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Development of an Index of Trophic Completeness for benthic macroinvertebrate communities in flowing waters

Timur I. Pavluk[1], Abraham bij de Vaate[2] & Heather A. Leslie[3]
[1]*Russian Research Institute for Integrated Water Management and Protection (RosNIIVH), Ekaterinburg, 23 Mira Street, 620049 Ekaterinburg, Russia*
E-mail: t.pavluk@water.uran.ru
[2]*Institute for Inland Water Management and Waste Water Treatment (RIZA), Lelystad, The Netherlands*
[3]*University of Amsterdam (ARISE), Amsterdam, The Netherlands*

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Abstract

The analysis of the trophic structure of benthic macroinvertebrate communities can be used in biological assessments of the condition of river ecosystems. Using the trophic, or functional approach, the Index of Trophic Completeness (ITC) was developed. The goal was to overcome the problems and drawbacks of using conventional diversity or biotic indices in biological assessments of rivers, such as limitation to distinct geographical regions or focus on species richness without regard for ecosystem functioning. Following an extensive review of the literature on the trophic characteristics of benthic macroinvertebrates, a large number of species (±300) were characterized according to a number of trophic criteria: plant:animal ratio in the diet, feeding mechanism, food size, food acquisition behaviour, and energy and substance transfers. On the basis of their trophic characteristics, the species could be divided into 12 trophic groups. After examination of data from geographically diverse rivers, it was concluded that any undisturbed riverine benthic macroinvertebrate community should be represented by members of each of these 12 trophic groups, with each group fulfilling a function in the benthic community. Being a community which plays a central role in the functioning of the aquatic ecosystem, the benthic invertebrates are expected to respond to disturbances to the hydrobiocoenose. The outcome of an ITC assessment is clearly presentable in the form of a pie graph with 12 wedges, each representing one of the 12 defined trophic groups. Functionally complete communities are represented by 12 wedges; a blank wedge indicates that a trophic group is not represented. This paper describes the preliminary developments in the ITC method, its potential as a biological assessment method in rivers in different geographical zones, and presents examples of trial mappings of Russian and European rivers. The application of the ITC to these rivers demonstrated the absence of ITC trophic groups at sites under the influence of anthropogenic activity.

Introduction

Benthic macroinvertebrate community structure has become an important element in many water quality assessments (Canfield et al., 1994; Chapman, 1994; Den Besten, 1993; Rosenburg & Resh, 1993). Advantages of benthic macroinvertebrates in biological assessments include their abundance, sedentary nature, suitable lifespans, diversity of phyla and trophic levels, sensitivity and swift response to various pollution types and the many sampling methods available (Metcalfe-Smith, 1994). Benthic organisms carry out the primary mechanical breakdown of coarse organic material (CPOM), consume fine organic matter (FPOM), microbes, diatoms, macrophytes, prey on other invertebrates and may parasitize larger vertebrates (e.g., Hirudinea). They also constitute a major food source for other invertebrates, fish, and waterfowl making them a link between microbes and vertebrates (Cummins, 1992). Macroinvertebrate communities are thus important foundations for energy and substance transformations in the aquatic ecosystem.

Anthropogenic disturbances such as input of (heavy) metals or organic pollutants have an impact on substance and energy flows in an aquatic system initially by affecting sensitive species. Imbalances caused by the damage to or disappearance of sensitive members of the ecosystem are reflected in the breakdown of food web connections if the function of missing members is not filled by other functional (but not necessarily taxonomic) relatives. Any significant disturbance to the ecosystem will affect the macroinvertebrate community because of the intricate system of trophic links between this community and the rest of the ecosystem.

The functional approach involves the assessment of trophic groups, which are made up of animals of the same feeding type, using similar sources of energy and matter (same trophic niche). The presence or absence of these trophic groups provides meaningful information on the state of functioning of the community to the water manager.

Table 1. Criteria for defining the five-digit trophic code, and thereby trophic group of a particular species (and in some cases, life cycle stage). For example, a five digit code of 15131 could belong to a herbivorous filter-feeder, totally ingesting particles > 1 mm, collecting food in an inactive way

	Trophic characteristic	Category
I	Diet composition (% animal food)	1 → herbivores (< 20%)
		2 → omnivores (20–70%)
		3 → carnivores (> 70%)
II	Feeding mechanism	1 → shredders/chewers
		2 → scrapers
		3 → collectors
		4 → suckers
		5 → filterers
III	Food size (average linear size)	1 → > 1 mm
		2 → < 1 mm
IV	Food acquisition behaviour	1 → active searching
		2 → moderate searching
		3 → passive ingestion
V	Energy/substance transfer	1 → total prey ingestion
		2 → incomplete prey ingestion

Development of the ITC index

In the past, various authors have devised systems of trophic classification for benthic macroinvertebrates. Konstantinov (1967) observed that benthic invertebrates could be classified according to main food source and the method of food acquisition. Cummins (1973) used food ingestion mechanism, energy source, and size of food item as criteria in the classification of benthic fauna. Miroshnichenko (1983) classified benthos into seven trophic groups based on a combination of trophic criteria which included feeding behaviour.

The Index of Trophic Completeness (ITC) assessment method is rooted in the functional approach to ecosystem study (Odum, 1971). On the basis of publications of Cummins (1973), Konstantinov (1967) and Miroshnichenko (1983) five aspects of the trophic character of macroinvertebrates were selected for the definition of the trophic groups (Table 1). Each aspect was subdivided into a number of categories for differentiation of the trophic groups and to optimize the power of the ITC.

For each species, a five-digit code was generated depending on the categories as shown in Table 1 using information from the literature on the trophic character of the individual species. In some cases a different code was designated for each (functional) stage in the life cycle of a species. By cluster analysis (with the computer program 'Statistics for Windows') the species could be divided into 12 groups of the same trophic code (Table 2). These groups were termed ITC trophic groups. Representatives of such a group occupy the same trophic niche.

Focusing on the benthic macroinvertebrate community in this way indicates the state of completeness of the functioning of the aquatic ecosystem as a whole because the 12 ITC groups are connected by trophic links to all other components of the aquatic ecosystem (Figure 1).

A computer program was written in basic format to facilitate rapid analysis of species lists (Pavluk, 1997). The program (free copies are available, including the data set with coded macroinvertebrate species) calculates the number of trophic groups represented in a given species list. A pie graph with 12 wedges is then used to clearly present the results, where black wedges represent missing trophic groups (Figure 2).

Table 2. The 12 trophic groups in the Index of Trophic Completeness. Aspects of trophic character defining codes; all benthic macroinvertebrates of rivers definable by one of these ITC code

Group no.	Diet	Feeding mechanism	Food size (mm)	Food acquisition	Prey ingestion	Code
1	Carnivory	Shredding/ chewing	>1	Active	Total	3-1-1-1-1
2	Carnivory	Shredding/ chewing	>1	Moderate	Total	3-1-1-2-1
3	Omnivory	Shredding/ chewing	>1	Active Moderate	Total	2-1-1-1-1 2-1-1-2-1
		collecting collecting		Active Moderate		2-3-1-1-1 2-3-1-2-1
4	Herbivory	Shredding/ chewing	>1	Moderate	Total	1-1-1-2-1
5	Herbivory	Shredding/ chewing	<1	Moderate	Total	1-1-2-2-1
6	Herbivory	Scraping	<1	Moderate	Total	1-2-2-2-1
7	Herbivory	Collecting	<1	Moderate	Total	1-3-2-2-1
8	Herbivory	Filtering	<1	Moderate passive	Total	1-5-2-2-1 1-5-2-3-1
9	Carnivory	Sucking	>1	Moderate	Incomplete	3-4-1-1-2 3-4-1-2-2
10	Carnivory	Sucking	>1	Moderate	Total	3-4-1-2-1
11	Herbivory	Sucking	>1	Moderate	Incomplete	1-4-1-2-2
12	Omnivory	Shredding/ chewing	<1	Moderate	Total	2-1-2-2-1

Application of ITC in practice: trial mappings

The next step was to apply the ITC criteria to existing species data from rivers in Western Europe (the rivers Rhine and Meuse) and the Urals (Chusovaya, Iset and Techa). Sampling in these rivers was conducted using standardized Dutch Artificial Substrate Samplers (De Pauw et al., 1994; Pashkevich et al., 1996).

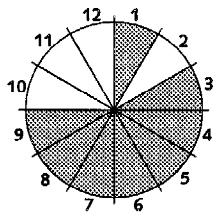
Specimens collected were identified to species, an essential condition for the application of the ITC. Species of which only one specimen was found on a sampling location per sampling date were left out of the analysis as they do not play a significant role in the community (change hit). From the data for the various sites the number of trophic groups were calculated and the results were mapped using the pie graph method of presentation. These graphs are shown in Table 3 with water quality data corresponding to the macrozoobenthos sampling periods.

Contamination in the rivers Rhine and Meuse is characterized by nutrient loading, organic enrichment, metals, and organic micropollutants. These rivers are highly channelized and although water quality has improved in recent years, lack of suitable habitats re-

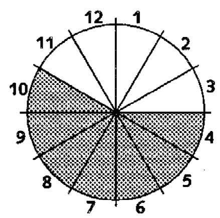
Table 3. Trial ITC assessments in European and Russian rivers. Mean values for a series of parameters (corresponding to the macrozoobenthos sampling periods) and results of ITC assessments (based on results of artificial substrate samples) in the Rhine at Lobith and Meuse at Borgharen for the period 1 May–30 September 1996, in the Chusovaya at Pervouralsk and Verkhniaya Oslianka (V.O.), period 15 May–19 September 1995, and in the Iset at Dalmatovo and Techa at Zatechenskoye, period 7 July–9 October 1992. na, not available

Parameter	Unit	Rhine	Meuse	Chusovaya (Pervouralsk)	Chusovaya (V.O.)	IsetTecha	
Temp.	°C	19.1	19.9	15.3	13.4	15.3	14.2
pH		7.8	7.4	7.2	8.0	7.9	7.7
Conductivity	mS/m (20 °C)	90	56	na	na	na	na
BOD_5	mg O_2/l	na	na	2.7	2.6	3.4	5.8
COD	mg O_2/l	na	na	19.1	12.1	44.9	50.6
O_2	mg/l	9.0	6.6	11.7	11.6	12.8	10.4
O_2 saturation	%	85	60	na	na	na	na
Cu	μg/l	5.1	3.5	20	6.0	3.6	3.6
Hg	μg/l	0.03	0.01	<0.1	<0.1	na	na
Cr	μg/l	2.4	0.76	2,230	31	8	3
Cd	μg/l	0.08	0.20	1.9	1.0	<5	<5
Ni	μg/l	3.1	4.6	26.3	7.7	3.8	3.2
Pb	μg/l	4.0	3.1	6.5	6.2	na	na
Zn	μg/l	19	35	436	139	3	8
Mn	μg/l	na	na	224	36	14	110
Cholinesterase inhibitors	μg parathion/l	0.25	1.86	na	na	na	na
PCBs tot.	μg/l	0.08	0.06	na	na	na	na
Oils	μg/l	na	na	na	na	85	87

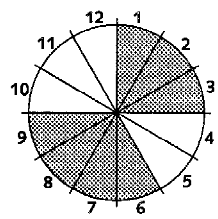
ITC result



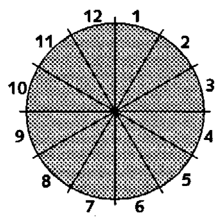
Rhine



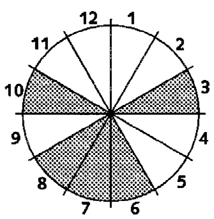
Meuse



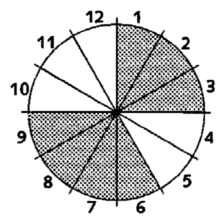
Chusovaya (Pervouralsk)



Chusovaya (V.O.)



Iset



Techa

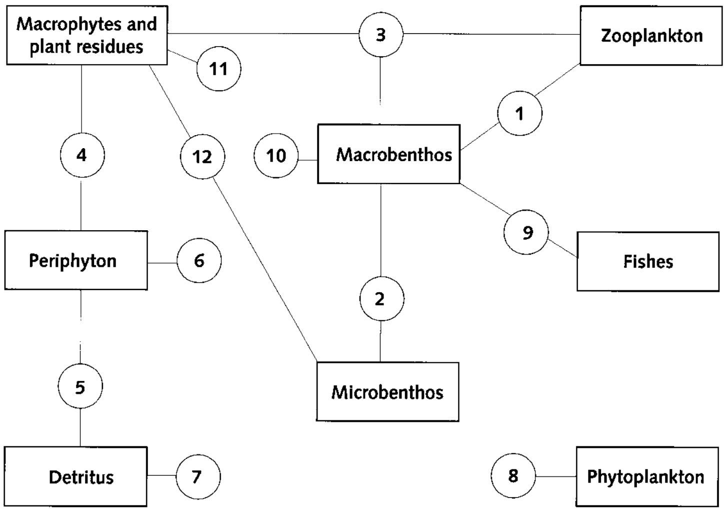


Figure 1. Scheme of the functional feeding links used in the development of the ITC. Each digit represents a trophic group indicated in Table 2.

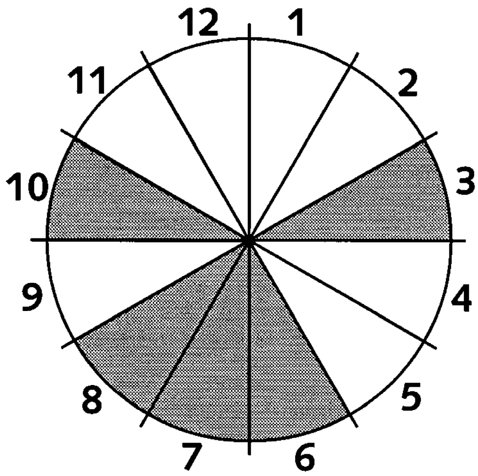


Figure 2. Example of an ITC pie graph showing present (grey) and absent (white) trophic groups.

mains an issue (Hendriks et al., 1997; Nijboer et al., 1998). ITC assessments of the sites on these rivers demonstrated cases of serious functional degradation of the macroinvertebrate communities. Five trophic groups were absent in the River Meuse, and four in the River Rhine (Table 3).

The Russian rivers included in the trial mappings are subject to much less dramatic river engineering than the European rivers, with little to no channelization. Less degradation was observed in the macroinvertebrate community in the chromium-contaminated Chusovaya River (South Ural Mountains), where five of the 12 trophic groups were absent. A chromium point source is responsible for this result (Leslie et al., 1999), while at sites downstream, a gradual improvement was observed due to self-purification processes in the river (Pavluk, 1997). A full recovery of all trophic groups was observed at Verhnyaya Oslianka, 350 km downstream from pollution sources (Table 3).

The South Urals rivers Iset and Techa (South Urals) showed severe degradation (seven and five absent trophic groups, respectively) which appears to be due to organic enrichment and the presence of oils in these rivers (Table 3).

Discussion

The analysis of samples collected from artificial substrates has shown that in disturbed river systems the number of ITC functional groups represented decreases. Various disturbance types may be responsible for the loss of groups, including toxic substances, either in mixtures (e.g., Rhine and Meuse) or single contaminants from point sources (e.g., Cr in the Chusovaya). River engineering also plays a role by having a direct effect on habitat availability, which likely contributes to the absence of ITC trophic groups in the highly channelized and regulated Rhine and Meuse rivers. Thus the ITC appears to be sensitive to both chemical and physical disturbances.

Another study on macroinvertebrate communities in the Chusovaya River also gave an indication of the sensitivity of the ITC method to physical effects such as changes to the flow regime caused by river engineering works. Downstream from a drinking water reservoir the flow is subject to strict regulation and extremely low flow with intermittent periods of very high discharge. Despite the excellent water quality at this site, the flow regime disturbances lead to the loss of trophic groups in the benthic macroinvertebrate community at this site (Leslie, 1998).

There are several examples which suggest that some of the trophic groups may show extra sensitivity to stresses in the system due to different exposure routes or due the different natures of disturbances. For example, biofilm grazers may be subject to extra exposure to contamination, such as metals, which become concentrated in the biofilms (Farag et al., 1998). In such a case, functional relatives could be under similar stress. Rivers lacking natural banks including typical aquatic and terrestrial vegetation may be expected to lack trophic groups dependent on macrophytes. Certain pollutants that are known to biomagnify in the food chain (e.g., Hg, PCBs), may be expected to be more of a risk to groups consisting of predators (higher in the food chain) than to groups consisting of herbivores. Filter feeders, especially those with relatively sedentary lifestyles (passive to moderate food searching behaviour) which rely on current velocity to bring food particles and prey may also be particularly sensitive to physical disturbances resulting in changes in flow regime. Other disturbances, such as dredging activities causing low visibility in the water may put extra stress on trophic groups consisting of actively hunting predators (Rusanov et al., 1990).

Various ITC trophic groups are bound to typical habitats typical for the function fulfilled, and in this way, trophic groups missing from communities (sampled from natural substrates) raise questions as to the availability of habitats which are often not recreated concomitantly with improvements in water quality.

Rehabilitation measures which improve ecosystem conditions in rivers often result in the colonization of available benthic habitats by non-indigenous species. The ITC method is not dependent on specific indicator species, and is thus also useful in assessing the functioning of rehabilitated river ecosystems, which always differ from the pristine state of the river. Another major advantage of the ITC approach is that it overcomes the geographical limitation of species to specific regions because it does not rely on indicator species (biotic indices) or reference community data (community comparison approach).

The ITC is considered to be a promising tool for river management and its further development worthwhile because of (a) the possibility of application of the ITC method to rivers in diverse geographical locations, (b) the ecological information provided by paying attention to the functioning within the community and ecosystem, (c) the initial results of trial mappings which indicate its sensitivity to a range of different disturbances, and (d) its clear form of presentation.

However, after the preliminary steps towards the development of the ITC method, a number of questions have arisen.

- How can the number of species per trophic group be incorporated into an ITC assessment to add qualitative information about the condition of the individual trophic groups (e.g., whether they are represented by many or very few species)?
- What factors are responsible for the sensitivity of certain trophic groups, leading to their disappearance before other groups?
- Does the type of disturbance determine which groups disappear first, and is there a typical disturbance-dependent order of disappearance?
- Initial data show that the more complex and severe the disturbances are, the more trophic groups were absent. What is the relationship between the severity of a disturbance and effects on community functioning detected in an ITC assessment?

Therefore, next steps in the development of the ITC assessment method include the trial applications using diverse data sets from rivers with various types of disturbance; the incorporation of a factor into the index which will give additional qualitative information on the diversity of the members of the trophic groups present in a community; investigations into the different effects of single pollutant types, contaminant mixtures, hydraulic and structural (habitat) effects, and how these stresses act together to produce the observed effect in the outcome of an ITC assessment.

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