The macroinvertebrate diversity was realized via Shannon-Weiner index (Gomes and Asaeda 2009) using genus level data. All macroinvertebrates were assigned

Table 1 GPS coordinates of the samples

Sample/Reach	GPS coordinates	Sample/Reach	GPS coordinates
C1	22°25′2.57”N 114° 1′17.03″E	E1	22° 24′ 54”N 114° 1′ 20″E
C2	22°24′59.34”N 114° 1′4.30″E	E2	22° 24′ 42”N 114° 1′ 25″E
C3	22°25′35.66”N 114° 1′21.04″E	E3	22° 24′ 28”N 114° 1′ 32″E
C4	22°26′18.47”N 114° 1′36.11″E	E4	22° 24′ 24”N 114° 1′ 32″E
C5	22°27′11.15”N 114° 1′44.94″E	E5	22° 24′ 16”N 114° 1′ 42″E
C6	22°25′34.54”N 114° 2′9.92″E	E6	22°24′10.7”N 114°1′40.8″E
C7	22°26′4.60”N 114° 1′48.34″E	E7	22°25′20.7”N 114°2′30.4″E
C8	22°25′28.07”N 113°59′45.47″E	E8	22° 25′ 26”N 114° 2′ 53″E
C9	22°25′43.30”N 113°59′40.65″E	E9	22°25′28.9”N 114°2′58.9″E
C10	22°25′59.39”N 113°59′46.42″E	E10	22°25′34.9”N 114°2′57.7″E

a functional feeding group based on Wallace and Webster (1996). For each site, benthic macroinvertebrate richness (BMR), benthic macroinvertebrate pollution tolerance index (PTI; higher PTI more pollution intolerance) (Mitchell and Stapp 2000), and percent and total abundance of grazers, shredders, collectors, filterers and predators were calculated.

Water quality

Turbidity and electrical conductivity (EC) were measured using turbidity (2100 N HACH, USA) and conductivity (WTW 720 inoLab, Germany) meters, respectively. Chlorophyll-a (Chl-a) was measured by spectrophotometric method (APHA 1998). The filtrate of Chl-a (0.45 μm porosity, 47 mm diameter) was used for subsequent nitrate, nitrite, ammoniacal nitrogen, and soluble reactive phosphorus (SRP) analyses. Nitrogen species were measured by HACH methods using HACH pocket colorimeter (model DR/820, USA). Nitrate and nitrite were measured by cadmium reduction and ferrous sulphate methods, respectively (Gomes and Wai 2014). The HACH-ammonia salicylate (Cat No. 23953–66) reagent powders and ammonia cyanurate (Cat No. 23955–66) was used for ammoniacal nitrogen measurements (Gomes and Wai 2014). Sulphate and sulphide was measured using HACH reagent powders. Method proposed by Murphy and Riley (1962) was used to measure SRP.

A water quality index (WQI) was defined using weighed arithmetic index method (Brown et al. 1972). WQI will be used as a rating reflecting the composite influence of different water quality parameters on the overall quality of water. The WQI was computed through three steps, and seven water quality parameters (Table 2) were incorporated. First, each parameter was assigned a weight according to its relative importance in the overall quality of water (Table 2). These weights were taken from Abbasi and Abbasi (2012), but scaled such that the range of WQI remains 0 to 100 (higher the WQI better the water quality).

Geomorphology and hydraulics

Each site was sampled at two or three places along the centerline. These two or three places were decided based on homogeneity or heterogeneity of the site. Homogeneous sites such as most of the concrete lined sections with prismatic cross sections were sampled at two locations (mid points of bisects). Whereas sites with heterogeneous cross sections such as the ones with mesoscale physical habitats (pools and riffles) sampling was done at each habitat. As an example, one concerted site (D8) had a silt trap (i.e. a pool) followed by a homogenous segment, two times of the silt trap. One reading was taken from the silt trap and another two were taken from the homogenous segment. This was done to get a better representation of the site. In all cases velocity was measured at 0.6 of the depth using OTT C2 current meter (A. OTT, Kempten, Germany). Where the water depth was less than 5 cm, velocity was estimated according to float method (Herschy 1995). With velocity, water depth was observed using a steel ruler with the narrow edge in line with the flow. Observations were also made for wetted width and depth. Number of mesoscale habitats (MPH) (see; Gomes and Wai 2014 for a list of MPHs) per unit longitudinal length of a site were observed also. Mean particle size (D50) was obtained at a combination of manual measurements (for particles larger than or equal to gravel) and sieve analysis (particles finer than gravel) (Doll et al. 2003). Also, percent aerial cover by floating, submerged and emergent plants were observed.

Table 2 Water quality variables and weights used in water quality index

Water quality parameter	Weightage
Dissolved oxygen (%)	0.27
pH	0.17
Soluble reactive phosphorus	0.16
Nitrate- nitrogen	0.16
Electrical conductivity	0.13
Total solids	0.11

Data analysis

Unless otherwise stated data shown will be the average of three sampling sessions conducted in the respective season during the 3 year period. Using average values would give the best representation against temporal variations. Initially data was analyzed using detrended correspondence analysis (DCA) to identify grouping or separation of sites. There was a separation based on season and section type. Therefore, it was decided to conduct separate analyses using a direct gradient method. The direct gradient method used was redundancy analysis (RDA). RDA was preferred due to short gradient length, and it was found by DCA (Ter Braak and Smilauer 2002; Cajo and Ter Braak, 2002). In RDA, species data (macroinvertebrate data) were used as response variables. To identify eco-hydraulic (hydraulic, vegetation and geomorphology) and water quality variables that best explained species composition, separate RDAs were done for these two types of explanatory variables (*in* sensu Legendre and Legendre 2012; Belley and Snelgrove 2016). Separation of eco-hydraulic and water quality variables also ensured the explanatory variables had variance inflation factors less than 5%. For each RDA only the best five (i.e. with highest explanatory power) explanatory variables were considered, selected by forward selection option. Forward selection option was done at a significance level of 0.05 and 9999 random permutations. This ensured the five most parsimonious set of variables were considered in each RDA model. The RDAs performed using water quality and eco-hydraulic variables together as explanatory variables showed very high variation of inflation (as high as 300) mainly for water quality variables, suggesting a multi collinearity. Therefore, combined usage of water quality and eco-hydraulic variables were not considered.

In RDA analyses explanatory variables were centered and standardized. Scaling focused on explanatory variable correlations, and explanatory variable scores were divided by standard deviation. A log transformation ($y = \log(A.y + C)$; $A = 10$ and $C = 1$) was used to reduce skewness. Conditional and marginal effects of explanatory variables on response variables were assessed using a Monte Carlo permutation test (with automatic variable selection), which was done using the reduced model from CANOCO for Windows, since the reduced model better handles Type I errors in small data sets (Gomes and Asaeda 2009). It should be noted that when two processes are highly auto correlated, observed Type I errors are significantly high (Gomes and Asaeda 2009). Furthermore, the permutation type was restricted for spatial structure as it accounts for the correlations among samples (Gomes and Asaeda 2009).

Concurrently with RDA, t-test and Pearson's' correlation analysis were performed using SPSS statistical package (IBM V21.0). These analyses will be used to strengthen and cross validate the results of RDA. DCA and RDA analyses were doing using CANOCO 4.5.

Results

Water quality of concrete lined and earthen sections

Table 3 shows the average water quality of concrete lined and earthen sections in dry and wet seasons. Results suggested that earthen section have a better water quality than concrete lined sections for many parameters; the difference in the wet season was more obvious and many parameters showed a significant difference (t-test; $P < 0.05$). The poor water quality in the concrete lined sections could be due spatial positioning (concrete lined sections are in the downstream side)~~,~~ or stream bed property related reasons (concerted surfaces are poor in assimilation and attenuation). As per the DCA plots drawn for wet and dry seasons for water quality (Fig. 2), a polarization or clustering was evident. For dry season two clusters consisting of concrete lined and earthen sites were evident, but the separation between the concrete lined and earthen sites was moderate. In the wet season, even though earthen and concrete lined sites were close to each other on DCA plots, they showed a clear separation.

Responses of functionally classified macroinvertebrates

Figure 3a–d show the fraction macroinvertebrates as grazers, shredders, collectors, filterers and predators, separately for earthen and concrete lined sections as well as for wet and dry seasons. The fractions shown are the averages of the 3 years of the respective seasons. The variance of responses was high in many sites (some cases about 50%). All five functional groups were observed in many earthen sites (6–8 sites, depending on the season), but to a less occurrence at concrete lined sites (only in 2–4 sites, depending on the season). However, in both section types the most abundant macroinvertebrate groups were grazers and filterers, which accounted for 40–70% of the total population. Even though water quality improved in wet season for most of the parameters (Table 3), the dominance of grazers and filterers in earthen or concreted sections did not show a considerable difference against the season.

Diversity and pollution tolerance index (PTI) variations

Figure 4 shows the variation of diversity and PTI of macroinvertebrates. The diversity was in line with the results depicted in Fig. 3a–d; sites with more functional groups also showed greater diversity. Interestingly, some earthen and concreted sites had similar diversities. However, a distinction could be made with respect to PTI, as some concrete lined sites with high diversity also had high PTI as a result of

Table 3 Water quality results during the study period. Parentheses show the standard deviation

Season	Parameter	Earthen samples	Concrete lined samples
Dry season	DO (mg/L)	8.00 (1.84)	5.65 (2.52)
	Chlorophyll-α (μg/L)	25.8 (51.2)	14 (14.1)
	Conductivity (μs/cm)	282 (216)	1013 (848)
	Turbidity (NTU)	14.7 (21.8)	10.9 (12.9)
	TS (mg/L)	157 (48.5)	487 (734)
	TSS (mg/L)	29 (14.6)	32.6 (44.9)
	pH	7.21 (0.22)	7.32 (0.63)
	Nitrate (mg/L)	1.65 (0.97)	4.64 (2.43)
	Nitrite (mg/L)	0.11 (0.14)	3.21 (3.26)
	Ammonia (mg/L)	2.45 (4.75)	5.83 (4.69)
	Sulphate (mg/L)	2.22 (2)	18.5 (10.6)
	Sulphide (mg/L)	0.04 (0.04)	0.2 (0.52)
	Soluble Reactive Phosphorus (mg/L)	3.28 (4.94)	6.9 (6.48)
	Water quality Index	79.2 (7.7)	64.3 (13.9)
Wet season	DO (mg/L)	6.69 (0.23)	5.62 (2.53)
	Chlorophyll-α (μg/L)	3.29 (2.37)	3.43 (2.05)
	Conductivity (μs/cm)	106 (51.2)	413 (268)
	Turbidity (NTU)	6.69 (2.63)	9.63 (6.31)
	TS (mg/L)	148 (66.2)	175 (84.9)
	TSS (mg/L)	9.04 (4.74)	25.4 (28)
	pH	7.12 (0.18)	7.12 (0.62)
	Nitrate (mg/L)	0.54 (0.17)	1.37 (0.79)
	Nitrite (mg/L)	0.02 (0.01)	0.80 (0.62)
	Ammonia (mg/L)	0.11 (0.11)	5.63 (6.71)
	Sulphate (mg/L)	1.2 (1.17)	13 (9.71)
	Sulphide (mg/L)	0.02 (0.01)	0.03 (0.03)
	Soluble Reactive Phosphorus (mg/L)	0.73 (0.21)	3.84 (3.37)
	Water quality Index	81.2 (2.5)	69.7 (13.2)

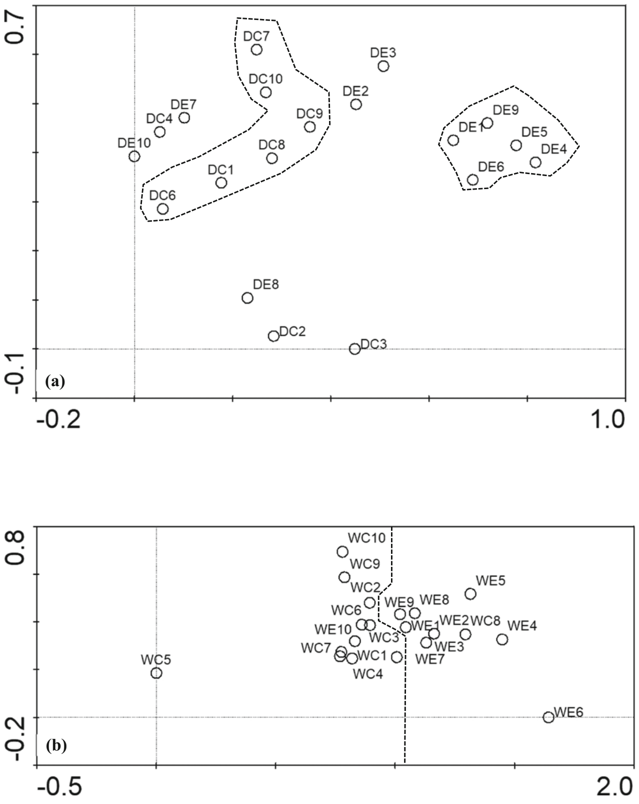

Fig. 2 DCA plot water quality **a** Dry season **b** wet season

more pollution tolerant species (e.g. D1; data not shown). On the other hand most of the earthen sites with high diversity were results of pollution intolerant species (e.g. A3; data not shown). Therefore, high diversity did not always correlate with superior stream quality. At the same time, some concrete lined sites had a low diversity and also a very low PTI. This was due to the domination by a few types of pollution intolerant species. These observations were further supported by Pearson's correlation analyses carried out for different combinations of seasons and section types (Table 4). When all sites were analysed separately for wet and dry seasons, the wet season showed a statistically significant relationship (Table 4). These significant correlations indicated a complex seasonal and section signature. The concrete lined section for both seasons showed weak and statistically insignificant correlations. On the other hand the earthen section in the wet season showed a very strong statistically significant positive correlation, whereas in the dry season the correlation was not as strong but was still considerable. Therefore, for the earthen sections, the high diversity was as a result of different types of pollution intolerant or moderately intolerant species. However, the concrete lined section had no correlation between PTI and diversity, suggesting that the macroinvertebrate compositions were rather complex as it had different combinations of pollution tolerant to intolerant species.

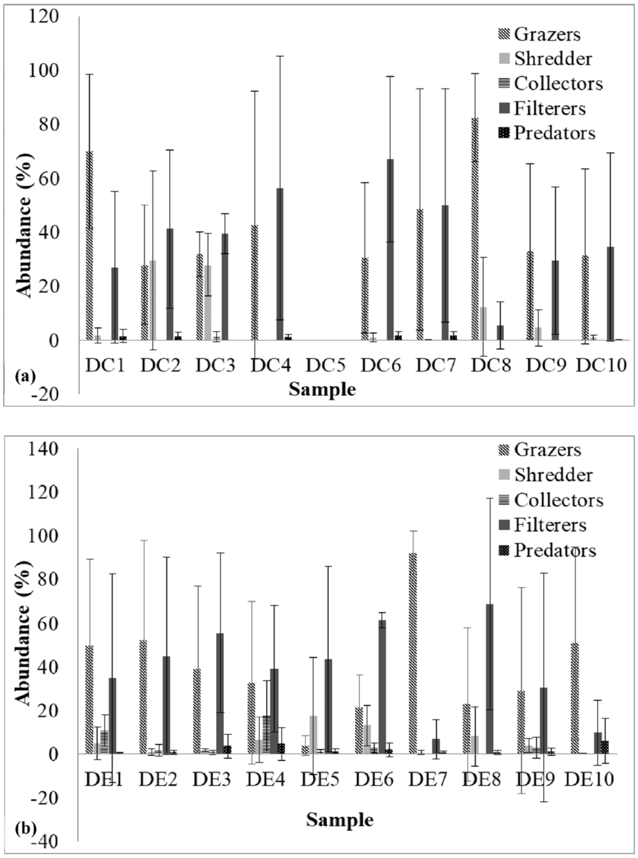

Fig. 3 Fraction macroinvertebrates classified according to functional feeding groups in dry season in **a** concrete lined and **b** earthen sections, and in wet season **c** concrete lined and **d** earthen sections

Diversity and water quality

Figure 5 shows the variation of WQI. Somewhat similar to the relationships between PTI and diversity, the correlation between, WQI and diversity were not strong either (Pearson's r < 0.1 at $P > 0.1$). Only earthen section in wet season had a close to statistically significant relationship (Pearson's r = 0.52; $P = 0.12$) (Table 5). This elucidated water quality may not play a major role in the macroinvertebrate composition (e.g. diversity). WQI may down weigh certain water quality parameters in its combined expression, therefore, individual impact of different water quality parameters need to be assessed separately.

Multivariate analysis: Role of water quality on macroinvertebrate responses

The RDA plots drawn for macroinvertebrate variables and water quality variables for different combinations of season and section type are shown in Fig. 6(a–d). It was revealed DO and nitrate to play an significant role in dry season irrespective of the section type, but in wet season it was section dependent (Table 6).

RDA results strengthened the observations of bivariate diagrams. Pollution intolerant macroinvertebrates abundance (NMI) and WQI showed a positive correlation in all four cases. However, the expected opposite relationship (i.e. a negative correlation) between WQI and

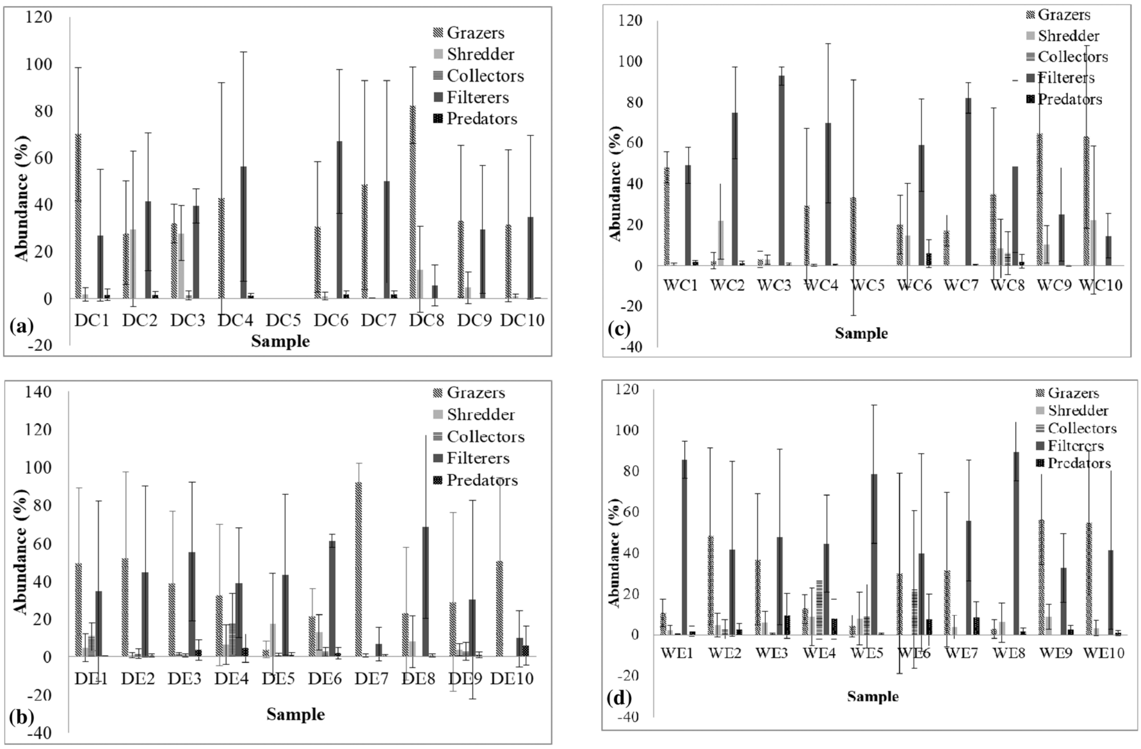

Fig. 4 Macroinvertebrate diversity in terms of Shannon-Wienner index (SWI) and Pollution tolerance index

Table 4 Pearson correlations between Pollution Tolerance Index and Macroinvertebrate diversity. Concrete lined (C); Earthen (E)

Description (season/sample)	Pearson R	P
Dry/C and E	0.07	0.77
Wet/C and E	0.47	0.04
Dry and Wet/E	0.59	0.00
Dry and Wet/C	0.27	0.26
Dry/C	0.15	0.68
Wet/C	0.32	0.39
Dry/E	0.53	0.11
Wet/E	0.62	0.05

pollution tolerant macroinvertebrate abundance (NMT) was evident only in the earthen section. Diversity (SWI) and WQI observed to have no correlation in the concrete lined sections in dry season. Whereas in all other cases SWI and WQI had positive correlations. Good water quality always resulted in high SWI and a low PTI. Poor water quality did not show proper correlation with macroinvertebrate abundance, irrespective whether they were pollution tolerant (NMT) or intolerant (NMI) elucidating the colonization of opportunistic species.

The correlations between percentage abundances of functional groups and water quality indices were not consistent, and in certain cases they were not in line with the commonly accepted relationships (e.g. grazers had negative relationship with chlorophyll-a in the earthen section in the dry season). This could be due to the factors other than the water quality, such as stream hydraulics and/or inter functional group competitions. As an example, the sample C2 with poor water quality (Fig. 5) showed high diversity (Fig. 4); according to Fig. 7 it was due to high heterogeneity. Also, the explanatory powers of water quality variables were strong in concrete lined sections especially in the dry season. In the wet season the explanatory powers of water quality variables were very weak, and the weakest was found in the earthen section (only 54% by first two axes) (Table 6).

Table 5 Pearson correlations between water quality index and macroinvertebrate diversity. Concrete lined (C); Earthen (E)

Description (season/sample)	Pearson R	P
Dry and wet/C and E	0.01	0.92
Dry/C and E	−0.17	0.46
Wet/C and E	0.17	0.47
Dry and wet/E	0.38	0.09
Dry and wet/C	0.05	0.82
Dry/C	−0.29	0.43
Wet/C	0.48	0.19
Dry/A	0.52	0.12
Wet/A	0.33	0.35

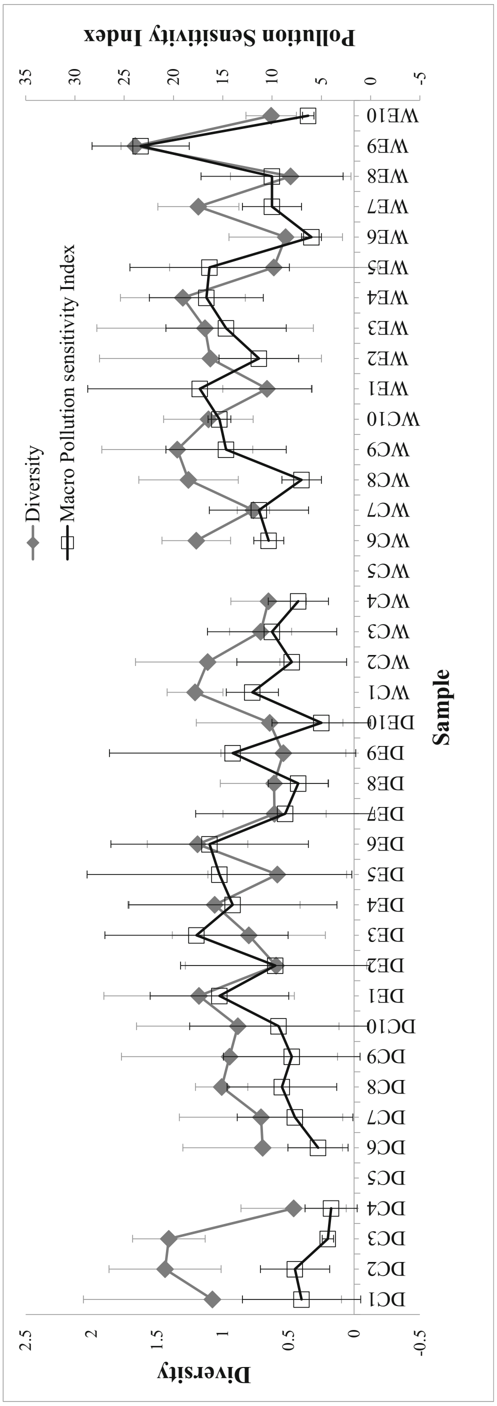

Fig. 5 Water quality index (WQI)

Multivariate analysis: Eco-hydraulics on macroinvertebrate responses

Figure 7 shows the RDA plots drawn for macroinvertebrate responses against eco-hydraulic variables. It was revealed

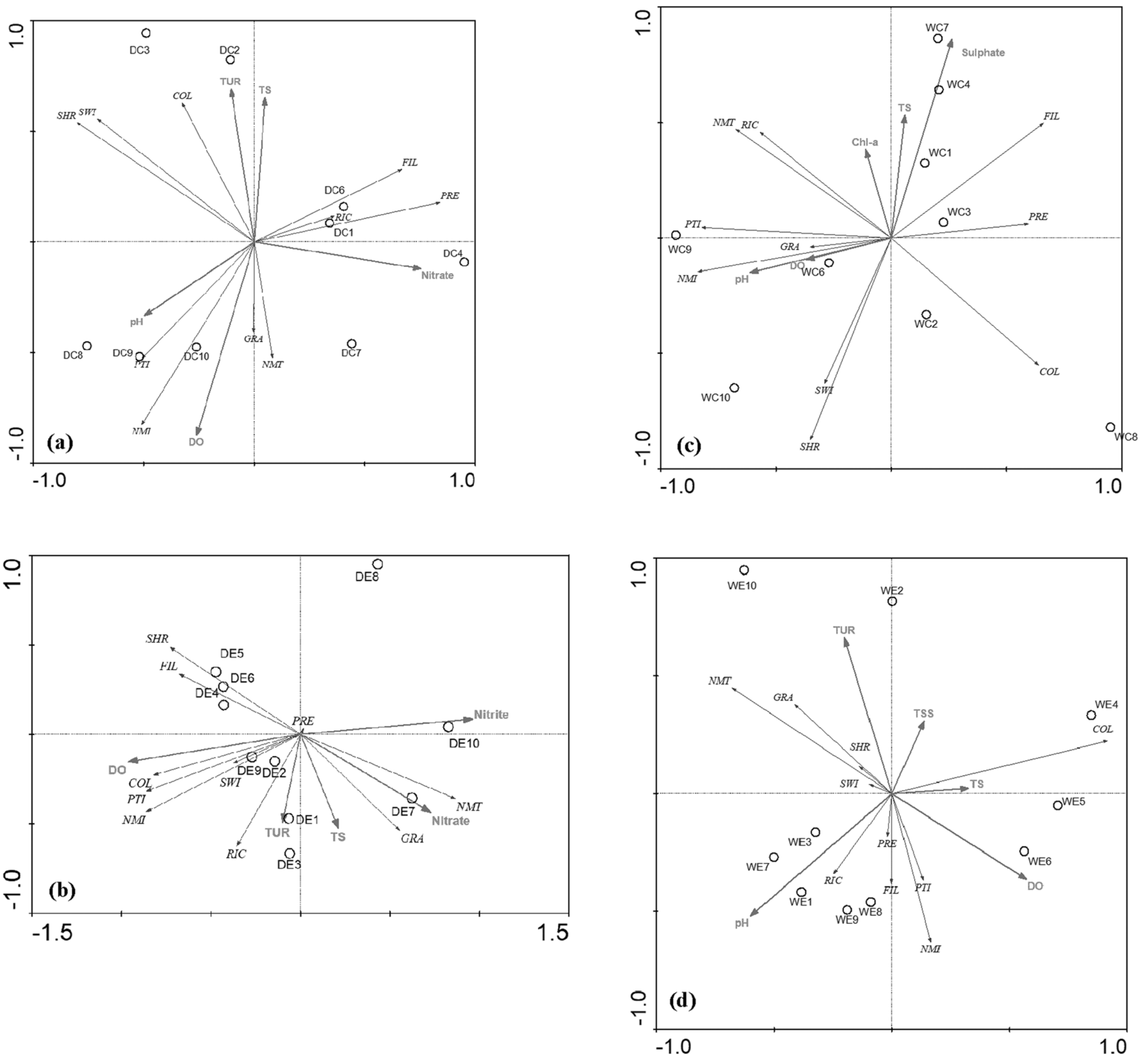

Fig. 6 Redundancy analysis tri-plots using water quality as explanatory variables: Dry season **a** concrete lined and **b** earthen sections; wet season **c** concrete lined and **d** earthen sections

Table 6 Explanatory powers of best two axes and all four axes by (a) water quality and (b) stream hydraulics

Description (Season/section)	% variation explained		Significant variables
	Best two axes	All four	$P < 0.05$; $P < 0.1$*
(a)			
Dry/C	79	94	DO, Nitrate
Dry/E	78	88	DO, Nitrate, Nitrite*
Wet/C	65	86	Sulphate*
Wet/E	54	67	pH*, DO*
(b)			
Dry/C	68	77	Velocity, Standard deviation of Froude number
Dry/E	76	84	Standard deviations of wetted width and depth, Emergent plant cover
Wet/C	68	87	Wetted depth and width, Submerged plant cover*, discharge*
Wet/E	57	73	Standard deviation of wetted depth

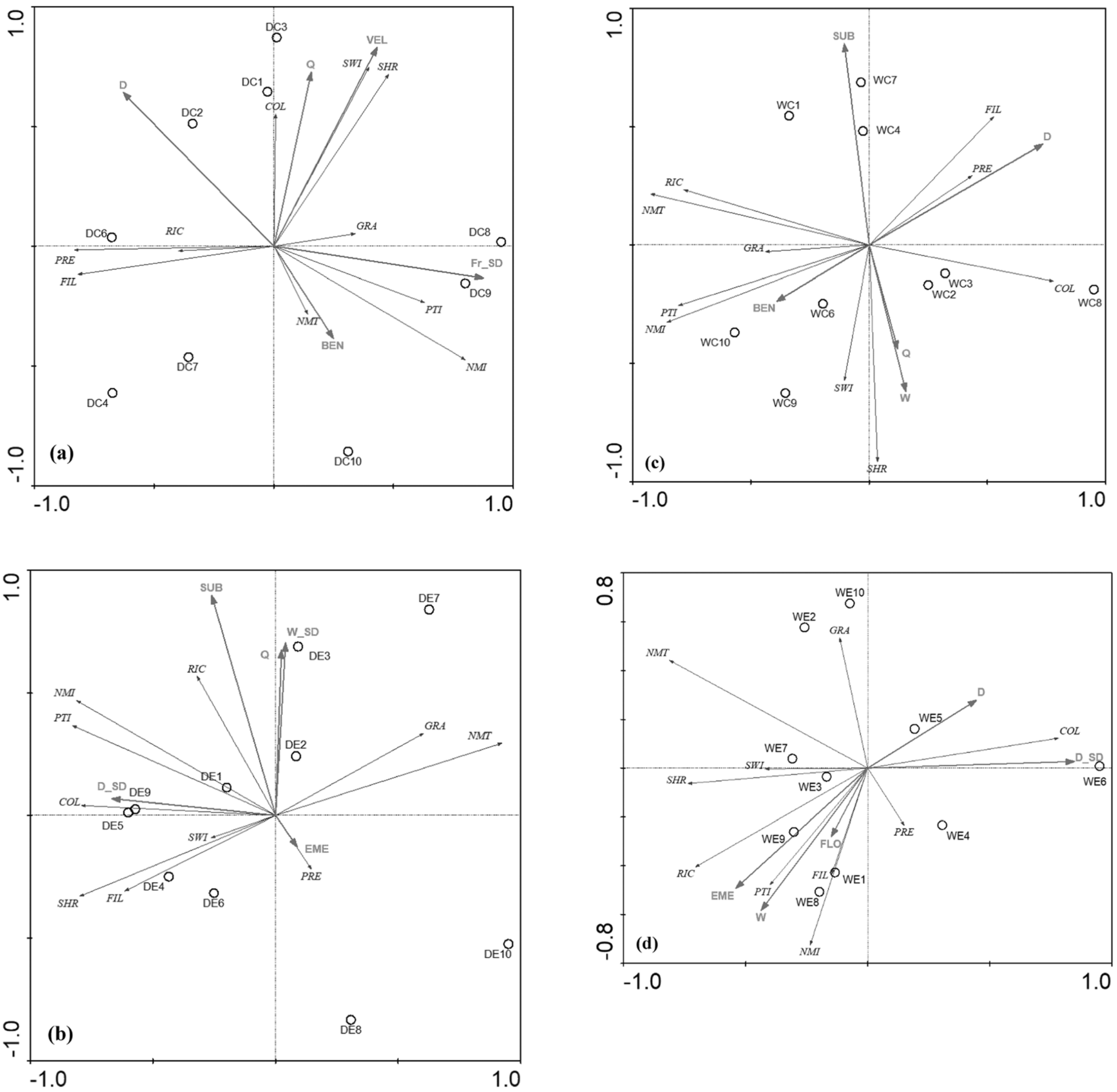

Fig. 7 Redundancy analysis tri-plots using eco-hydraulics as explanatory variables: Dry season **a** concrete lined and **b** earthen sections; wet season **c** concrete lined and **d** earthen sections

that the discharge in the concrete lined sections was an important variable as it was among the best five variables in most of the time. Standard deviation of the wetted depth was a significant variable (Monte Carlo; $P < 0.05$) for the earthen sections. In addition standard deviation of wetted width was a significant variable in earthen section in both seasons. The important role of aquatic vegetation (emergent and submerged plant cover) was evident and the influence was significant (Monte Carlo; $P < 0.05$) in the dry season of earthen section and in wet season of concrete lined sections. In comparison with the explanatory powers of water quality fed model, the explanatory powers were more or less the same (Table 6). A reduction in explanatory power by the best two axes with season changing from dry to wet was evident here as well. But unlike the water quality fed case, it was only marginal.

Discussion

Spatial position of sites and macroinvertebrate composition

As all concrete lined sites were in the downstream side, a direct comparison of macroinvertebrates between earthen and concrete lined sites was not appropriate. Usually low order stream segments (e.g. earthen in our case) as per river continuum concept should show a relatively high fraction (about 60% or more) of shredders and collectors (Vannote et al. 1980). The earthen section at best showed 30% for shredders and collectors in wet season, therefore, earthen section showed a marginal conformity. Even though it was not easy, the earthen sites could be categorized as low order sections after some extensive investigation with high certainty.

However, owing to the extent of stream regulation, assignment of a stream order or even qualitatively categorizing as low or mid order was not easy for concrete lined sites. Nevertheless, sites close to the earthen sites may be considered low orders and further away may be considered as mid order streams. Besides, due to the absence of riparian vegetation, reconstruction into prismatic narrow low flow and wide high flow sections (thus dominant energy source is solar radiation), those sites behave similar to mid to high order streams. As stream order increases, such as from earthen to concrete lined section, the community shifts from being dominated by shredders and collectors to being dominated by grazers and collectors, usually with an equal split (Delong and Brusven 1998). This was reflected to a certain extent considering large contribution (as high as 60% irrespective of the season) of grazers of the total population. However, the collector population was considerably low (on average less than 5%). Even if concrete lined sections treated as low orders (same as earthen), it too showed non conformity to river continuum concept considering the very low (less than 5%) shredder population.

Overview of macroinvertebrate assemblages

Our results proved that concreted sections were not ecologically dead. It had in general low, but quantifiable and viable macroinvertebrate populations. Interestingly, some macroinvertebrate indices of concreted sections were without a significant difference with those in the earthen section. A few native and red list species were observed in the earthen section. Nevertheless, some concrete lined sites were also refuged by some native macroinvertebrates (data not shown).

Irrespective of the season and section type grazers and filterers were the dominant functional groups. There was a negative relationship between these two groups as shown in Fig. 8. Dominance of filterers was understandable considering of the substrate limitations and current (water flow) conditions. Streams with limited stable substrate and sufficient flow velocities can often support massive standing stocks of filter-feeders (e.g. black flies) (Wallace and Webster 1996). Filterer density can be higher than other functional groups because filterers make use of the kinetic energy of the flow to consume foods produced in the upstream habitats (Wallace and Webster 1996). Whereas dominance of grazers also understandable considering the thick periphyton cover (Tomanova et al. 2007). Population control of gastropoda by predation seemed to be not happening, as predators such as birds were not common in the area. According to Wallace and Webster (1996) filterers are animals with specialized anatomical structures that act as sieves to remove particulate matter from suspension. Higher amounts of suspended particles in the water lead to richness of filterers and decreasing of light penetration. Insufficient sunlight weakens the development of periphyton which is the main food source of grazers, thus resulting in a negative relationship between populations of grazers and filterers.

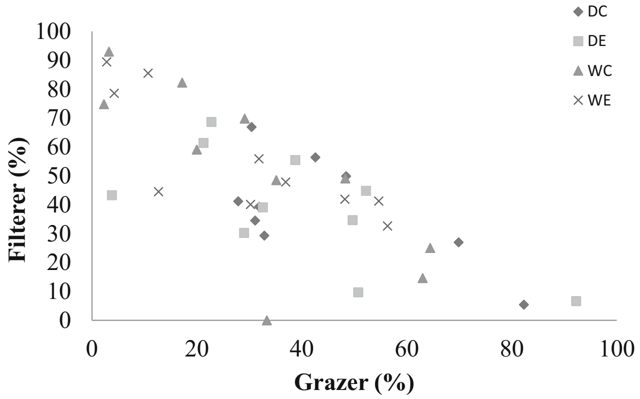

Fig. 8 Percent grazers and percent filterers (fraction abundance of filterer and grazers) for different combinations of season Dry (D) or wet (W)) and section type (concrete lined (C), earthen (E)) (e.g. DE, dry season earthen section)

Water quality and macroinvertebrates

Influence of water quality was evident mainly in the dry season, especially in the concrete lined sections. The influence can be direct as well as indirect. Nitrate and other nutrients aided vegetation growth and supported macroinvertebrates (Vermonden et al. 2009). In the dry season, macroinvertebrates in concrete lined sites were strongly related to benthic vegetation, which could be due to high nutrient content, light availability and relatively low water depth. In addition, unlike soil surfaces, high albedo surfaces such as the concrete lined promote periphyton growth (Alum et al. 2008). Nutrients and light availability are the main factors that lead to the accrual of periphyton biomass. Whereas the main factors leading to the loss of periphyton production are disturbances, such as floods and droughts (O'Brien and Wehr 2010). Earthen as well as concrete lined sections receive nutrient rich water via expedient connections. However, due to simplified physical heterogeneity (thus less attenuation) and absence of a sediment layer (thus less assimilation) (Gomes and Wai 2014), the availability of nutrients in water column is high in concrete lined sections. More periphyton, create conditions suited for grazers, especially gastropods (Tomanova et al. 2007). For the earthen section in the dry season, nitrite was a significant variable. Nitrite is an intermediate species in the oxidation of ammonium to nitrate, and is the most toxic form of nitrogen species. This is because nitrite may cause anoxia in aquatic environments (Lewis Jr and Morris 1986, Van Der Vliet et al. 1997), resulting in less diversity and less number of macroinvertebrate functional groups. It should be noted that most of the gastropods found were left sided ones (sinistral) that have the ability to breathe air from atmosphere (Merritt and Cummins 1984) and are representatives of polluted water. Despite the correlations were more or less the same across section types and seasons, the influence of water quality on macroinvertebrates was weak in the wet season particularly in the earthen section.

Eco-hydraulic variables and macroinvertebrates

Eco-hydraulic variables showed similar potential as water quality in explaining the variation of the macroinvertebrate composition for all four cases. by Gomes and Wai (2019) for the same study area observed that the flow rate in the dry season was a surrogate for water quality due to the contribution of wastewater inputs (was about 10% of the total flow rate and was about 5% in wet season.) In contrast to the expectations, flow rate did not show a statistically significant influence on the macroinvertebrate responses. Nevertheless, it was among the best five explanatory variables, and always resulted in high diversity and/or richness (irrespective whether the high diversity was due to pollution tolerant species or not). Apparently stream discharge was significant in the wet season in concrete lined sections. In addition, wetted depth, width and submerged plants too were significant too. It should be noted that the vegetation indicators in concrete lined sections were subject to modifications (e.g. pruning) due to maintenance works by the government, thus no room for long standing vegetation patches.

For the earthen sections, the influencing factors were variations of wetted depth and width. These two variations could be considered as surrogates of physical heterogeneity. They correlated positively with diversity and richness, and showed equal importance on abundances of pollution tolerant as well as intolerant species. However, promotion of pollution tolerance species could not be considered as a positive aspect.

In certain cases it was observed that the vegetation was important to macroinvertebrate assemblages, including diversity and richness. Vegetation is important for macroinvertebrates as they provide habitats, food and refuge (Newman 1991). Also submerged vegetation will keep water bodies in clear state minimizing the suspension of particles (Dosskey et al. 2010).

Management options for urban streams

Nutrient levels need to be limited to enhance diversity of pollution intolerant species. It should be noted that most of the pollution tolerant species were exotic and invasive. As per the study results, vegetation (especially submerged) observed to be important. Nevertheless, government agencies harvest them out in maintenance works, and could have negative consequences on macroinvertebrates. In the dry season the overgrown vegetation may result in water pockets and could be breeding grounds for mosquitos. Overgrown vegetation in the low flow channel in the dry season will reduce the flow capacity and may result in a minor flow in the main flow channel. This will result in periphyton growth in the main flow channel and produce foul smell. Furthermore, it would be an ideal place for mosquito breeding. Thus, an optimal mowing regime is recommended (Vermonden et al. 2009).

This study did not support a comparison of macroinvertebrate composition against catchment land use classified as urban, peri-urban, rural-urban fringe or rural. This was mainly due to the fact that Hong Kong is a small region with small catchments and also due to the fact that no stream was able to be found with rural land use in its entire stream course (downstream side always had urban land use). Furthermore, it should be noted that instream alterations such as concrete lining could be an obvious intervention when land use change from rural to urban, therefore, instream regulations and land use is rather complementary (in sensu Caro-Borrero et al. 2016). Also, it was difficult to assess the impact of instream disturbances and land use separately. However, the poor macroinvertebrate composition observed in this study, especially in the concrete lined sections, was also noted by several past studies in the context of urban land use. As an example Roy et al. (2003) observed urban land cover to explain 29–38% of the variation in macroinvertebrate indices, and resulted in more of pollution tolerant macroinvertebrates. Also, our study showed the water quality to be a governing factor of macroinvertebrates and it is related to the land use. Therefore, any management strategy that governs urban streams should consider the role of land use as a source of diffuse pollution and should take action to mitigate negative impacts.

Conclusion

In this study an urban stream network with concreted and earthen sections was investigated for macroinvertebrate assemblages and factors governing them. Concrete lined sections too had macroinvertebrates, including some with conservation value. These proved that the concrete lined streams are not ecologically dead. However, smaller number of functional groups and dominance of pollution tolerant and invasive species indicated situation needs improvement. Macroinvertebrate assemblages were equally well explained by water quality as well as eco-hydraulic variables, thus indicating a surrogation between these two types of variables. By analyzing of the relationships, we proposed low flow instream vegetation with controlled harvesting and increased physical heterogeneity as potential rehabilitation options for concrete lined streams.

Acknowledgements This research was funded by Environment and Conservation Fund, Hong Kong (Project number 39/2011) and Research Grants Council Funds of Hong Kong (PolyU 152230/17E). Special thanks to Drainage Services Department, Hong Kong for the help provided during field sampling. Authors would like to thank the support extended by Derek Lam, Sarah Chan, Taing Lian, K.H. Leung, Yan Xufeng, and the other members of the Hydraulics Laboratory.

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