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REVIEW PAPER

Biomonitoring of lakes using macroinvertebrates: recommended indices and metrics for use in West Africa and developing countries

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Abstract Lake systems are under heavy pressure impacting on their biodiversity and associated ecosystem services. This is especially acute in West Africa and developing countries which lack resources and technical capacities for waste disposal, water purification, as well as sufficient scientific capacities for biomonitoring and integrated management. The preservation, monitoring and improvement of lake quality in these countries are, however, of paramount importance. Throughout the developed world, an array of indicators and multimetric indices have been incorporated into lake biomonitoring and assessment. Here, we assess the numerous procedures, metrics and indices using macroinvertebrates as indicators for lake quality and assess applicability in West African lakes and in developing countries more generally. We propose a framework for macroinvertebrate-based monitoring adapted to these countries, including recommendations for developing new indices and adapting tolerance scores of taxa to local conditions. This work underlines the importance of macroinvertebrates for biomonitoring of lake health in West African lakes and developing countries more generally.

Keywords Ecological indicator · Multimetric indices · Lakes · Developing countries

Introduction

Bioindication—referring to the use of animals and plants for assessing past, current, or future risks or processes of the ecosystem—is a common tool used to describe and to evaluate environmental conditions,

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and to assess the effectiveness of environmental policies (Dziock et al., 2006). Bioindicators can be based on a single taxon or on entire assemblages/communities of species which presence/absence, abundance or diversity patterns can provide information about human- and natural-induced changes in ecosystems (Angermeier & Davideanu, 2004; Cousins & Lindborg, 2004; Nahmani et al., 2006; Van Den Broeck et al., 2015). The use of bioindicators for monitoring is advantageous since biological communities reflect overall ecological quality and have great power of information integration (Bervoets et al., 1989; Cairns & Pratt, 1993; Odountan & Abou, 2015). More specifically, they are able to integrate the effects of different stressors providing a broad measure of their impact (Iliopoulou-Georgudaki et al., 2003).

Vertebrates, macroinvertebrates, phytoplankton, zooplankton and macrophytes can all be used as biological indicators (O' Connor et al., 2000, Van Den Broeck et al., 2015). In lotic aquatic ecosystems, macroinvertebrates are the most commonly used because of specific life history traits and ecology (e.g., limited mobility, relatively long life spans, broad tolerance range) (Rosenberg & Resh, 1993; Voshell, 2002). Literature reviews of biological indicators used for water quality assessment of lentic and lotic systems show that at least 60% of the indices developed over the past 20 years are based on macroinvertebrate species or communities (Czerniawska-kusza, 2005). Yet, even though several indicators have been developed for different types of aquatic ecosystems (Cairns & Pratt, 1993; Herman & Nejadhashemi, 2015; Van Den Broeck et al., 2015), the biomonitoring of lake systems using macroinvertebrate assemblages is less developed compared to that in lotic systems (Poikane et al., 2016). This is mainly due to sampling and identification difficulties, alongside the large biogeographical and spatial variation in physical and chemical characteristics of lakes, especially the heterogeneity of their littoral zone (White & Irvine, 2003, Gnohossou, 2006; Poikane et al., 2016), preventing a 'one fits all' approach for a certain region. The general preference for biomonitoring of lake systems by means of plankton also stems from the assumption that the major part of such systems is rather the water column and that often the benthic zone is anoxic (e.g., Ekau et al., 2010). This has led to a lack of knowledge on oxygenated benthic parts of lakes (both along the shores and in shallow waters) and neglecting a large part of the fauna with a potential indicator value and important role in the food web (e.g., Hu et al., 2016). Several studies tested macroinvertebrates as indicators for lakes to fill this knowledge gap (e.g., White & Irvine, 2003; Brauns et al., 2007; McGoff et al., 2013). Moreover, many methods have been developed for addressing different pressures or combinations of pressures, often using different sampling methodologies and focusing on different lake habitats (profundal, sublittoral or littoral) (Poikane et al., 2016). Barbier et al. (2011) list the ecosystem 'goods and services' and their values (consumptive, non-consumptive, direct, indirect) provided by aquatic ecosystems, highlighting the link between a healthy ecosystem and healthy human populations. Unfortunately, lakes around the world are increasingly under pressure due to anthropogenic activities and climate change (Eggermont et al., 2010; Sheela et al., 2011). It is therefore of paramount importance to have adequate knowledge on the applicability of major methods or indices used to assess and monitor the water quality and biota, especially in developing countries, where human populations often rely in a more direct way on the goods and services that biodiversity supplies (Eymann et al., 2010).

A parsimonious approach to index development would be for ecologists to place greater emphasis on evaluating the suitability of existing indices prior to the development of new ones (Borja & Dauer, 2008). When using macroinvertebrates to monitor Lake Nokoue in Benin, however, very few studies of relevance to African countries were found (Odountan & Abou, 2015, 2016) and thus it was difficult to build upon existing indices or metrics from the region. Here, we present a review of selected literature published worldwide over the past 15 years concerning macroinvertebrate biomonitoring in lakes in an attempt to draw some lessons for West Africa and developing countries in general. This review is complementary to others (see Poikane et al., 2016) as we discuss how methods used in Europe, North America, Asia and Oceania for biomonitoring of lakes might be applicable to developing countries. The approach is aimed at gaining a better understanding of the underlying logic of tools used (indices or metrics), and to suggest some ways forward for these countries. To limit the scope of this paper, we excluded the use of morphological deformities in Chironomidae, often used as an indicator for heavy metals and pesticide pollution (see e.g., Janssens de Bisthoven et al., 1998).

Materials and methods

In this study, we considered a lake ecosystem to be an enclosed body of water with no direct access to the sea (Thomas et al., 1996; Wetzel, 2001). We analysed 31 selected articles gathered through the most common scientific databases using Web of Science (SCI; Thomson Reuters) and Google Scholar with a Boolean search and quotation marks. The search terms used were 'macroinvertebrates, benthic invertebrate, lake, water quality, monitoring, biomonitoring, ecological status, assessment, biological metrics, pollution, biotic index and multimetric index'. To draw relevant conclusions, preference has been given to countries with a strong tradition of biomonitoring (Birk et al., 2012; Guo et al., 2015; Poikane et al., 2016) and tools and indices currently used by official water authorities. Of these, twenty-one referred to Europe, five to North America, four to Asia and one to Oceania. None of the studies were conducted in Africa. Most of these articles (i.e. 27 out of 30) were published during the period 2000–2015, while three were retained from before 2000. The latter allows us to get a more complete overview and to properly understand the context of these methods. For calibration purposes, we added into Table 1 an overview offered by Poikane et al. (2016) of macroinvertebrate-based methods in EU countries.

Results

Thirty-one studies were reviewed, as summarized in Table 1. It provides an overview of different indices, metrics and organisms used for monitoring, their advantages/implications and disadvantages/limitations and other information including the type of habitat, the addressed pressure and region of application. Table 1 clearly shows that macroinvertebrates can be used to assess several pressures and pressure combinations, such as eutrophication (twelve studies), acidification (three studies), hydromorphological alterations (two studies) and multiple disturbances or biotic integrity (thirteen studies). These studies are mainly based on biodiversity metrics, biotic indices, multimetric indices or multivariate analysis.

Discussion

With the exception of phytoplankton, macroinvertebrates are the most commonly used group of organisms in biological monitoring of lakes (Birk et al., 2012). They display a wide range of biological characteristics useful in this respect—such as ubiquity, high number of species, short generation time (allowing for rapid response to environmental disturbance) and relatively well-known life history (Innis et al., 2000), among others. Following the approaches used for rivers by Ollis et al. (2006) and Herman and Nejadhashemi (2015), we distinguished four broad biomonitoring approaches to assess lake water quality by means of macroinvertebrate assemblages: biodiversity metrics, biotic indices, multimetric indices and multivariate methods.

Biomonitoring approaches

Biodiversity metrics

In order to decide whether a particular macroinvertebrate assemblage corresponds to a certain level of pollution of a lake, and hence can serve through biomonitoring as scientific basis for management or conservation measures by policy and decision makers, the biodiversity as main indicator of ecosystem health needs to be assessed and related to biotic and abiotic factors. Koperski (2011) identified at least 10 indices related to species abundance and composition of macroinvertebrates. The relationship between primary productivity (nutrient load) and taxa richness of many aquatic organisms is unimodal (Dodson et al., 2000): taxa richness is low at oligotrophic level, it generally peaks at mesotrophic levels and decreases as lakes become eutrophic. Therefore, the sites that are less polluted are generally characterized by relatively higher species richness. Diversity measures and associated metrics are mostly referring to α or γ biodiversity (Whittaker & Whittaker, 1972; Diomande et al., 2013), with as basic metrics the Species Richness (S), the Shannon–Weaver Index and Simpson Index (DeJong, 1975). In lakes, these indices are widely

Table 1 Overview of criteria derived from 30 studies on biomonitoring of lakes worldwide with macroinvertebrate communities. A summary of official methods used in EU countries is added in the first row for benchmarking

Taxon	Method/index	Region	Metrics and organisms	Habitat: pressure	Advantages/ implications	Disadvantages/ limitations	References
Macroinvertebrates in the EU: benchmarking of methods	(1) Multimetric Macroinvertebrate Index Flanders (MMIF) (Belgium) (2) German Macroinvertebrate Lake Assessment (AESHNA) for lowland or alpine lakes (Germany) (3) Estimation of freshwater quality using macroinvertebrates (Estonia) (4) Benthic Quality Index (BQI)(Finland) (5) Lithuanian Lake Macroinvertebrate Index (LLMI) (Lithuania) (6) WFD—Metrics for Natural Water Types (Netherlands) (7) Multimetric assessment method for acidification of clear lakes (MultiClear) (Norway) (8) Multimetric Index for Lake Acidity (MILA)(Sweden) (9) Benthic Quality Index (BQI)(Sweden) (10) Slovenian Lake littoral benthic invertebrate index (LBI)(Slovenia) (11) Chironomid Pupal Exuviae Technique (CPET)(United Kingdom) (12) Lake Acidification Macroinvertebrate Metric (LAMM)(United Kingdom)			(Numbers refer to left column) Eulittoral 1,2,3,5,6,7,8,9,11 Eutrophication 1,2,3,4,5,6,9, 11 Morphological pressures 1,2,3,5,6,10, Profundal 4,9 Acidification 7,8,12 Whole lake 11	See Poikane et al. (2016)	See Poikane et al. (2016)	Wiederholm (1980) Gabriels et al. (2010) McFarland et al. (2010) Ruse (2010) Timm & Möls, (2012) Miler et al. (2013) Šidagyte et al. (2013) Johnson & Goedkoop (2007) Jyväsjärvi et al. (2010) Sandin et al. (2014) Böhmer et al. (2014) Urbanič (2014) Poikane et al. (2016)
Chironomidae and Oligochaeta	Benthic Quality Index (BQI)	Sweden	Percentage of taxa, tolerance of taxa	Profundal lake: eutrophication	Very long history of use Easy to evaluate and integrates autotrophic and heterotrophic disturbances	Restricted to 7 indicator taxa of Chironomidae and five of Oligochaeta Exclusion of depth Indicator taxa missing for natural reasons or simply undetected	Wiederholm (1980)

Table 1 continued

Taxon	Method/index	Region	Metrics and organisms	Habitat: pressure	Advantages/ implications	Disadvantages/ limitations	References
Mollusca	Index based on Lacustrine Mollusca (ILM)	France	Presence/absence and generic criteria	Small lakes area: biotic integrity	Sampling protocol standardized Easy to evaluate Rapid and accurate Adapted for larger, deeper and very shallow lakes or ponds	More accurate for small area (< 500 hect.), deeper than 10 m and situated at altitude lesser than 1000 m	Mouthon (1993)
Chironomidae	Benthic Quality Index	Finland	Percentage of taxa, tolerance of taxa	Profundal lake: eutrophication	Availability of reference values of BQI based on morphometric data of lakes	Restricted to 7 indicator taxa of Chironomidae Indicator taxa missing for natural reasons or simply undetected	Wiederholm (1980), Jyväsjärvi et al. (2010)
Chironomidae	Benthic Quality Index Modified (BQIM)	Italia	O_2% saturation, transparency, total phosphorus the species abundances	Lakes (Northern Italy, volcanic and artificial): eutrophication and organic pollution	Accurate as trophic status index Based on different types of lakes Sometimes less detailed identification required	Moderately difficult to evaluate Must be tested for profundal communities in great lakes and brackish water lakes	Rossaro et al. (2007)
Chironomidae	The chironomid pupal exuvial technique (CPET)	United Kingdom	Species abundance, nr. of taxa, total nitrogen, total phosphorus	Whole lake: eutrophication	Easy and effective sampling method for the most species-rich and ubiquitous family, already calibrated for other European member states	Exclusion of acidified lakes and naturally acidic humic lakes Difficult to use when many species are scarce Fairly identification expertise	Ruse (2010)
Chironomidae	Profundal Invertebrate Community Metrics (PICM)	Finland	Percentage of taxa, tolerance of taxa	Profundal lake: eutrophication	High generality, accuracy and representativeness of lake profundal assessment Be compared to BQI	Approach and method need to be modified for regional faunas and conditions before being applicable to other regions and organisms.	Jyväsjärvi et al. (2014)

Table 1 continued

Taxon	Method/index	Region	Metrics and organisms	Habitat: pressure	Advantages/ implications	Disadvantages/ limitations	References
Macroinvertebrates	Macroinvertebrate Biotic Index of Saint-Francois Lake	Canada	% of some taxa, relative abundance of 62 pollution-tolerant taxa	Fluvial lake: eutrophication and toxic pollution	Combined ecological and toxicological factors Relatively easy to evaluate	Large amount of unexplained variance (49.286.6%) limits the use	Pinel-Alloul et al. (1996)
Macroinvertebrates	Multiple taxonomic groups to index the ecological condition of lakes	New England	Taxa richness, % individuals as dominant taxon %, multimetric index of benthic integrity	Lakes: general anthropogenic stress	Robust and useful and address very well multiple stress	Required high taxonomic expertise also in diatoms Low perceived social value of diatoms	O'Connor et al. (2000)
Macroinvertebrates	Lake Bioassessment Integrity Index (LBII)	United States	HBI, taxa richness, relative abundance, % of some taxa, community loss Index, community similarity index, trophic condition index, Dominant-in-Common-5	New England States lakes: anthropogenic disturbances	Easy to evaluate; integrate Condense, and summarize 12 biological parameters Detects stressed lakes and differentiate between different levels of stressors	Based on limited data from a small area Some of the individual metrics are less discriminating and contribute less to the final index score	Lewis et al. (2001)
Macroinvertebrates	Lake Macroinvertebrate Integrity Index (LMII)	USA	HBI, % chironomid, % collector-gatherer taxa, number of diptera taxa and % oligochaetes/ leeches	Sublittoral (Lakes and reservoirs): eutrophication	Easy to evaluate Accuracy to detect changes in condition at a given lake through time or differences between two lakes	Lake origin lacked Not appropriate when reference conditions lack Designed for silt or intermediate sediment types High detailed identification (specie)	Blocksom et al. (2002)

Table 1 continued

Taxon	Method/index	Region	Metrics and organisms	Habitat: pressure	Advantages/ implications	Disadvantages/ limitations	References
Macroinvertebrates	Swan Wetlands Aquatic Macroinvertebrate Pollution Sensitivity	Australia	Sensitivity grades of taxa, percentage of taxa and abiotic variables	Wetlands (including lakes): eutrophication, habitat degradation and anthropogenic changes	Effective index for disturbances and morphological changes, based on local habitat Encourage assessment and conservation of ecosystems Confers substantial benefits to trophic status	Required good statistical expertise, Family-level index was no substitute for a species index Be tested modified and required the derivation of sensitivity grades of additional taxa for another region	Chessman et al. (2002)
Macroinvertebrates	Prediction system for lake stony-bottom: RIVPACS-type models	Sweden	Lake surface area variables; geographic position variables; catchment classification variables; riparian classification variables, habitat classification substratum variables, water chemistry and vegetation variables	Littoral of mixed forest, coniferous forest and arctic/alpine regions: biotic integrity	Observed/Expected interpretation is intuitive and rather straightforward Adapted for assessing and monitoring of ecological quality of lakes	Implement required high statistical expertise, and reference condition Required high abiotic variables Must be developed for each ecoregion	Johnson (2003)
Macroinvertebrates	Lake Biotic Index (LBI)	France	Depth, taxonomic richness, density, isobaths length	Littoral and relative profundal zone: morphological pressures, eutrophication	Accurate for functional studies and for lake diagnosis and lake surveys, less detailed identification required	Some components difficult to measure Limited period study Separated interpretations of biogenic potential and functional capacity of lakes	Verneaux et al. (2004)
Macroinvertebrates	Macroinvertebrate Index of Biotic Integrity for the Lake Agassiz (MIBI)	USA	% swimmers, % diptera, % dominant taxa, collector taxa, burrower taxa, clinger taxa, taxa richness	Lake Agassiz: human disturbance	Based on 62 biological metrics relatively easy to evaluate Integrated physical and land use aspects Standardized index	Insufficient numbers of impaired, least disturbed and reference sites Be continually revised and updated for each lake	Haugerud (2006)

Table 1 continued

Taxon	Method/index	Region	Metrics and organisms	Habitat: pressure	Advantages/ implications	Disadvantages/ limitations	References
Macroinvertebrates	Macroinvertebrates based metrics in a Mediterranean shallow lake	Spain	% Insecta, Shannon–Weaver diversity index and the qualitative taxonomic metrics (measures based on number of taxa)	Mediterranean shallow lake: eutrophication	Considered natural variation (both spatial and temporal) of biological communities	Capacity of metrics to discriminate between impaired and non-impaired is not enough considered	Trigal et al. (2006)
Macroinvertebrate	Taxonomic resolution	Finland, Ireland, Sweden and the United Kingdom	Abundance of taxa; taxa richness; ASPT; Biological monitoring working party score (BMWP), Chlorophyll-a, total phosphorus alkalinity, rK relationship, % FFG	Littoral and profundal lakes: eutrophication	Useful tool for ecological status classification Address well trophic status	High harmonization of sampling methods Statistically tools less robust Not appropriate for littoral High detailed identification (specie)	O'Toole et al. (2008)
Macroinvertebrates	Species-based indicators of lake acidification	EU (UK, Norway and Sweden)	Sensitivity of species; abundance of taxa; taxa richness	Littoral: acidification	Relatively easy approach; robust response of biotic indices to acidification into a new multimetric index	Large amount of unexplained variance of quality (> 70%); method required further harmonization and standardization of sampling effort and taxa identification	Schartau et al. (2008)
Macroinvertebrates	Multimetrics Index for bioassessment of water quality	China	Total number of taxa, the number of mollusca & crustacea taxa, % mollusca & crustacea, % gastropoda, Goodnight–Whitley index, HBI index and % Collector-gatherers	Lake: human disturbance	Based on 21 biological metrics candidates Relatively easy to evaluate Basic, suitable for water quality assessment in different areas of Taihu Lake	Based on single sampling Required appropriate location and high number of sampling sites	Taowu et al. (2008)

Table 1 continued

Taxon	Method/index	Region	Metrics and organisms	Habitat: pressure	Advantages/ implications	Disadvantages/ limitations	References
Macroinvertebrates	Ecological quality ratio (EQR)	Ireland	Taxa sensitivity to total phosphorus, invertebrate abundance	Littoral of lakes: eutrophication	Robust prediction of nutrient status, allows the incorporation of new taxa,	Adapted for hard than soft substrata High statistical expertise Required paleontological data	Donohue et al. (2009)
Macroinvertebrates	Multimetric Macroinvertebrate Index Flanders (MMIF)	Belgium	Taxa richness, number of EPT taxa, number of sensitive taxa, Shannon–Wiener diversity index, mean tolerance score	Eulittoral: eutrophication and morphological pressures	Relatively easy to evaluate Robust and reliable index Less detailed identification (genus level) Reflect a number of criteria of the EU WFD	Only developed for Flanders (Belgium) Not appropriate during winter	Gabriels et al. (2010)
Macroinvertebrates	Lake Acidification Macroinvertebrate Metric (LAMM)	United Kingdom	Acid sensitivity value of taxa, Indicator weight of taxa, Abundance rating of taxa k.	Eulittoral: acidification	Accurate in clear and humic lakes for all ranges of acid neutralizing capacity Important tool for management and conservation of whole acidic lakes (naturally and anthropogenically)	Difficult to evaluate Seasonal variation not considered during sampling Sometimes LAMM status is at variance with nutrient and chemical status	McFarland et al. (2010)
Macroinvertebrates	Assessment of biological recovery of acid-and metal-damaged lakes	Canada	Trichoptera, EPT and taxon richness, Diptera richness, % of some taxa and functional feeding group (FFG), Shannon–Wiener and Simpson indices	Littoral of lakes: acidification	Relatively easy to measure lake recovery; Less detailed identification required (family level)	Lack of quality class boundaries Difficult of use for biomonitoring Required further investigation before adoption	Wesolek et al. (2010)

Table 1 continued

Taxon	Method/index	Region	Metrics and organisms	Habitat: pressure	Advantages/ implications	Disadvantages/ limitations	References
Macroinvertebrates	Macroinvertebrate-based Nepal Lake Biotic Index (NLBI)	Nepal	Richness and tolerance measures	Lake and reservoir: human disturbance	Effective tool of ecological assessment, less detailed identification required for many taxa	Longterm reliability and usefulness of the NLBI is not proved, Lake typology and seasonal attributes are not considered	Shah et al. (2011)
Macroinvertebrates	Macroinvertebrates in Estonia: Score of Hydromorphology (MESH)	Estonia	Indicator taxa score	Eulittoral: eutrophication and morphological pressures	Easy to evaluate Reliable Index of prevailing bottom substratum type Inter-annual variation considered	Reference samples insufficient Has to be improved by including generalized bottom types (stony, sandy, and muddy)	Timm & Möls (2012)
Macroinvertebrates	Littoral Invertebrate Multimetric based on Habitat samples (LIMHA) Littoral Invertebrate Multimetric based on Composite samples (LIMCO)	European	Taxonomic and functional composition, diversity indices, abundance, disturbance sensitive taxa. abundance class.	Eulittoral: morphological pressures	Integrates seven natural and heavily morphologically degraded lakes Method involving a uniform methodology and regionalized optimization Complement of assessment approaches focusing solely on lake eutrophication so far	Required validation with other independent lakeshore data Tested only with one morphological method (Lake Habitat Survey) and forsaked other interested methods (Hydro morphology of Lakes)	Miler et al. (2013)
Macroinvertebrates	Lithuanian Lake Macroinvertebrate Index (LLMI)	Lithuanian	Average score per taxon (ASPT), first Hill's number (H), Number of Coleoptera, Ephemeroptera and Plecoptera taxa (CEP); % Coleoptera, Odonata and Plecoptera (COP)	Eulittoral: eutrophication and morphological pressures	Suitable for a reliable evaluation of lake status of stony/ pebbly and vegetated littoral mesohabitat Fully complies with the WFD requirements	Has to be developed (validated and adjusted reference values) for application over a broader range of disturbances	Šidagyte et al. (2013)

Table 1 continued

Taxon	Method/index	Region	Metrics and organisms	Habitat: pressure	Advantages/ implications	Disadvantages/ limitations	References
Macroinvertebrates	Littoral Fauna Index (LFI)	Slovenia	Occurrences of taxa, physical alterations and human use	Eulittoral: morphological pressures	Nearly no detailed identification required (family level) Cost-effective and appropriate index for routine monitoring Independent to alpine lake	Needs to be tested on other lake types Assumed weaker responses to other pressures is not proved	Urbanič (2014)
Macroinvertebrates	Multi-biotic Integrity Index for Dongting lake (LMII-D)	China	6 metrics based on algae, % facultative individuals, % Chironomidae individuals, % predators individuals and total number of taxa.	Eulittoral freshwater: eutrophication and human disturbance	Based on 39 biological metrics Accurate and strongly related to the major chemical and physical stressors	Difficulties of identification and evaluation of the index Low perceived social value of diatoms, Lack of many metrics (habitat, hydrology, physics and chemistry) Insufficient sampling sites	Wang et al. (2015)
Macroinvertebrates	Bangladesh Lake Biotic Index (BLBI)	Bangladesh	Environmental variables, taxa tolerance scores, percentage of taxa	Eulittoral: organic pollution	Tolerance values calibrated locally, easy to evaluate and intuitive interpretation, correlated to structural metrics. Encourage assessment and conservation of lakes	Exclusion of lake typology and seasonal attributes Be tested modified, calibrated for other lake types and Asian countries Required good statistical expertise	Chowdhury et al. (2016)

Table 1 continued

Taxon	Method/index	Region	Metrics and organisms	Habitat: pressure	Advantages/implications	Disadvantages/limitations	References
Macroinvertebrates and zooplankton	Biological index to evaluate water quality (QAELS[e] 2010)	Catalunya (Spain)	Composition of microcrustaceans and sensitivity of species to water quality (ACCO[e] 2010), crustacean and insect richness (RIC value)	Wetlands and shallow lakes: biotic integrity	Robust and adapted to all lentic, temporary or permanent systems High sensitivity to multiple stressors Used by official water authorities	Required high taxonomic expertise for microcrustaceans Highly unstable index between habitats	Quintana et al. (2015)

used for comparing diversity between various habitats (sites) and used as measures of disturbance (e.g., Imoobe, 2008; Kouadio et al., 2008; Adandedjan et al., 2012; Diomande et al., 2013; Yakub & Igbo, 2014) eventually in combination with other metrics (Parsons et al., 2010; Odountan & Abou, 2015, 2016). Assemblages can also be assessed for their 'evenness' (i.e. a measure of the relative abundance of the different species making up the richness in an area) with well-known indices such as Pielou's (Pielou, 1966) or Hill's index (Hill, 1973), next to Margalef's index, Odum's index and Menhinick's index (Haugerud, 2006; Rossaro et al., 2007; Parsons et al., 2010). The interpretation step from raw biodiversity data towards scores calculated by indices (see overview in Table 1 and next paragraph) towards inferring a certain level of pollution should be done cautiously and any transfer of methods to different ecosystems or regions needs some calibration (Simboura & Zenetos, 2002). Besides the biodiversity indices listed above, species composition and functional feeding groups (FFGs) can also be used for biomonitoring as alternatives or in complement (Mandaville, 2002; Wang et al., 2007; Gamito & Furtado, 2009; Mereta et al., 2013). The use of FFG metrics is, however, often based on entire insect orders or families, which in fact include several FFGs, hence reducing their resolution power (e.g., Gabriels et al., 2010; Parsons et al., 2010). For better management of West Africa lake ecosystems, where the taxonomic expertise is limited, "evenness feeding diversity" (EFD) is suggested (Gamito & Furtado, 2009). It consists of an evaluation of the evenness of observed functional feeding groups. This method assumes that the evenness increases in healthy environments (Gamito & Furtado, 2009). This approach is a practical and robust method to estimate the ecological status of lakes and it has the advantage of needing low taxonomic resolution and being less sensitive to small samples.

Biotic indices

The so-called biotic indices are relatively straightforward methods, used to assess aquatic ecosystem conditions by the calculation of one single metric (e.g., Herman & Nejadhashemi, 2015). Biotic indices such as the Biotic Index (or Family Biotic Index) (Hilsenhoff, 1987, 1988), the Belgian Biotic Index (see Bervoets et al., 1989) and Valle del Cauca Biotic

Index (Mathuriau, 2002) use a single parameter or criterion which is the tolerance score of taxa to organic pollution (Haugerud, 2006). Two main approaches are used to estimate tolerance (Gnohossou, 2006). The first method assigns prior scores to organisms based on observations and knowledge about their distributions and ecology, whereas the second method is referred to as the 'method of sites groups'. See also Hilsenhoff (1988), Hellawell (1978), and Alba-Tercedor and Sánchez-Ortega (1988) for discourses about tolerance score setting. These biotic indices are originally used for evaluating the health of streams but could in principle also be used for lakes (Gnohossou, 2006; Odountan & Abou, 2015), although we expect that the oxygen sensitive taxa will be less prominent in lakes and hence might mitigate the power to discriminate between moderate pollution and absence of pollution. A drawback of the biotic index is that effects of multiple stressors (e.g., eutrophication coupled to acidification) are not easily detected or distinguished. This situation is due to the fact that organisms do not have the same tolerance towards several types of disturbances. It is therefore difficult for a biotic index to be effective for a combination of stress.

Multimetric indices

Multimetric indices (MMI) are intended to inform on the ecosystem conditions by means of multiple metrics. Multiple stressors disturbances need robust monitoring tools, combining several techniques in a global approach of MMI in order to better capture all kinds of anthropogenic stress and the possible origin of the effects observed. In an MMI, each metric represents a physical, chemical or biological component of ecosystem quality or of biological variables (e.g., Gerhardt et al., 2004; Gabriels et al., 2010; Van Den Broeck et al., 2015). Multimetric indices are flexible and offer the possibility for adjustment by adding or removing metrics (Gabriels et al., 2010). Provided there is sufficient expertise and technical capacity, they can be combined with, or they can integrate, other methods designed for specific pollution types such as percentage of deformed chironomids as a measure of sediment pollution by heavy metals and or pesticides (e.g., Janssens De Bisthoven et al., 1998). The development of MMI, however, does require the consideration of the following factors: type of disturbance, metric selection and index calculation, quality class boundaries, sampling design, number and period of sampled habitat (Gabriels et al., 2010; Gupta, 2014). Sampling design not capturing natural variability, or wrong number and period of samples can affect the precision of the developed index (see for example the fish index developed by Irz et al. (2008). Taxonomic identification level, correct classification and identification and correlation with environmental variables (validation) (e.g., Gabriels et al., 2010) are also prerequisites for sound biological multimetric indices. Some examples include the Macroinvertebrate Index of Biotic Integrity for the Lake Agassiz Plain Ecoregion (48) in North Dakota (Haugerud, 2006), the Lake Macroinvertebrate Integrity Index (LMII) for New Jersey lakes and reservoirs (Blocksom et al., 2002) and the Multimetric Macroinvertebrate Index Flanders (Gabriels et al., 2010) (see examples in Table 1).

Multivariate methods

As a useful complement to biotic and multimetric indices, multivariate statistical methods aim at providing a better view of the biotic and abiotic features potentially responsible for the assemblage of the observed organisms, by detecting groups of sites or taxa with similar attributes. Commonly used multivariate methods for macroinvertebrates include self-organizing map (SOM) and Discriminant Analysis (DA) (e.g., Yang et al., 2010; Adandedjan et al., 2013), Cluster Analysis (CA), Factorial Analysis (FA), Principal Component Analysis (PCA) (Panigrahi et al., 2007) and correlation analysis (e.g., Odountan & Abou, 2015). Moreover, Canonical Correspondence Analysis (CCA) was developed especially for ecological analysis, and together with Redundancy Analysis (RDA) and Detrended Canonical Analysis (DCA), they take unimodal and linear ordination approaches into account (Lepš & Šmilauer, 2003). As illustrated by Sheela et al. (2011) for urban lakes in India, such multivariate techniques applied on macroinvertebrates are pertinent tools of classification, modelling and monitoring. As explained further, PCA can be used to identify and scale the main disturbance gradient of a lake.

Several studies comparing dozens of lakes in Europe or the US for the ability of macroinvertebrates to be indicators by means of metrics, using multivariate analysis, conclude that they can effectively be used in lake monitoring, provided the variability of littoral mesohabitats and substrate is taken into account as nested variability into the inter-site variability. White & Irvine (2003) recommend that macroinvertebrate assemblages can provide meaningful assessment of ecological differences across lakes. Monitoring can, however, produce a substantial amount of 'noise' from the data that reflect the complexity of macroinvertebrate community structure in littoral zones. It is recommended as a solution that incorporation of macroinvertebrates in ecological assessment is most useful when confined to well-defined mesohabitats rather than trying to incorporate a complete range of mesohabitats within a single lake. In another broad study on lowland lakes, Brauns et al. (2007) demonstrated that macroinvertebrates tend to correlate with total phosphorus, the proportion of woody debris and root habitats and the proportion of grassland (as land use). They conclude that trophic state influenced the composition of eulittoral macroinvertebrate communities but to a lesser extent than has been previously reported for profundal habitats. They also concluded that macroinvertebrates are not strong indicators of the trophic state of lowland lakes but that they may be used to assess other anthropogenic impacts on lake shores. Similarly, in a Canadian study of 13 lakes, littoral invertebrates provided an early indication of lake perturbation, but their response varied according to the substratum. Oligochaetes were positively associated to perturbation, whereas mayflies were negatively associated. Sediments were a better indicator substratum than rocks for biomonitoring the impact of lake residential development (De Sousa et al., 2008). In another approach, the power of the physical characteristics of streams (e.g., order, slope, substratum) to effectively predict macroinvertebrate assemblages has been developed in the RIVPACS models in the UK (Wright et al., 1998). Johnson (2003) demonstrated that this approach is applicable to small boreal lakes as well. These studies essentially underline the potential of macroinvertebrates for the biomonitoring of lake health. However, more attention should be paid when using macroinvertebrates as indicators of hypertrophic lowland lakes with predominance of invasive species, low water residence times and connected to a larger river system (Brauns et al., 2007). Also, in view of the large existing capacity gaps, development or application of multivariate method in modelling approaches could be more difficult to implement in West Africa as this cluster of methods require more statistical expertise than biotic or multimetric indices.

A proposed biotic index per lake system

Table 1 gives the scope, regions of implementation, implications and limitations of a selection of indices for biomonitoring with macroinvertebrates of lake systems, the eulittoral zone of lakes, fluvial lakes which are shallow or profundal lakes. Below, we will discuss to what extent these methods could be useful in the context of West African lakes.

Profundal lakes

Although the proposed framework in Fig. 1 is more specifically entailed for shallow lakes (see below), which are more common in West Africa, we also include some discussion on deeper lakes for sake of completeness. Deep lakes (depth often > 5 m), are relatively scarce in West Africa but elsewhere in Africa they are more common (e.g., the rift valley lakes Tanganyika and Kivu). A quarter of the selected articles (Table 1) predominantly used Chironomidae as the main macroinvertebrates representatives for biomonitoring purposes. This clearly reflects the dominant position of chironomids in lake sediments and shore vegetation. One reason is the extreme tolerance of the subfamily of Chironomini to near anoxic conditions, often prevalent in the profundal. This is due to the presence of haemoglobin in their body, hence facilitating oxygen transport (Lee et al., 2006). Besides Chironomini larvae, Oligochaeta worms also are frequently used in biomonitoring of deep lakes (Wiederholm, 1980; Jyväsjärvi et al., 2014). For the bioassessment of profundal lakes, the Benthic Quality Index (BQI) (Wiederholm, 1980) is probably one of the, most effective and most widely used indices (Table 1). The chironomid Benthic Quality Index (BQI) ranks from 0 to 5 (with 5 being the least polluted) and includes 7 taxa. The Oligochaeta BQI ranks from 0 to 4 (with 4 being the best) and includes 5 taxa. The indices are calculated using k_i = score of the various groups, respectively; n_i = number of individuals of the various groups, respectively, and N = total number of indicator species (Eqs. 1, 2).

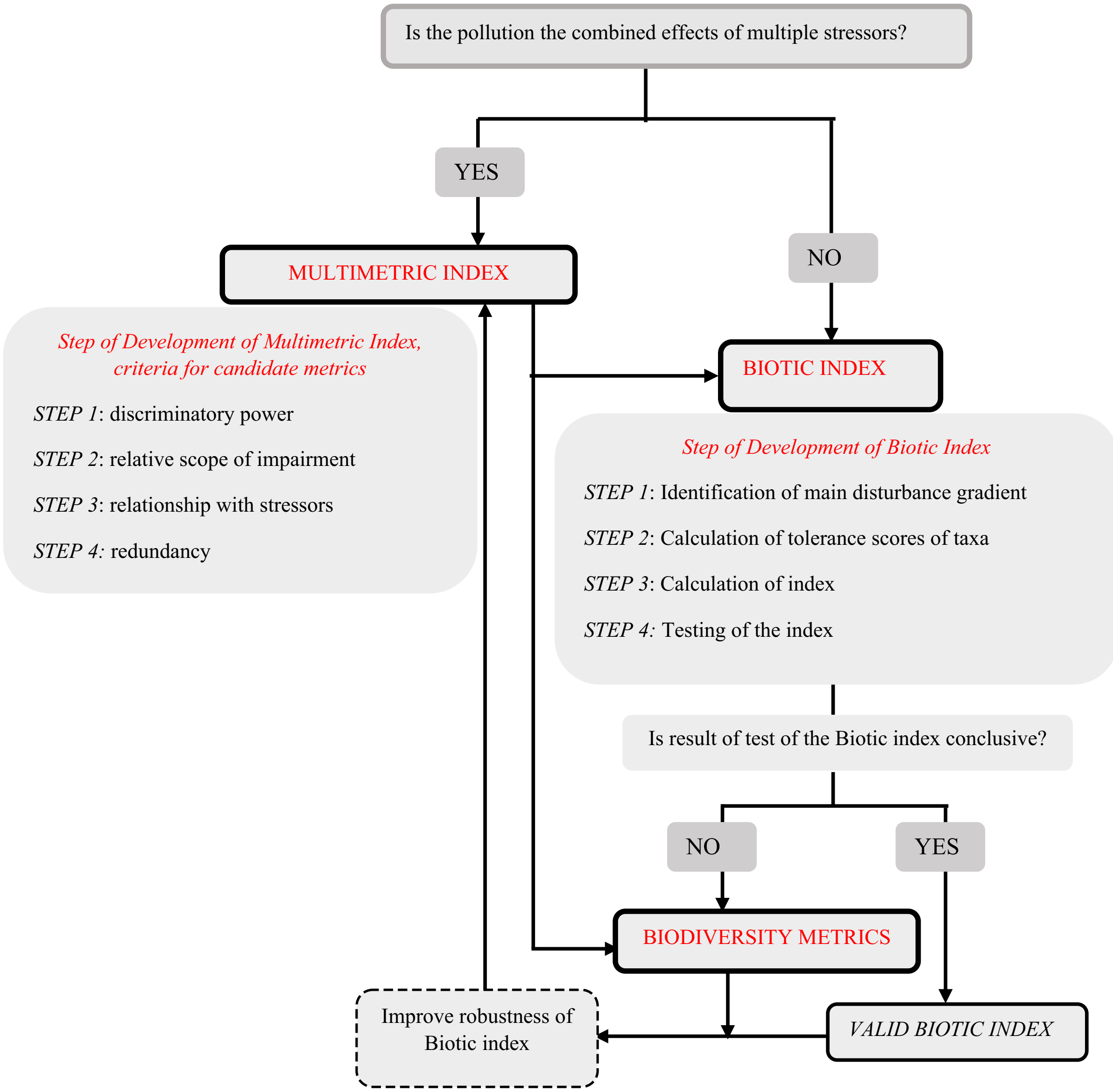

Fig. 1 A proposed general framework for developing biomonitoring of lake systems in developing countries

$$\text{BQI (Chironomids)} = \sum_{i=0}^{5} \frac{n_i.k_i}{N} \tag{1}$$

$$\text{BQI (Oligochaetes)} = \sum_{i=0}^{4} \frac{n_i.k_i}{N}. \tag{2}$$

Although the chironomid BQI was mostly adopted as a profundal habitat-monitoring tool (Johnson, 1998; Raunio et al., 2007; Verbruggen et al., 2011), the restriction of this index to only 7 chironomid indicator taxa led Jyväsjärvi et al. (2014) to extend the indicator taxa by including 70 taxa specifically for Finland. These taxa represent all common profundal macroinvertebrates of 735 lake basins in Finland. This extension of the number of indicator taxa and correction of taxa scores is encouraged and recommended for profundal zones in developing countries. However, chironomid BQI and oligochaetes BQI require species-level identification and taxonomic experts which are rare even in developed countries. Although we might have a few of these experts in West Africa, we have no certainty about their availability and capacity on the task of identifying all samples for biomonitoring program. Corrections and calibrations are essentially only needed during the development of the index under local conditions. Afterwards, simple calculation will allow to appreciate the water quality. The Benthic Quality index can be part of a multimetric index with biodiversity indices to assess the global state of the ecosystem and for effects of multiple stressors.

Shallow lakes

Shallow lakes are common in West Africa. Macroinvertebrate communities of shallow lakes are used in biomonitoring with several indices including Hilsenhoff Biotic Index (HBI) (Table 1). HBI is a successful index based on the tolerances of observed taxa in the ecosystem to organic pollutants (Hilsenhoff, 1982). While Hilsenhoff's index was originally developed for lotic ecosystems, it has also been used for the monitoring of lake systems in developing countries because of its simplicity and intuitive interpretation (Chowdhury et al., 2016). Originally, Hilsenhoff (1982) only considered the arthropods in the calculation of the indices and aimed at evaluating organic pollution of streams. It was based on the tolerances of observed taxa to organic pollutants and their relative abundance. Later, tolerance scores of other invertebrate taxa such as mollusks and annelids were included (MDDEFP, 2013). Depending on the level of identification attained, Hilsenhoff's index proposes tolerances at genus or family level or beyond as presented in Eq. 3 (MDDEFP, 2013).

$$\mathrm{HBI} = \sum_{i=1}^{n} \frac{n_i . t_i}{N}, \quad (3)$$

where n_i = number of individuals of each taxonomic group; t_i = taxa tolerance score of the taxon i and N = total individuals number of the n scored taxa.

A bioassessment of Nokoue Lake (Benin) showed that HBI at family level turned out to be more appropriate than diversity indices which proved to be less sensitive to intermediate pollution levels (Odountan & Abou, 2015). Additionally, the HBI has been included as a metric in other multimetric indices in the USA (e.g., Lewis et al., 2001, Blocksom et al., 2002) or throughout the world (e.g., Chowdhury et al., 2016) to provide information about the condition of the lake with respect to organic pollutants. In short, changes of taxonomic level from genus to family, choice of indicator taxa, adaptation of tolerance score and integration in multimetric indices are some possible modifications of HBI, which can be adapted e.g., for West Africa, for local conditions.

A proposed framework for biomonitoring of shallow lakes in developing countries

Major indices require prior modifications and calibrations that consider the local conditions before a better and proper use locally. Therefore, a simple framework to guide such development based on our research experience and this overview is presented. We believe this framework offers a simple procedure that can be used as a starting base by researchers in developing countries who do not have the means to develop complex programs, to obtain an index adapted to local realities and at the same time based on scientific evidence and internationally accepted norms and standards in this field of research and biomonitoring. It is also meant as a stimulation towards the scientific community in developing countries to start comparing methods with intercalibration exercises, as was reported in Poikane et al. (2016) for Europe. These intercalibration exercises were undertaken in several EU countries to harmonize 13 lake-based macroinvertebrates methods to address acidification, eutrophication and morphological alterations.

For shallow lake ecosystems and to some extent for the shores of profundal lakes as well, based on our research and the present review, we suggest the following framework (Fig. 1): development of biotic index using the Chowdhury et al. (2016) approach. This method was preferred as it proved its effectiveness in e.g., Bangladesh on shallow lakes threatened by organic pollution with the presence of hyacinth like in West Africa. Likewise, it is based on the Hilsenhoff Biotic Index which is simple to use with intuitive interpretation and proved its usefulness in Benin (Odountan & Abou, 2015). It is also one of the most used indices worldwide for monitoring lakes. For the calculation of tolerance taxa scores (whether for a single lake or for several lakes in a single region), the database of environmental and macroinvertebrate community must cover all seasons over several years (multi-year, at least 2 years) in order to consider inter-annual and seasonal variation. The most difficult task will be the definition of reference sites. The definition of reference sites can be established by assessing 'minimally impaired sites' instead. The development of the Index involves 4 main steps (Chowdhury et al., 2016): (1) identification of the main disturbance gradient, (2) calculation of tolerance scores of taxa, (3) calculation of index and (4) testing of the index. These steps are integrated in the general framework proposed in Fig. 1.

As regards step 1 (Fig. 1), *identification of the main disturbance gradient*: This step consists of selecting the main disturbance gradient affecting the studied lakes. It will not be a question of measuring all the existing environmental variables but only those related to the suspected pollution (inferred by visual and olfactive observation, grey literature, surveys, personal communication, mapping of pollution sources) and for which the macroinvertebrates are good indicators: organic pollution, eutrophication and/or acidification (see Table 1). For eutrophication and human disturbances related to organic pollution, input variables of analysis can be temperature, pH, dissolved oxygen, total nitrogen, total phosphorous, conductivity, chlorophyll-a, calcium hardness, transparency, turbidity, biochemical oxygen demand (BOD) and fecal coliform count (FC). For an assessment focusing on acidification, Ca^{2+}, ammonia (NH_4^+), alkalinity, dissolved organic carbon and acid neutralizing capacity (ANC) must be priorities (McFarland et al., 2010). Afterwards, if there are differences between seasons, principal components analysis (PCA) of physical and chemical variables can be performed separately on the selected variables. If there are no differences, all data can be pooled. The first PCA axis (PC1) can be used as a disturbance gradient due to the fact that this axis accounts for the greatest variability among physical and chemical data and represents the commonest disturbance gradient present among the sites (Chowdhury et al., 2016).

For step 2 (Fig. 1), calculation of taxa tolerance scores: Here, information on the disturbance intensity tolerated by each taxon must be gathered to calculate their tolerance. Tolerance scores for given taxa can be calculated based on the PCA axis 1 scores (scaled) per site and the mean proportion of the taxon as proposed by Chowdhury et al. (2016). Due to lack of taxonomic expertise for macroinvertebrates in West Africa, tolerance scores could be based on taxonomic family level or any morphologically distinguishable taxonomic unit (receiving a unique code). However, genus level is strongly recommended because some taxa differ hugely within a single family in terms of their tolerances to disturbances. Taxa tolerance scores should eventually be rescaled (to a 0–10 range or 0–100 range) for an easy interpretation and comparison.

Then, as regards step 3 (Fig. 1), calculation of index: Once tolerance scores of indicator taxa are known, an index can be calculated. For that, we suggest either Hilsenhoff (1987, 1988) equation or Mathuriau (2002). The first involves taxa tolerance scores and relative abundance of each taxon in the sample while the latter just considers the taxa tolerance scores and the taxa richness of the sample. The Calculated Index must be categorized into ecological condition classes (nominal appreciation from e.g., bad to excellent).

Finally for step 4 (Fig. 1), testing of the index: This involves correlating the index with a suite of biodiversity metrics (see above) to assess its ability to reflect variation of macroinvertebrate community assemblages in relation to environmental stress and natural variability of the studied lakes, and eventually selection of specific habitats where the macroinvertebrates have more discriminatory power relative to the local nested variability (Hering et al., 2004; Odountan, 2017).

If the proposed index is found to be effective (high discriminatory power along a disturbance gradient), it may be more robust in being part of a Multimetric index. We favour the straightforward approach proposed by Blocksom et al. (2002): 4 characteristics must be evaluated for each candidate metric for being part of a multimetric index: (1) discriminatory power, (2) relative scope of impairment, (3) relationship with stressors and (4) redundancy. Discriminatory power of a metric is its ability to distinguish between reference and impaired sites by examining their distributions using box-and-whisker plots. Relative scope of impairment is a measure of the ease of detecting specific impairment compared to some ideal condition and is of course very much linked to discriminatory power. Relationship with stressors examine the correlation between the remaining metrics (after the last steps) and environmental variables related to potential stressors. Redundancy analysis among metrics allows to ensure that each metric in the multimetric index provides sufficient new information (Blocksom et al., 2002). The criteria proposed by Blocksom et al. (2002) for candidate metrics are complementary to the criteria for a multimetric index which should contain at least one metric from the following metric types (1) richness/diversity, (2) sensitivity/tolerance, (3) composition and (4) functional metrics in order to reflect the complexity of biological communities (Hering et al., 2006; Karr, 2008; Stoddard et al., 2008).

Concluding remarks and recommendations

The Gulf of Guinea consists of coastal and offshore areas from the Liberian border to the west edge of the Niger Delta, which includes Liberia, Ivory Coast, Ghana, Togo, Benin and Nigeria. These countries of West Africa are facing severe biodiversity declines, both for freshwater and coastal ecosystems (e.g., Scheren et al., 2004; Kone et al., 2006). The global decline observed in aquatic ecosystems affects several critical benefits, or ecosystem services. Future action plans must include further ecological research and biomonitoring, improving institutional and legal frameworks for management, controlling and regulating destructive economic activities, and developing ecological restoration options (Barbier et al., 2011).

To assess the ecological health of an ecosystem, there are no universally valid metrics and indices. The choice of the ''best'' tool depends not only on system-specific features such as pressure, the hydrobiological features and the lake types, but also on the local technical and scientific capacities for biomonitoring and research, integrated management, linked to governance, policies and decision making. Following the findings of Lewis et al. (2001) and Mandaville (2002) and our studies on Lake Nokoue of Benin (Odountan and Abou, 2015), and after considering the examples listed in Table 1 of the present review, we recommend that lakes in West Africa, and more generally in developing countries, be assessed using a multimetric approach. This approach combines biodiversity indices, FFGs and species composition metrics (% Contribution of Dominant Family, ratio EPT/Chironomidae, % EPT, % Chironomidae, % Oligochaeta, % amphipods, % insects, % dipteran insects, % intolerant taxa, % non-insects, % gastropods, % pelecypods), combined with one of the above-discussed indices within their specific constraints (especially Benthic Quality Index, Hilsenhoff Biotic Index, development of biotic index). If expertise, skills and technical capacities are present, combination with more specific methods using chironomid deformities, zooplankton or diatoms is encouraged as well (O'Connor et al., 2000; Quintana et al., 2015). The multimetric approach is flexible and offers the possibility for adjustment by adding or removing metrics or fine-tuning the metric scoring system. Multivariate analysis can be added as support to describe spatial or temporal patterns and clusters but requires some statistical expertise which could be a limiting factor for use in the management of the West Africa ecosystems. Multimetric or biotic indices must be calibrated and adapted before being used in developing countries, since these methods were developed in other regions of the world.

In the early 1990s, a survey of the International Lake Environmental Committee has already indicated that some 40–50% of lentic ecosystems (lakes and reservoirs) are under eutrophication, which undoubtedly today is, together with climate change, the most challenging global threat to aquatic lentic ecosystems (Istvánovics, 2009). The biomonitoring challenges for lakes systems in developing countries, in particular in West Africa, can be met by providing an easy way to interpret numerical values (e.g., Gabriels et al., 2010) or allowing to report on anthropogenic stressors and compare ecological states between lakes or sites (Chowdhury et al., 2016). Table 1 shows that benthic macroinvertebrate assessment methods allow one to highlight several pressures (natural or not) such as eutrophication, acidification, hydromorphological alterations and could be used by ecologists for rapid (on field) assessment of lake systems. These biomonitoring data offer essential science-based evidence for policy makers and managers. The present study pleads for strengthening the science–policy interface for a better integrated management of lakes in developing countries. High priority is warranted given the current rapid degradation of biodiversity and related ecosystem services and in face of a high demography, threatened food security and threatened healthy environment for human populations.

For the assessment of the ecological status of lake systems, a 'perfect' or 'optimum' biotic index (i.e. an index examined in this review without constraints or implications) does not exist. However, tools/frameworks/protocols that have been developed elsewhere could largely be implemented in West Africa by adapting them to the specific ecosystems. Challenges would be to solve obstacles related to issues such as lack of taxonomic expertise, lack of statistical expertise, poor mastery of analysis tools, lack of field and laboratory facilities, lack of research funding and priorities, lack of implementation of national water acts and lack of clear political regional policies (such as e.g., the European Water Framework Directives).

Consequently, the best strategy for African countries will be to try to capitalize on the experience gained over many years by the United State Environmental Protection Agency (USEPA) and the European Union countries as illustrated in Table 1. This paper provides a plea to fill the knowledge gap by promoting the development of local, nation-wide or regional (including intercalibration exercises) indices for macroinvertebrates in lakes. The development of a new or locally adapted index or the modification of tolerance scores can lead to modified scores of several families (if possible use genus level) and even inclusion of several taxa that were not existing in the original scores (due to altitude, latitude, salinity, climate etc.), therefore improving the relevance and efficiency of the index. Many aspects and applications using macroinvertebrates discussed herein are of potential interest to African countries, which paradoxically share the challenges of improvement of environmental quality of lakes systems but have few developed appropriate tools. Due to their important socio-economic role and increasing anthropogenic stress, African lake ecosystems need to be the focus of future research.

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