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A Review of Biological Monitoring of Aquatic Ecosystems Approaches: with Special Reference to Macroinvertebrates and Pesticide Pollution

R. G. I. Sumudumali[1] · **J. M. C. K. Jayawardana**[2]

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Abstract
Biological monitoring is the evaluating changes in the environment using the biological responses with the intent of using such information in quality control of the ecosystem. Biomarkers and bioindicators are two main components of the hierarchy of biomonitoring process. Bioindicators can be used to monitor changes of ecosystems and to distinguish alteration of human impact from natural variability. There is a wide range of aquatic taxa such as macroinvertebrates, fish and periphyton, planktons which are successfully used in the biomonitoring process. Among them, macroinvertebrates are an important group of aquatic organisms that involves transferring energy and material through the trophic levels of the aquatic food chain and their sensitivity to environmental changes differs among the species. The main approaches of assessing freshwater ecosystems health using macroinvertebrates include measurement of diversity indices, biotic indices, multimetric approaches, multivariate approaches, Indices of Biological Integrity (IBI), and trait-based approaches. Among these, biotic indices and multimetric approaches are commonly used to evaluate the pesticide impacts on aquatic systems. Recently developed trait-based approaches such as SPEcies At Risk of pesticides (SPEAR) index was successfully applied in temperate regions to monitor the events of pesticide pollution of aquatic ecosystems but with limited use in tropics. This paper reviews the literature on different approaches of biomonitoring of the aquatic environment giving special reference to macroinvertebrates. It also reviews the literature on how biomonitoring could be used to monitor pesticide pollution of the aquatic environment. Thus the review aims to instil the importance of current approaches of biomonitoring for the conservation and management of aquatic ecosystems especially in the regions of the world where such knowledge has not been integrated in ecosystem conservation approaches.

Keywords Biomarkers · Bioindicators · Invertebrates · Pesticides · Freshwater

Introduction

Freshwater ecosystems in the world are most vulnerable to a variety of anthropogenic impacts (Hellawell 2012). Physical habitat changes due to dam constructions, the input of agrochemicals from agricultural activities, urbanization (Kripa et al. 2013), and recreational activities have a profound impact on aquatic ecosystems (Allan 2004; Bae et al. 2005; Barletta et al. 2010). Agricultural pollutants have been identified as the major contributors to aquatic pollution, worldwide (Gunawardhana et al. 2016; Jayawardana et al. 2017). Excessive use of fertilizers, hormones and pesticides in crop production often leads to contamination of waterways with such chemicals (Cooper 1993; Hapeman et al. 2002; Kripa et al. 2013) and they are most noticeable when they produce immediate or delayed toxic effects on aquatic life (Brühl and Zaller 2019; Cooper 1993; Khan and Law 2005; Zacharia 2011). Consequently, these may cause the alteration of the species composition in aquatic systems (Brühl and Zaller 2019; Wang et al. 2007). In addition to that, Persistent Organic Pollutants and heavy metals can accumulate in the aquatic food chains causing impacts on nontarget species (Cui et al. 2015; Ribeiro et al. 2005).

✉ J. M. C. K. Jayawardana
jayawardanack@yahoo.com

[1] Faculty of Graduate Studies, Sabaragamuwa University of Sri Lanka, Belihuloya, Sri Lanka

[2] Department of Natural Resources, Faculty of Applied Sciences, Sabaragamuwa University of Sri Lanka, Belihuloya, Sri Lanka

A significant measure of a healthy freshwater ecosystem is the state of the physical-chemical environment and biological integrity (Bae and Park 2014; Butcher et al. 2003; Herman and Nejadhashemi 2015; Hughes et al. 2000). Traditional methods of measuring physical and chemical water quality parameters were found not accurately representing the status and disturbance events that took place in the freshwater systems over time. For example, most pesticide residues in the aquatic environment are not readily detectable as they often occur at low concentrations and due to their diffuse and transient nature (Beketov et al. 2009; Comoretto et al. 2008). Nonetheless, even at extremely low levels, such chemicals can cause physiological impairments in aquatic species that are often expressed at the level of the population. However, biological monitoring has proven to be most successful in capturing such transient impacts caused by toxicants at very low concentrations (Barr and Needham 2002; Sanders et al. 2009). This paper therefore reviews the literature on various approaches of biomonitoring currently being adopted in different regions of the world, with particular reference to macroinvertebrates and the pollution of pesticides. Given the inadequacy of biomonitoring information and the scarcity of biomonitoring-related data in some regions of the world, the review seeks to integrate biomonitoring concepts for environmental management in regions where they are not adequately recognized.

Bioindicators and Biomarkers

The environmental stressors can act on various hierarchical levels of biological organization and most ecologically relevant ones occur at higher levels, for example, population or community levels. Population responses to environmental stress are regarded as a primary caution of ecosystem changes due to the alteration of growth and reproduction of aquatic communities (Orfanidis et al. 2007). Also, aquatic organisms can respond to contamination at even very low levels when the contaminants are present in water or sediments (Wijeyaratne and Pathiratne 2006). The real bioavailable fraction of pollutants and pollution effects at low levels can be studied using bioindicators and validated under both field and laboratory conditions (Hamza-Chaffai 2014). Moreover, bioindicators reflect the present state and past trends of additional and accurate information concerning the environmental behavior (Oertel and Salánki 2003) since it reflects cumulative changes over time. Two main levels of organization of biomonitoring can be addressed as biomarkers and bioindicators (Adams and Greeley 2000; Van der Oost et al. 2003). In general, bioindicators have intermediate relevance of sensitivity, high ecological relevance and diagnostic utility (Adams and Greeley 2000), while biomarkers are pollutant sensitive and measure potentially much more diagnostically, but its ecological relevance is low (Van der Oost et al. 2003). Aquatic organisms are often used as bioindicators or biomarkers since they are exposed to widespread environmental variations during their life cycle. At first, limnologists used the presence or absence of selected indicator species for biomonitoring programs. However, with the development of quantitative analytical methods using computers and other sophisticated techniques, more advanced biomonitoring techniques have been developed. "Saprobic Index, Saprobic Valency, Indicative Weight, Trent Biotic Index (TBI), Score System, and Hilsenhoff Biotic Index" are some of these common biological indices that have been developed (Resh and Rosenberg 1993). These biological monitoring studies using macroinvertebrates include an understanding of indirect consequences, mechanisms of recovery and relative pollutant sensitivities.

Bio monitors or bioindicators are living organisms that can be used to measure contaminants or collect information on the impacts of contaminants on environmental spatial and temporal variance. These organisms reflect the bioavailable fraction of pollutants and interest for environmental managers because of their potential ecotoxicological significance (Hamza-Chaffai 2014). Compliance indicators, diagnostic indicators and early warning indicators are three classes of bioindicators that are classified based on the purpose of their use. Deviations from acceptable health limits of the aquatic ecosystem are revealed by the compliance indicators while diagnostic indicators express the causes for the deviations in the environment. The early warning indicators signify the impending decline of the health of the aquatic ecosystem. Although all three groups of indicators should be represented in an integrated assessment of ecosystem health, indicator selection is based on the purpose and objective of the specific assessment (Cairns and McCormick 1992; Hamza-Chaffai 2014).

Good bioindicator organisms possess several desirable characteristics such as clear taxonomy, cosmopolitan distribution, sufficient abundance, and wide distribution for replicate sampling. In addition, low genetic and ecological variability, suitable body size and ease of finding, low mobility (local indication), long life-span to the comparison between various ages, well-studied ecology, optimal for being "actively" monitored, bioaccumulation without death, higher sensitivity toward stressors to be monitored, the higher capability for quantification, and standardization are among the other characters (Füreder and Reynolds 2003; Hilty and Merenlender 2000; Resh and Rosenberg 1993; Zhou et al. 2008). However, it is too stringent to choose bioindicator species with all the characteristics, but it is more possible to select indicators with suitable characteristics that serve the purpose of biological evaluation

(Zhou et al. 2008). Especially, the use of bioindicators are useful in situations in where the indicated environmental factor cannot be measured or difficult to interpret (Gerhardt 1999). The commonly used bioindicators for the assessment of aquatic environment are macroinvertebrates, bivalves, gastropods, fishes, zooplankton, phytoplanktons, and macrophytes (Hamza-Chaffai 2014; Marbà et al. 2006; Zhou et al. 2008).

In different levels of biological organization (i.e., molecular, cellular, or physiological levels), biomarkers are measurable parameters that affect or change the metabolic regulatory processes due to environmental stressors (Van der Oost et al. 2003). Another definition for biomarkers is a measurable biologic system or sample which can induce variation in cellular or biochemical structures or functions, components or processes, xenobiotically (Hamza-Chaffai 2014; Van der Oost et al. 2003). Biomarkers occur at a molecular level followed by cellular, tissue/organ, and whole-body levels. Higher levels of effects such as individual, population, and ecosystem-level are less irreversible, more detrimental and generally accepted to have ecological relevance. Hence, routine biomonitoring program needs to be focused towards on identifying and understanding the toxic effects which initiated at the sub-organism levels of molecular, biochemical, or physiological changes when developing biomonitoring programs.

Examples of biomarkers that are widely studied in laboratories are metallothioneins (MTs), malondialdehyde, acetylcholinesterase (AchE) glycogen, and stress on stress test (Hamza-Chaffai 2014). There are several applications of biomarkers for detecting the aquatic ecosystem health (De la Torre et al. 2002; Hamza-Chaffai et al. 2000). De la Torre et al. (2002) have assessed the effect of prolonged exposure of urban pollutants on brain AchE activity on caged *Cyprinus carpio* and field-captured *Cnesterodon decemmaculatus* and demonstrated high sensitivity of AChE activity as an exposure biomarker. The use of the marine bivalve *Ruditapes decussatu* to validate the relationship between MTs and metals (Cd, Cu, and Zn) under field conditions is another example of the use of biomarkers for detecting environmental pollutants. The study showed that MTs in the digestive gland of *R. decussatus* reacted to moderate rises in metal contamination and may be a promising biochemical metal exposure predictor (Hamza-Chaffai et al. 2000). A study investigating the activation of biochemical stress responses in *Macrobrachium malcolmsonii* in response to their exposure to endosulfan, demonstrated an elevated levels of glutathione S-transferase and a decreased content of AchE in test prawns. Also, phosphatases and lactate dehydrogenase levels alterations were also noted in tissues. This suggested the disruption of fundamental metabolic activities in research prawns due to the exposure to endosulfan pesticide (Bhavan and Geraldine 2001). Biomarkers may be used as an early warning system in environmental quality assessment to diagnose exposure to environmental pollution in the aquatic environment that has risen in recent decades (Hamza-Chaffai 2014).

Macroinvertebrates as Indicators

Organisms that live entirely or part of their life cycle in the bottom substrates such as sediments, debris, logs, etc. in aquatic ecosystems which are observed by naked eyes are regarded as benthic macroinvertebrates (Chessman 2003; Resh and Rosenberg 1993). In terms of species richness and individual abundance, ~95% of benthic macroinvertebrates comprise freshwater arthropods (Bae et al. 2005). Chukwu and Nwankwo (2003) and Roozbahani et al. (2010) showed that benthic macroinvertebrates diversity can be used as a good indicator for evaluating the ecological status of the aquatic system. The advantages of using benthic macroinvertebrates for biomonitoring are that they are universal thus can be used in many different types of aquatic systems, exhibit high species richness and abundance, respond to wide range of environmental stress. Also, their sedentary or benthic habitat and long-life cycle compared to other aquatic organisms such as algae and planktons in freshwater are useful effect-based indicators for assessing spatial and temporal analysis respectively and thus sampling may be less frequent (Bae et al. 2005; Borisko et al. 2007; Mathuriau et al. 2012). According to Voshell (2002), at least 60% of the biological indices that have been identified in running water over the past years, are macroinvertebrates. Macroinvertebrates are an essential part of the aquatic environment as they transfer the energy to other trophic levels in the aquatic food web (López-López and Sedeño-Díaz 2015) and their degree of sensitivity to environmental changes differ among various groups. Physico-chemical conditions of a given location can be predicted using the morphology, presence/absence, abundance, physiology, or behavior of these macroinvertebrates (Sharma et al. 2008). Factors regulating macroinvertebrates in freshwater habitats are food, current speed, the substratum, riffle depth, vegetation, water temperature and conductivity, shade, effects of altitude and season, liability to drought and floods, competition between species and zoogeography.

In this context, macroinvertebrates are ideal for determining site-specific impacts because they have restricted migration, differ in quantity and types of contaminants in their tolerance levels and are easy to recognize (Sharma et al. 2006). Further, macroinvertebrate communities contain board range of species which belong to various trophic levels and their life cycles generally limited to ~1 year of which most is spent in the water (Agouridis et al. 2015; Hauer and Lamberti 2011). They also exhibit pollution sensitivity (Compin and Céréghino 2003) and provide aggregate impact for different stressors in short term and long term (Girgin et al. 2003; Sharma and Rawat 2009). Also, suitable taxonomic keys are available to identify the specimens because of standardized field sampling methods and laboratory processing protocols (Chirhart 2003). Water quality degradation is demonstrated by the presence or absence of sensitive and tolerant organisms because different taxa have different habitat preferences and wide tolerances for pollutants (López-López and Sedeño-Díaz 2015).

Despite the relative advantages of using macroinvertebrates as indicators of water quality monitoring, it also has several limitations. Some of these limitations include the difficulty of quantitative sampling as their distribution is nonrandom in riverbed because some invertebrates life cycles are showing seasonality and the effects of natural and catastrophic drift (López-López and Sedeño-Díaz 2015). Another limitation is macroinvertebrates exhibit limited spatial dispersal ability in response to environmental changes or stresses frequently occurring in the aquatic environment. As a result, organisms located at the edge of their natural aquatic habitat are more vulnerable to environmental stress than those at the center of their distribution. It, therefore, limits the use of universal biological assessment based on the same species/taxa response.

"Hilsenhoff's Biotic Index", "Invertebrate Community Index", "Biological Monitoring Working Party Score (BMWP)", "Macroinvertebrate Water Quality Index", "Average Score per Taxon", "Percent Model Affinity", and "EPT Richness Index" are few of the commonly used indices which integrated macroinvertebrates composition to assess the quality of aquatic environment in different regions of the world (Kripa et al. 2013). However, many of these protocols and biological monitoring methods are developed based on the taxa relevant to regions of northern hemisphere of the world including North America and Europe. However, few countries in Asian and African regions make use of such indices after modifications for biomonitoring. But these indexes with European threshold values did not well explain the stress on the aquatic system (Cornejo et al. 2019; Rasmussen et al. 2016). According to Morse et al. (2007) inadequate knowledge on macroinvertebrate fauna and their aquatic stages in most Asian countries, scarcity of necessary equipment, and lack of support and understanding of biomonitoring by the respective authorities are some of the challenges to the introduction of biomonitoring techniques for water quality monitoring. Though research on tropical streams has been increasing over the last two decades, there is still a lack of knowledge on aquatic fauna and ecological understanding (Al-Shami et al. 2011; Gopal 2005).

Different Approaches of Biomonitoring

There are many different biomonitoring techniques employed for biological monitoring of aquatic ecosystems addressing many different organizational levels (Bonada et al. 2006; Mandaville 2002). Available resources and the issue being addressed depend on the selection of suitable biomonitoring techniques. "The diversity indices, Biotic indices, Multimetric approaches, Multivariate approaches, Indices of Biological Integrity (IBI), Functional Approaches and macroinvertebrate trait-based approaches" are the approaches used for assessing the freshwater ecosystem using macroinvertebrates (Li et al. 2010).

Diversity Indices

Diversity indices reflect the combined effect of species richness (number of species), evenness (homogeneity of distribution abundances among species) and abundance (total number of species) of a community to environmental variations. Abundance indicators are used to provide information about the condition of a freshwater environment by evaluating key or sensitive macroinvertebrates such as the EPT index (Johnson et al. 2012). Stream health based on species distribution or qualitative measure of diversity found within the ecosystem is measured using species richness (Wan et al. 2010). High diversity, even distribution among species and the high number of individuals in a community represent undisturbed environments. Diversity indices that developed based on species richness, evenness, and abundance at the community level are Shannon-Wiener Index, Simpson Index, Margalef's and Menhinick's Indices, and Pielou evenness etc. (Andem et al. 2013; Roozbahani et al. 2010). These indexes can be used as an indicator of disturbed aquatic environment comparing with reference aquatic environments (Schäfer et al. 2011a).

There are also several limitations of the use of diversity indices in community ecology (Okpiliya 2012). In community ecology, the use of diversity indices has been highly criticized because diversity does not transmit any information on a community's actual species composition (Rosenzweig 1995). Diversity of species is a population overview measure which does not take into account individual species' uniqueness or possible ecological significance (Sanders 1968; Risser and Rice 1971; Whittaker 1972). A community can have a high diversity of species, but mainly common or undesirable species are included. A community, on the other hand, may have low species diversity, but it is composed of particular, uncommon, or highly desirable species. For instance, Sanders (1968), Risser and Rice (1971), and Whittaker (1972) stated that the Simpson index as a measure of diversity is that the abundance of the two or three most abundant species in a population is too heavily affected. So the Simpson index gives the uncommon species very less weight and the common species more weight.

Biotic Indices

Biotic indices evaluate river health based on certain taxonomic groups (Bioindicator) to sensitivity and tolerance for environmental variations of eutrophication, organic pollution, pesticides, heavy metals, and pH in the community through numerical scores or single index. According to Perry (2005), the abundance of pollution sensitive organisms indicates the stream healthiness as the sensitivity and tolerance of indicator assemblages are different according to the environmental characteristics. The advantages of this indices are used simple calculations and utilize only one stressor or metrics to evaluate stream health. The disadvantage is that biotic indices do not utilize the combined effects on multiple stressors within the aquatic ecosystem (Fierro et al. 2017; Herman and Nejadhashemi 2015). Several biotic indices have been developed for particular regions, but many of these indices can be used with modifications in other regions. Examples of region-specific indices are "Nepalese Biotic Score and National Sanitation Foundation Water Quality Index" in India (Sharma et al. 2008; Sharma et al. 2006) "Trent Biotic Index (TBI)" and the "Biological Monitoring Working Party (BMWP) score" for the UK (Hooda et al. 2000), the "Belgian Biotic Index" for Belgian rivers, the "South African Scoring System" for southern Africa, the "Zambian Invertebrate Scoring System" for Zambia, the "Namibian Scoring System" for Namibia, the "Okavango Assessment System" used in Okavango Delta, Botswana, and the "Tanzanian River Scoring System" for Tanzanian rivers (Shimba and Jonah 2016). BMWP score has been widely used in other regions in the world (Kumar et al. 2013; Romero et al. 2017; Uherek and Pinto Gouveia 2014; Varnosfaderany et al. 2010).

Multimeric Approaches

Multimetric indices (MMIs) have been used as standard tools for presenting single "Multimetric" value for the biological condition of water body of various structural and functional metrics of an ecosystem, describing a specific assemblage such as fish, macroinvertebrates, or periphyton (Blocksom 2003; Stoddard et al. 2008). MMIs are highly recommended since it provides robust, quantitative measures, and sensitive insights toward the responses to natural and human-induced stressors from regional to continental level (Stoddard et al. 2008; Zhou et al. 2016). Structural and functional metrics used in Multimetric approaches include "taxa richness, taxonomic composition, relative abundance, dominance, pollution tolerance, functional feeding groups, life history strategies, and behavioral habits" (Ferreira et al. 2011). Examples of MMIs are "Index of Biotic Integrity" and "Benthic Index of Biotic Integrity". In the sense of natural variability, biotic integrity, and associated indices reflects aquatic system's ability to sustain characteristic functional and structural populations, to resist loss of this function and structure due to disturbance, and to recover from such disturbance (Perera et al. 2012). The disadvantages associated with use of such indices are their complexity of calculations in determining the stream health (Fierro et al. 2017).

Multivariate Approaches

Multivariate approaches are effective for predicting the relationship between bioindicators (absence or presence of site-specific fauna patterns) and environmental characteristics using statistical analysis (Ordination analyses and cluster analyses or combination of these) under the major environmental stress to the reference site (López-López and Sedeño-Díaz 2015; Niemi and McDonald 2004). Predictive models are required in multivariate methods that relate the physicochemical properties of an aquatic ecosystem with bioindicator organisms, which are represented under reference conditions. Widely used such multivariate techniques are RIVPACS (River Invertebrate Prediction and Classification System) which was first implemented in the UK and its derivative models AusRivAS (Australian Rivers Assessment System), BEAST (BEnthic Assessment Sediment), and ANNA (Assessment by Nearest Neighbor Analysis) (Davies 2000; Li et al. 2010; López-López and Sedeño-Díaz 2015). Other similar approaches include LIMPACT (LIMnology and imPACT) in Germany, the integrated evaluation system SERCON in Scotland and the Rapid Bioassessment Protocols in the USA (Neumann et al. 2003). The advantages of this approach are the representativeness of the various stressors and can be used to evaluate the stream health beyond the sampling points. Disadvantages are the complexity of developing the approach, which require expert knowledge (Herman and Nejadhashemi 2015).

Functional Approaches

A functional approach is a proper approach for reflecting ecological integrity based on the information on both structure and function of the aquatic ecosystem. This approach is focused on similar biological characteristics (life cycle, reproductive characteristics, mobility, modes of resistance, food, feeding, and breathing habits) and ecological characteristics (temperature preferences, trophic stage, biogeographic distribution, longitudinal zoning, substratum, organic pollution tolerance, and current velocity) which are susceptible to the local environmental gradient (Charvet et al. 1998; Jayawardana and Westbrooke 2010; Menezes et al. 2010; Poff et al. 2006). Moreover, this approach better detects anthropogenic impacts than traditional methods such as diversity indices or chemical methods (Tomanova et al. 2008). The increased sensitivity and mechanistic linkage of biotic responses to environmental conditions are intrinsic feature of such indices and they aid in ecological risk assessment by providing useful information relevant changes of structure and function of the aquatic ecosystem (Culp et al. (2011). The disadvantages of this approach are less sensitivity to sampling effort, taxonomic resolution level, and large-scale spatial taxonomic differences (Bonada et al. 2006).

Indices of Biological Integrity (IBI)

Macroinvertebrates occupy the entire aquatic system of sediments, water columns and submerged substrates of streams, rivers, lakes and wetlands and may represent the biological integrity of the entire aquatic system (Chirhart 2003). IBI was first developed for communities then subsequently been modified for aquatic macroinvertebrates, terrestrial macroinvertebrates, and algae (Chirhart 2003). IBI developed using a combination of univariate and biotic indices to detect the impacts of anthropogenic disturbances on the aquatic environment. Metrics in IBI denote changes in a predictable way of quantifiable attributes which are the biological assemblage of different levels of anthropogenic stress on the ecosystem. The total number of taxa or the number of "EPT taxa" (Ephemeroptera, Plecoptera, and Trichoptera) is a typical example of the metrics used in IBI macroinvertebrates. Each metric value is based on a comparison of anthropogenic disturbances with little to no effect (Karr 1991). Attributes used to the development of IBI fall into four categories namely "Richness measures", "Tolerance measures", "Composition measures", and "Trophic structure measure". Inclusion of one or more metrics from each of these categories improves the predictability of IBI (Chirhart 2003; Karr and Chu 1998). A "RIVPACS (River Invertebrate Prediction and Classification System)" is an example of IBI, which is a particular case of IBI and multivariate approaches. The advantage of this approach is that it is proven to be very adaptable in different regions (Karr and Chu 1998).

Macroinvertebrate Traits Based Approaches

Trait-based macrobenthic indicators are being developed in recent years to overcome the problem of less sensitivity of taxonomy based indicators to specific stressors related to the aquatic ecological impairment (Knillmann et al. 2018; Liess et al. 2008; Reynoldson et al. 1997; Schäfer et al. 2007). Generally, taxonomy based indicators do not identify specific stressors responsible for impairment but respond to multiple stresses associated with such impairments (Schäfer et al. 2011a). In recent years Biotic indicators based on biological traits such as generation time, body size and mode of reproduction along with physiological traits such as physiological sensitivity have been developed to identify specific effects of identified stresses (Liess et al. 2008). SPEcies At Risk $(\mathrm{SPEAR})_{\mathrm{pesticides}}$ approach is a recently developed trait-based approach which incorporate macroinvertebrate traits sensitive to pesticide contamination for monitoring pesticide contamination (Knillmann et al. 2018; Schäfer et al. 2007). $\mathrm{SPEAR}_{\mathrm{salinity}}$ is another trait-based indicator developed for South East Australia to assess the impacts of salinization of rivers (Schäfer et al. 2011a). $\mathrm{SPEAR}_{\mathrm{organic}}$ indicator is a trait-based indicators which was developed to assess the impact of organic toxicant on the trait composition of invertebrate communities in streams of Europe and Siberia (Beketov and Liess 2008).

In order to establish trait-based indicators in biomonitoring, it is important to compile the trait information for taxa present in the area under consideration. These data bases have been well developed in most of the Europe or North America regions. However, such data bases are not available for most regions of the Southern hemisphere and Asia (Schäfer et al. 2011a).

Pesticide Pollution Monitoring

Pesticides are widely used for securing agricultural production and has worldwide applications. However, impacts of the chemicals applied to crop fields may not only act on target pest populations but also have impacts on nontarget species. According to Kaoga et al. (2013), over 95% of applied insecticides and herbicides on the field end up in nontarget areas. Most frequently pesticides applied into crop fields may travel through the land as surface runoff or leach through soil and end up in aquatic systems (Mutuku et al. 2014). In the aquatic environment, pesticide residues accumulate and are found to affect aquatic species in various ways. Specifically, it has been found that pesticides may cause the decline of species in the aquatic environment (Schäfer et al. 2007; Schäfer et al. 2012). The use of pesticides is expected to increase due to climate change in the future and it is considered to be an important cause of the loss of biodiversity in the world (Beketov et al. 2013). Increase in temperature and change in precipitation patterns caused due to climate change can increase crop pests. As a consequence, increased use of pesticides is anticipated in the form of higher quantities, concentrations, frequencies and various varieties or forms of products used (Delcour et al. 2015; Schäfer et al. 2011a). Runoff, leaching, spray drift, preferential flow through soil macropores, or a combination of these processes from agricultural areas are regarded as a nonpoint source of aquatic pesticide contamination (Loewy et al. 2011; Phillips and Bode 2004). Among them, the main route by which pesticides are transported to the aquatic environment is runoff, but the rate depends on the types of soil, the physicochemical properties of the pesticides, the timing and rate of application, and the precipitation after application of the pesticide (Phillips and Bode 2004). Abiotic factors (photodecomposition by sunlight or hydrolysis by water) can lead to degradation of pesticides or adsorb to the sediments or organic matter whereas biotic factors of uptake, metabolization, and accumulation in organisms determine the fate of pesticides in the aquatic environment (Schäfer et al. 2011b). Exposure through contaminated food sources and uptake from overlying water through body walls or respiratory surfaces are the main routes of pesticide entry to bodies of aquatic species (Reynoldson 1987).

Pesticides can be classified as organochlorines (OCPs), organophosphates (OPPs), carbamates (CMs), pyrethroids, and inorganics according to their active ingredients and these synthetic pesticides have been used since the 1940s to control insects around the world. Low cost, broad-spectrum, and persistence nature are reasons for OCPs widely used in the past. The high lipophilic nature, and low biodegradability of OCPs facilitate them to bioaccumulate and biomagnifies in the aquatic food chains causing lethal or sub lethal effects. Most OCPs are banned in the world due to such harmful effects (Keithmaleesatti et al. 2009), however, OCPs residues are still detected in certain areas of the world due to its persistent nature as well as due to the continuation of application of such pesticides in some regions of the world (Rathore and Nollet 2012).

OPPs are the most widely used pesticide in agriculture worldwide and are considered by the WHO to be one of the most hazardous pesticides to vertebrate (Ross et al. 2013). OPPs are easily hydrolyzed and highly toxic to insects (Chambers et al. 2010). CMs are also commonly used in agricultural lands, but it is less toxic to insects and the mode of action is similar to OPPs (Gupta 2006). Pyrethroids are the most widely used group of synthetic pesticide and it is highly toxic to invertebrates and fish and capable of killing invertebrates at ppb levels (Shimba and Jonah 2016).

The bioavailability of pesticides is highly dependent on the pesticide sorption behavior in the aquatic environment. The toxicity of most agricultural chemicals is temperature-dependent (Rathore and Nollet 2012). At high temperatures, several OPP insecticides exhibit increased toxicity to invertebrates, whereas, at low temperatures, pyrethroid insecticides exposure shows increased toxicity. These temperature effects may alter contaminant uptake, or biotransformation rates which result in modification of an organism's capacity to detoxify xenobiotics and ultimately influence the toxicity (Willming et al. 2013). Chemical stability and cation exchange capacity of organic matter and pH (Gunnarsson et al. 1999; Katagi 2006) are also found to determine the sorption characteristics of pesticides in the sediment layer.

The pesticide contamination is found to contribute to the loss of biodiversity in aquatic systems, but physiological acclimation or genetic adaptation increases the tolerance of aquatic biota to pesticides. Simple mutations at a single locus have been found to cause the development of resistance of invertebrates to toxicants (Becker and Liess 2015). Adaptation of nontarget aquatic species to insecticides is less known (Becker and Liess 2017; Liess and Ohe 2005; Muenze et al. 2015). Weston et al. (2013) disclosed that moderate levels of resistance to CMs and OPPs (<2-fold increase in LC50) have been developed by the water flea "*Daphnia magna*". Crustacean "*Hyalella Azteca*" laboratory cultures and wild populations demonstrated 550-fold resistance to pyrethroid insecticides through mutations in the voltage-gated sodium channel at the target site for pyrethroid toxicity (Weston et al. 2013). In nontarget black flies, high levels of resistance to DDT, and pyrethroids were also observed (Montagna et al. 2003) in which 355-fold pyrethroid resistance was developed due to esterase enzyme activity (Montagna et al. 2012).

The most popular and widely used group of invertebrates which is used to assessing pesticide pollution of water is benthic macroinvertebrates. Benthic communities play an important role in transferring energy from one tropic level to another. Modern insecticides are found to have adverse impacts on nontarget aquatic invertebrates in the aquatic habitats (Friberg-Jensen et al. 2003; Schulz and Liess 2001; Wendt-Rasch et al. 2003). Benthic macroinvertebrates are well suited for estimating the toxicity of currently used pesticides because the detection of actual concentrations of pesticides in the environment is difficult and expensive due to their episodic and low-concentration levels and the existence of a multitude of substances (Castillo et al. 2006; Schäfer et al. 2011). For example, "invertebrates *Daphnia magna, Hyalella azteca*, and *Chironomus tentans* were about ≥200 times more sensitive than the fish fathead minnow (*Pimephales promels*) to the AChE inhibiting organophosphorus insecticide chlorpyrifos" (Moore et al. 1998). Macroinvertebrate groups of "Ephemeroptera, Plecoptera, and Trichoptera" (commonly known as EPT taxa) are very sensitive species to pollution while midge larva, pouch snails and rat-tailed maggots are tolerant to environmental

Table 1 Examples of pesticide effects on macroinvertebrate community using biological indices on different regions of the world

Indices used	Region	Sampling sites	Pesticide toxicity quantification	Relationship between pesticide toxicity and biological parameters	Variance in index and pesticide toxicity (R^2_{adj})	References
Biotic SPEAR and BMWP/PAN	Pacific coast of western Panama	13 Stream sites	Toxic units	Affected the BMWP/PAN not the SPEAR index	0.13	(Cornejo et al. 2019)
Diversity Shannon–Wiener index H′ S, total density	Argentina	1 Stream 6 Sites	Pesticide concentrations	Highly affected	0.61 Species richness and 0.59 abundance	(Macchi et al. 2018)
Biotic BMWP-CR SPEAR pesticides ASPT	Coast Rica	1 Stream 3 Sites	Toxic units	Affected the ASPT not the BMWP-CR SPEAR pesticides	0.6	(Rasmussen et al. 2016)
Multimetric EPTR, RICHTOL, INTOL_RICH, MMI	Midwestern United States	100 Streams	Pesticide concentrations	Moderately affected	0.22	(Schmidt et al. 2018)
Diversity Community composition/abundance	Netherlands	14 Sites ditches and ponds	Pesticide concentrations	Highly affected	5.4% Of community variance	(Ieromina et al. 2016)
Biotic SPEARpesticides	France and Finland	29 Streams	Toxic unit	Highly affected	0.64	(Schäfer et al. 2007)
Biotic SPEARpesticides	Southeast Australia	24 Streams	Toxic unit	Highly affected	0.67	(Schäfer et al. 2011)
Biotic SPEARpesticides	Denmark	14 Streams	Toxic unit	Highly affected	Between 0.4 and 0.68	(Rasmussen et al. 2012)
Biotic SPEAR	Central Germany	19 Streams	Toxic unit	Highly affected	0.59	(Muenze et al. 2015)

Indices used—*BMWP/Col* Biological Monitoring Working Party Colombia, *NLSMI* Neotropical Low-land Stream Multimetric Index, *ASPT* Average Score per Taxon, *H′* Shannon–Wiener index, *S* taxon richness, *EPTR* richness of the three dominant sensitive aquatic insect groups tolerance, *RICHTOL* average tolerance of all taxa in a sample based on supplemented EPA tolerance values, *INTOL_RICH* richness of intolerant taxa, *MMI* six individual invertebrate metrics: % EPT, Shannon diversity, scraper richness, clinger richness, Ephemeroptera richness, and % richness of tolerant taxa (scores 8–10)

contaminants (Agouridis et al. 2015). "Species-at-risk (SPEAR)" pesticides index is commonly used to indicate changes in the abundance of the taxa vulnerable to aquatic pesticide concentrations (Liess and Ohe 2005; Schäfer et al. 2007; Schäfer et al. 2011; Rasmussen et al. 2012).

Monitoring of invertebrate community composition is highly ecologically relevant for detecting pesticide pollution of the aquatic environment because the pesticide exposure from agriculture and the macroinvertebrates establishment has shown a clear exposure effect relationship (Table 1). Studies comparing the variance of stream macrobenthic communities based on the pesticide exposure indicated that the benthic macroinvertebrate fauna in control sites of immediately upstream of an area of agricultural land and downstream sites are having a significant difference in sensitive and tolerant taxa where sensitive taxa showing declining trends in comparison to control sites (Neumann and Dudgeon 2002; Thiere and Schulz 2004). Another study by Macchi et al. (2018) indicated the dominance of a single taxon in places of pesticide application. However, these studies characteristically relied on the comparison of sensitive and tolerant taxa in sites located in proximity, to eliminate the other environmental variations such as stream size, discharge, substrate characteristics, and riparian vegetation. Hence these studies raise the question of representativeness because they were not adequately representing broader spatial scales.

The use of various macroinvertebrate-based indices to evaluate the levels of contamination of pesticides in streams is widely practiced in temperate regions. However, these are of limited use for assessing tropical streams and the sensitive species of macroinvertebrates in tropical regions are largely unknown. On the other hand, BMWP index which is one of the most often used biotic indices based on macroinvertebrates to measure organic pollution (nutrient enrichment) and association with oxygen depletion in streams, has been successfully used in tropical environments such as

Ecuador, Brazil and Costa Rica with slight modification to the index although it was developed for the temperate regions (Damanik-Ambarita et al. 2016; Nascimento et al. 2018; Svensson et al. 2018). SPEAR pesticides index is a widely used index for pesticide monitoring which is a trait-based approach to assess responses of macroinvertebrate communities to pesticides. It has been developed and successfully applied in different biogeographical regions in Europe, however, additional researches are needed to the application of the SPEAR pesticides index through its development in other regions of the world that are having different climatic, geographic conditions and/or agricultural practices (Cornejo et al. 2019; Rasmussen et al. 2016; Schäfer et al. 2013). Many studies done in temperate countries have shown a strong negative correlation between pesticide concentrations in aquatic systems and the SPEAR index but shown poor correlations in tropical regions (Rasmussen et al. 2012; Schäfer et al. 2007; Schäfer et al. 2011). This weak associations recorded in tropical aquatic systems may have been attributed to the frequent exposure of invertebrates to high doses of pesticides during the crop cycles during the year that is released from the crop fields. In addition, the post-contamination recovery period for pesticides and the vulnerability of aquatic phases may differ in tropical taxa (Rasmussen et al. 2016). Among the other research gaps related to understanding of effects of pesticides and biomonitoring, a few studies are conducted to explore the synergistic effects of different pesticides on aquatic invertebrates (Shahid et al. 2019). Therefore, further research is needed to carryout to understand the synergistic effects of different pesticides on aquatic biota. In addition to that, lentic systems are highly vulnerable to pesticide accumulation, but very few studies were conducted in the lentic aquatic ecosystems to assess the applicability of these indices (Molozzi et al. 2012). However, some countries are widely using biological indices, for example, “SWAMPS index” in Australia (Chessman et al. 2002), a “Biological Integrity Index” developed for wetlands of the Missouri River (Haugerud 2003) and “Multimetric Index” for wetlands in southwest Ethiopia to assess the lentic systems (Mereta et al. 2013).

In conclusion, use of macroinvertebrates in biological monitoring is a powerful tool to study changes within the aquatic system more importantly to assess the effects of agricultural pesticides. they are an important group involved in the transfer of energy in the aquatic food chain to higher levels and are also a good indicator of pollution in the aquatic environment. although research on tropical streams has increased over the last two decades, there is still a knowledge gap on use of macroinvertebrate fauna for biomonitoring in tropical regions of the world. “biotic indices” and “multimetric approaches” are widely used to evaluate the health of aquatic ecosystems worldwide. review of literature on past studies suggested that bmwp and ept taxa richness do not correlate well with pesticide toxicity but largely sensitive to other environmental variables (Schäfer et al. 2011a). SPEAR pesticide index is successfully applied in temperate regions to monitor the effects of pesticides on aquatic ecosystems but with limited use in tropics. We suggest that future studies should focus on characterizing the sensitivity and vulnerability of tropical species and their response to multiple stressors for use in biomonitoring programs.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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References

Adams S, Greeley M (2000) Ecotoxicological indicators of water quality: using multi-response indicators to assess the health of aquatic ecosystems. Water Air Soil Pollut 123:103–115. https://doi.org/10.1007/978-94-011-4369-1_10

Agouridis CT, Wesley ET, Sanderson T M, Newton B L (2015) Aquatic Macroinvertebrates: Biological Indicators of Stream Health. Agriculture and Natural Resources Publications. 175. https://uknowledge.uky.edu/anr_reports/175

Allan JD (2004) Landscapes and riverscapes: the influence of land use on stream ecosystems. Annu Rev Ecol Evol Syst 35:257–284. https://doi.org/10.1146/annurev.ecolsys.35.120202.110122

Al-Shami SA, Rawi CSM, Ahmad AH, Hamid SA, Nor SAM (2011) Influence of agricultural, industrial, and anthropogenic stresses on the distribution and diversity of macroinvertebrates in Juru River Basin, Penang, Malaysia. Ecotoxicol Environ Saf 74:1195–1202. https://doi.org/10.1016/j.ecoenv.2011.02.022

Andem AB, Okorafor KA, Eyo VO, Ekpo PB (2013) Ecological impact assessment and limnological characterization in the intertidal region of Calabar River using benthic macroinvertebrates as bioindicator organisms. Int J Fish Aquat Stud 1:8–14. http://www.fisheriesjournal.com/vol1issue2/pdf/6.1.pdf. Accessed 23 Feb 2020

Bae M-J, Park Y-S (2014) Biological early warning system based on the responses of aquatic organisms to disturbances: a review. Sci Total Environ 466:635–649. https://doi.org/10.1007/bf02829098

Bae YJ, Kil HK, Bae KS (2005) Benthic macroinvertebrates for uses in stream biomonitoring and restoration. KSCE J Civ Eng 9:55–63. https://doi.org/10.1007/bf02829098

Barletta M et al. (2010) Fish and aquatic habitat conservation in South America: a continental overview with emphasis on “neotropical systems”. J Fish Biol 76:2118–2176. https://doi.org/10.1111/j.1095-8649.2010.02684.x

Barr DB, Needham LL (2002) Analytical methods for biological monitoring of exposure to pesticides: a review. J Chromatogr B 778:5–29. https://doi.org/10.1016/S1570-0232(02)00035-1

Becker JM, Liess M (2015) Biotic interactions govern genetic adaptation to toxicants. Proc R Soc B Biol Sci 282:1806. https://doi.org/10.1098/rspb.2015.0071

Becker JM, Liess M (2017) Species diversity hinders adaptation to toxicants. Environ Sci Technol 51:10195–10202. https://doi.org/10.1021/acs.est.7b02440

Beketov M et al. (2009) SPEAR indicates pesticide effects in streams–comparative use of species-and family-level biomonitoring data. Environ Pollut 157:1841–1848. https://doi.org/10.1016/j.envpol.2009.01.021

Beketov MA, Liess M (2008) Potential of 11 pesticides to initiate downstream drift of stream macroinvertebrates. Arch Environ Contam Toxicol 55:247–253. https://doi.org/10.1007/s00244-007-9104-3

Beketov MA, Kefford BJ, Schäfer RB, Liess M (2013) Pesticides reduce regional biodiversity of stream "invertebrates". Proc Natl Acad Sci USA 110:11039–11043. https://doi.org/10.1073/pnas.1305618110

Bhavan PS, Geraldine P (2001) Biochemical stress responses in tissues of the prawn Macrobrachium malcolmsonii on exposure to endosulfan. Pestic Biochem Physiol 70:27–41. https://doi.org/10.1006/pest.2001.2531

Blocksom KA (2003) A performance comparison of metric scoring methods for a multimetric index for Mid-Atlantic Highlands streams. Environ Manag 31:0670–0682. https://doi.org/10.1007/s00267-002-2949-3

Bonada N, Prat N, Resh VH, Statzner B (2006) Developments in aquatic insect biomonitoring: a comparative analysis of recent approaches. Annu Rev Entomol 51:495–523. https://doi.org/10.1146/annurev.ento.51.110104.151124

Borisko JP, Kilgour BW, Stanfield LW, Jones FC (2007) An evaluation of rapid bioassessment protocols for stream benthic invertebrates in Southern Ontario. Can Water Qual Res J 42:184–193. https://doi.org/10.2166/wqrj.2007.022

Brühl CA, Zaller JG (2019) Biodiversity decline as a consequence of an inadequate environmental risk assessment of pesticides. Front Environ Sci 7:177. https://doi.org/10.3389/fenvs.2019.00177

Butcher JT, Stewart PM, Simon TP (2003) A benthic community index for streams in the northern lakes and forests ecoregion. Ecol Indic 3:181–193. https://doi.org/10.1016/s1470-160x(03)00042-6

Cairns Jr J, McCormick PV (1992) Developing an ecosystem-based capability for ecological risk assessments. Environ Prof 14:186–196

Castillo LE, Martínez E, Ruepert C, Savage C, Gilek M, Pinnock M, Solis E (2006) Water quality and macroinvertebrate community response following pesticide applications in a banana plantation, Limon, Costa Rica. Sci Total Environ 367:418–432. https://doi.org/10.1016/j.scitotenv.2006.02.052

Chambers JE, Meek EC, Chambers HW (2010) The metabolism of organophosphorus insecticides. In: Hayes' handbook of pesticide toxicology. Academic Press, New York, USA. pp 1399–1407. https://doi.org/10.1016/b978-0-12-374367-1.00065-3

Charvet S, Kosmala A, Statzner B (1998) Biomonitoring through biological traits of benthic macroinvertebrates: perspectives for a general tool in stream management. Arch für Hydrobiol 142:415–432. https://doi.org/10.1127/archiv-hydrobiol/142/1998/415

Chessman BC, Trayler KM, Davis JA (2002) Family-and species-level biotic indices for macroinvertebrates of wetlands on the Swan Coastal Plain, Western Australia. Mar Freshw Res 53:919–930. https://doi.org/10.1071/mf00079

Chessman B (2003) SIGNAL 2–A scoring system for macro-invertebrate ('water Bugs') in Australian rivers, monitoring river heath initiative technical report No. 31 Commonwealth of Australia, Canberra

Chirhart J (2003) Development of a macroinvertebrate Index of Biological Integrity (MIBI) for rivers and streams of the St. Croix River basin in Minnesota. Minnesota Pollution Control Agency, St. Paul, Minnesota. https://www.pca.state.mn.us/sites/default/files/biomonitoring-mibi-stcroix.pdf. Accessed 26 Feb 2020

Chukwu L, Nwankwo D (2003) The Impact of land based pollution on the hydrochemistry and macro benthic community of a tropical West African creek. Diffus Pollut Conf Dublin Tropical Freshw Biol 4:1–27

Comoretto L, Arfib B, Talva R, Chauvelon P, Pichaud M, Chiron S, Höhener P (2008) Runoff of pesticides from rice fields in the Ile de Camargue (Rhône river delta, France): Field study and modeling. Environ Pollut 151:486–493. https://doi.org/10.1016/j.envpol.2007.04.021

Compin A, Céréghino R (2003) Sensitivity of aquatic insect species richness to disturbance in the Adour–Garonne stream system (France). Ecol Indic 3:135–142. https://doi.org/10.1016/s1470-160x(03)00016-5

Cooper C (1993) Biological effects of agriculturally derived surface water pollutants on aquatic systems—a review. J Environ Qual 22:402–408

Cornejo A et al. (2019) Effects of multiple stressors associated with agriculture on stream macroinvertebrate communities in a tropical catchment. PloS ONE 14:8. https://doi.org/10.1371/journal.pone.0220528

Cui L, Ge J, Zhu Y, Yang Y, Wang J (2015) Concentrations, bioaccumulation, and human health risk assessment of organochlorine pesticides and heavy metals in edible fish from Wuhan, China. Environ Sci Pollut Res 22:15866–15879. https://doi.org/10.1007/s11356-015-4752-8

Culp JM et al. (2011) Incorporating traits in aquatic biomonitoring to enhance causal diagnosis and prediction. Integr Environ Assess Manag 7:187–197. https://doi.org/10.1002/ieam.128

Damanik-Ambarita MN et al. (2016) Ecological water quality analysis of the Guayas river basin (Ecuador) based on macroinvertebrates indices. Limnologica 57:27–59. https://doi.org/10.1016/j.limno.2016.01.001

Davies P (2000) Development of a national river bioassessment system (AUSRIVAS) in Australia. In: Assessing the biological quality of fresh waters: RIVPACS and other techniques. Proceedings of an International Workshop held in Oxford, UK, on 16–18 September 1997. Freshwater Biological Association (FBA), UK pp 113–124. https://www.cabdirect.org/cabdirect/abstract/20013003038. Accessed 3 Mar 2020

Delcour I, Spanoghe P, Uyttendaele M (2015) Literature review: Impact of climate change on pesticide use. Food Res Int 68:7–15. https://doi.org/10.1016/j.foodres.2014.09.030

De la Torre F, Ferrari L, Salibian A (2002) Freshwater pollution biomarker: response of brain acetylcholinesterase activity in two fish species. Comp Biochem Physiol C Toxicol Pharmacol 131:271–280. https://doi.org/10.1016/s1532-0456(02)00014-5

Ferreira W, Paiva L, Callisto M (2011) Development of a benthic multimetric index for biomonitoring of a neotropical watershed. Braz J Biol 71:15–25. https://doi.org/10.1590/s1519-69842011000100005

Fierro P, Valdovinos C, Vargas-Chacoff L, Bertrán C, Arismendi I (2017) Macroinvertebrates and fishes as bioindicators of stream water pollution. Water Quality Intechopen, Rijeka. 23–38. https://doi.org/10.5772/65084

Friberg-Jensen U, Wendt-Rasch L, Woin P, Christoffersen K (2003) Effects of the pyrethroid insecticide, cypermethrin, on a freshwater community studied under field conditions. I. Direct and indirect effects on abundance measures of organisms at different trophic levels. Aquat Toxicol 63:357–371. https://doi.org/10.1016/s0166-445x(02)00201-1

Füreder L, Reynolds J (2003) Is austropotamobius pallipes a good bioindicator? Bulletin Français de la Pêche et de la Pisciculture. 157–163. https://doi.org/10.1051/kmae:2003011

Gerhardt A (1999) Recent trends in online biomonitoring for water quality control. In: Biomonitoring of polluted water. Reviews on actual topics. Environmental Research Forum, TTP Switzerland, pp 95–118

Girgin S, Kazanci N, Dügel M (2003) Ordination and classification of macroinvertebrates and environmental data of a stream in Turkey. Water Sci Technol 47:133–139. https://doi.org/10.2166/wst.2003.0681

Gopal B (2005) Does inland aquatic biodiversity have a future in Asian developing countries? In: Segers H, Martens K (eds) Aquatic Biodiversity II. Developments in Hydrobiology, vol 180. Springer, Dordrecht, The Netherlands. https://doi.org/10.1007/1-4020-4111-X_10

Gunawardhana W, Jayawardhana J, Udayakumara E (2016) Impacts of agricultural practices on water quality in Uma Oya catchment area in Sri Lanka. Procedia Food Sci 6:339–343. https://doi.org/10.1016/j.profoo.2016.02.068

Gunnarsson JS, Granberg ME, Nilsson HC, Rosenberg R, Hellman B (1999) Influence of sediment-organic matter quality on growth and polychlorobiphenyl bioavailability in Echinodermata (Amphiura filiformis). Environ Toxicol Chem Int J 18:1534–1543. https://doi.org/10.1002/etc.5620180728

Gupta RC (2006) Classification and uses of organophosphates and carbamates. In: Toxicology of organophosphate & carbamate compounds. Academic Press, USA, pp 5–24. https://doi.org/10.1016/b978-012088523-7/50003-x

Hamza-Chaffai A (2014) Usefulness of bioindicators and biomarkers in pollution biomonitoring. Int J Biotechnol Wellness Ind 3:19–26. https://doi.org/10.6000/1927-3037.2014.03.01.4

Hamza-Chaffai A, Amiard J, Pellerin J, Joux L, Berthet B (2000) The potential use of metallothionein in the clam Ruditapes decussatus as a biomarker of in situ metal exposure Comparative Biochemistry and Physiology Part C: Pharmacology. Toxicol Endocrinol 127:185–197. https://doi.org/10.1016/s0742-8413(00)00147-x

Hapeman CJ, Dionigi CP, Zimba PV, McConnell LL (2002) Agrochemical and nutrient impacts on estuaries and other aquatic systems. J Agric Food Chem 50:4382–4384. https://doi.org/10.1021/jf020457n

Hauer FR, Lamberti G (2011) Macroinvertebrates. In: Methods in stream ecology. Gupta RC (2006) Classification and uses of organophosphates and carbamates. In: Toxicology of organophosphate & carbamate compounds. Academic Press, USA pp 5–24. https://doi.org/10.1016/b978-012088523-7/50003-x, pp 435–464

Haugerud NJ (2003) Macroinvertebrate biomonitoring criteria and community composition in seasonal floodplain. Wetl Up Mo River Arch für Hydrobiol 162:187–210. https://doi.org/10.1127/0003-9136/2005/0162-0187

Hellawell JM (2012) Biological indicators of freshwater pollution and environmental management. Springer Science & Business Media, Germany. https://doi.org/10.1007/978-94-009-4315-5

Herman MR, Nejadhashemi AP (2015) A review of macroinvertebrate- and fish-based stream health indices. Ecohydrol Hydrobiol 15:53–67. https://doi.org/10.1016/j.ecohyd.2015.04.001

Hilty J, Merenlender A (2000) Faunal indicator taxa selection for monitoring ecosystem health. Biol Conserv 92:185–197. https://doi.org/10.1016/s0006-3207(99)00052-x

Hooda P, Moynagh M, Svoboda I, Miller A (2000) Macroinvertebrates as bioindicators of water pollution in streams draining dairy farming catchments. Chem Ecol 17:17–30. https://doi.org/10.1080/02757540008037658

Hughes R, Paulsen S, Stoddard J (2000) EMAP-Surface Waters: a multiassemblage, probability survey of ecological integrity in the USA. In: Jungwirth M, Muhar S, Schmutz S (eds) Assessing the ecological integrity of running waters. Springer, Dordrecht, The Netherlands. pp 429–443. https://doi.org/10.1007/978-94-011-4164-2_33

Ieromina Q, Peijnenburg WJGM, Musters CJM, Vijver MG (2016) The effect of pesticides on the composition of aquatic macrofauna communities in field ditches. Basic and Applied Ecology 17(2):125–133

Jayawardana J, Westbrooke M (2010) Potential effects of riparian vegetation changes on functional organisation of macroinvertebrates in central Victorian streams. Vic Nat 127:36

Jayawardana J, Gunawardana W, Udayakumara E, Westbrooke M (2017) Land use impacts on river health of Uma Oya, Sri Lanka: implications of spatial scales. Environ Monit Assess 189:192. https://doi.org/10.1007/s10661-017-5863-0

Johnson RC, Carreiro MM, Jin H-S, Jack JD (2012) Within-year temporal variation and life-cycle seasonality affect stream macroinvertebrate community structure and biotic metrics. Ecol Indic 13:206–214. https://doi.org/10.1016/j.ecolind.2011.06.004

Kaoga J, Ouma G, Abuom P (2013) Effects of farm pesticides on water quality in Lake Naivasha, Kenya. Am J Plant Physiol 8:105–113. https://doi.org/10.3923/ajpp.2013.105.113

Karr JR (1991) Biological integrity: a long-neglected aspect of water resource management. Ecol Appl 1:66–84. https://doi.org/10.2307/1941848

Karr JR, Chu EW (1998) Restoring life in running waters: better biological monitoring. Isl Press 18:297–298. https://doi.org/10.2307/1468472

Katagi T (2006) Behavior of pesticides in water-sediment systems. In: Reviews of environmental contamination and toxicology. Springer, New York, NY. pp 133–251. https://doi.org/10.1007/978-1-4612-1280-5_4

Keithmaleesatti S, Varanusupakul P, Siriwong W, Thirakhupt K, Robson M, Kitana N (2009) Contamination of organochlorine pesticides in nest soil, egg, and blood of the snail-eating turtle (Malayemys macrocephala) from the Chao Phraya River Basin, Thailand. World Acad Sci Eng Technol 52:444–449. http://idc-online.com/technical_references/pdfs/civil_engineering/Contamination%20of%20Organochlorine.pdf. Accessed 2 Feb 2020

Khan MZ, Law FC (2005) Adverse effects of pesticides and related chemicals on enzyme and hormone systems of fish, amphibians and reptiles: a review. Proc Pak Acad Sci 42:315–323

Knillmann S, Orlinskiy P, Kaske O, Foit K, Liess M (2018) Indication of pesticide effects and recolonization in streams. Sci Total Environ 630:1619–1627. https://doi.org/10.1016/j.scitotenv.2018.02.056

Kripa P, Prasanth K, Sreejesh K, Thomas T (2013) Aquatic macroinvertebrates as bioindicators of stream water quality-a case study in Koratty, Kerala, India. Res J Recent Sci https://www.semanticscholar.org/paper/Aquatic-Macroinvertebrates-as-Bioindicators-of-A-in-P.K-Prasanth/. Accessed 3 Mar 2020

Kumar A, Colton MBM, Springer M, Trama FA (2013) Macroinvertebrate communities as bioindicators of water quality in conventional and organic irrigated rice fields in Guanacaste, Costa Rica. Ecol Indic 29:68–78. https://doi.org/10.1016/j.ecolind.2012.12.013

Li L, Zheng B, Liu L (2010) Biomonitoring and bioindicators used for river ecosystems: definitions, approaches and trends. Procedia Environ Sci 2:1510–1524. https://doi.org/10.1016/j.proenv.2010.10.164

Liess M, Ohe PCVD (2005) Analyzing effects of pesticides on invertebrate communities in streams. Environ Toxicol Chem Int J 24:954–965. https://doi.org/10.1897/03-652.1

Liess M, Schäfer RB, Schriever CA (2008) The footprint of pesticide stress in communities—species traits reveal community effects of toxicants. Sci Total Environ 406:484–490. https://doi.org/10.1016/j.scitotenv.2008.05.054

Loewy RM, Monza LB, Kirs VE, Savini MC (2011) Pesticide distribution in an agricultural environment in Argentina. J Environ Sci Health B 46:662–670. https://www.tandfonline.com/doi/abs/10.1080/03601234.2012.592051. Accessed 19 Feb 2020

López-López E, Sedeño-Díaz JE (2015) Biological indicators of water quality: the role of fish and macroinvertebrates as indicators of water quality. In: Environmental indicators. Springer, Dordrecht, The Netherlands. pp 643–661. https://doi.org/10.1007/978-94-017-9499-2_37

Macchi P, Loewy RM, Lares B, Latini L, Monza L, Guiñazú N, Montagna CM (2018) The impact of pesticides on the macroinvertebrate community in the water channels of the Río Negro and Neuquén Valley, North Patagonia (Argentina). Environ Sci Pollut Res 25:10668–10678. https://doi.org/10.1007/s11356-018-1330-x

Mandaville S (2002) Benthic macroinvertebrates in freshwaters: Taxa tolerance values, metrics, and protocols. Citeseer. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.516.2776&rep=rep1&type=pdf. Accessed 12 Feb 2020

Marbà N, Santiago R, Díaz-Almela E, Álvarez E, Duarte CM (2006) Seagrass (Posidonia oceanica) vertical growth as an early indicator of fish farm-derived stress. Estuar Coast Shelf Sci 67:475–483. https://doi.org/10.1016/j.ecss.2005.11.034

Mathuriau C, Silva NM, Lyons J, Rivera LMM (2012) Fish and macroinvertebrates as freshwater ecosystem bioindicators in Mexico: current state and perspectives. In: Water resources in Mexico. Springer, Berlin, Heidelberg. pp 251–261. https://doi.org/10.1007/978-3-642-05432-7_19

Menezes S, Baird DJ, Soares AM (2010) Beyond taxonomy: a review of macroinvertebrate trait-based community descriptors as tools for freshwater biomonitoring. J Appl Ecol 47:711–719. https://doi.org/10.1111/j.1365-2664.2010.01819.x

Mereta ST, Boets P, De Meester L, Goethals PL (2013) Development of a multimetric index based on benthic macroinvertebrates for the assessment of natural wetlands in Southwest Ethiopia. Ecol Indic 29:510–521. https://doi.org/10.1016/j.ecolind.2013.01.026

Molozzi J, Feio MJ, Salas F, Marques JC, Callisto M (2012) Development and test of a statistical model for the ecological assessment of tropical reservoirs based on benthic macroinvertebrates. Ecol Indic 23:155–165. https://doi.org/10.1016/j.ecolind.2012.03.023

Montagna C, Anguiano O, Gauna L, Pechen DE, D-Angelo A (2003) Mechanisms of resistance to DDT and pyrethroids in Patagonian populations of Simulium blackflies. Med Vet Entomol 17:95–101. https://doi.org/10.1046/j.1365-2915.2003.00401.x

Montagna CM, Gauna LE, D'Angelo APD, Anguiano OL (2012) Evolution of insecticide resistance in non-target black flies (Diptera: Simuliidae) from Argentina. Mem do Inst Oswaldo Cruz 107:458–465. https://doi.org/10.1590/s0074-02762012000400003

Moore M, Huggett D, Gillespie Jr W, Rodgers Jr J, Cooper C (1998) Comparative toxicity of chlordane, chlorpyrifos, and aldicarb to four aquatic testing organisms. Arch Environ Contamin Toxicol 34:152–157

Morse JC et al. (2007) Freshwater biomonitoring with macroinvertebrates in East Asia. Front Ecol Environ 5:33–42. https://doi.org/10.1890/1540-9295(2007)5[33:fbwmie]2.0.co;2

Muenze R et al. (2015) Pesticide impact on aquatic invertebrates identified with Chemcatcher® passive samplers and the SPEAR-pesticides index. Sci Total Environ 537:69–80. https://doi.org/10.1016/j.scitotenv.2015.07.012

Mutuku M, Njogu P, Nyaga G (2014) Assessment of pesticide use and application practices in tomato based Agrosystems in Kaliluni sub location, Kathiani District, Kenya. J Agric Sci Technol 19:1–10. http://journals.jkuat.ac.ke/index.php/jagst/article/view/1168. Accessed 12 Feb 2020

Nascimento AL, Alves-Martins F, Jacobucci GB (2018) Assessment of ecological water quality along a rural to urban land use gradient using benthic macroinvertebrate-based indexes. Biosci J 34:194–209. https://doi.org/10.14393/bj-v34n1a2018-37842

Neumann M, Dudgeon D (2002) The impact of agricultural runoff on stream benthos in Hong Kong, China. Water Res 36:3103–3109. https://doi.org/10.1016/s0043-1354(01)00540-1

Neumann M, Baumeister J, Liess M, Schulz R (2003) An expert system to estimate the pesticide contamination of small streams using benthic macroinvertebrates as bioindicators II. The knowledge base of LIMPACT. Ecol Indic 2:391–401. https://doi.org/10.1016/s1470-160x(03)00025-6

Niemi GJ, McDonald ME (2004) Application of ecological indicators. Annu Rev Ecol Evol Syst 35:89–111. https://doi.org/10.1146/annurev.ecolsys.35.112202.130132

Oertel N, Salánki J (2003) Biomonitoring and bioindicators in aquatic ecosystems. In: Modern trends in applied aquatic ecology. Springer, Boston, MA. pp 219–246. https://doi.org/10.1007/978-1-4615-0221-0_10

Okpiliya FI (2012) Ecological diversity indices: any hope for one again. J Environ Earth Sci 2:45–52

Orfanidis S et al. (2007) Benthic macrophyte communities as bioindicators of transitional and coastal waters: relevant approaches and tools. Transitional Waters Bull 1:45–49. http://siba-ese.unisalento.it/index.php/twb/article/view/1093. Accessed 12 Feb 2020

Perera R, Wattavidanage J, Nilakarawasam N (2012) Development of a macroinvertebrate-based Index of Biotic Integrity (M-IBI) for Colombo-Sri Jayawardhanapura canal system (a new approach to assess stream/wetland health). J Trop For Environ. https://doi.org/10.31357/jtfe.v2i1.32

Perry JB (2005) Biotic indices of stream macroinvertebrates for fun and (educational) profit. Test Stud Lab Teach 26:281–294. http://www.ableweb.org/biologylabs/wp-content/uploads/volumes/vol-26/15-Perry.pdf. Accessed 2 Feb 2020

Phillips PJ, Bode RW (2004) Pesticides in surface water runoff in south-eastern New York State, USA: seasonal and stormflow effects on concentrations Pest Management Science: formerly. Pestic Sci 60:531–543. https://doi.org/10.1002/ps.879

Poff NL, Olden JD, Vieira NK, Finn DS, Simmons MP, Kondratieff BC (2006) Functional trait niches of North American lotic insects: traits-based ecological applications in light of phylogenetic relationships. J N Am Benthol Soc 25:730–755. https://doi.org/10.1899/0887-3593(2006)025[0730:ftnona]2.0.co;2

Rasmussen JJ, Wiberg-Larsen P, Baattrup-Pedersen A, Friberg N, Kronvang B (2012) Stream habitat structure influences macroinvertebrate response to pesticides. Environ Pollut 164:142–149. https://doi.org/10.1016/j.envpol.2012.01.007

Rasmussen JJ, Reiler EM, Carazo E, Matarrita J, Muñoz A, Cedergreen N (2016) Influence of rice field agrochemicals on the ecological status of a tropical stream. Sci Total Environ 542:12–21. https://doi.org/10.1016/j.scitotenv.2015.10.062

Rathore HS, Nollet LM (2012) Pesticides: evaluation of environmental pollution. CRC press, pp 259–300. https://doi.org/10.1201/b11864-30

Resh VH, Rosenberg DM (1993) Freshwater biomonitoring and benthic macroinvertebrates. J N Am Benthol Soc 12:220–222. https://doi.org/10.2307/1467358

Reynoldson TB, Norris R, Resh VH, Day K, Rosenberg D (1997) The reference condition: a comparison of multimetric and multivariate approaches to assess water-quality impairment using benthic macroinvertebrates. J N Am Benthol Soc 16:833–852

Reynoldson TB (1987) Interactions between sediment contaminants and benthic organisms. In: Thomas RL, Evans R, Hamilton AL, Munawar M, Reynoldson TB, Sadar MH (eds) Ecological effects of in situ sediment contaminants. Springer, Dordrecht, The Netherlands. pp 53–66. https://doi.org/10.1007/978-94-009-4053-6_6

Ribeiro CO, Vollaire Y, Sanchez-Chardi A, Roche H (2005) Bioaccumulation and the effects of organochlorine pesticides, PAH and heavy metals in the Eel (Anguilla anguilla) at the Camargue Nature Reserve, France. Aquat Toxicol 74:53–69. https://doi.org/10.1016/j.aquatox.2005.04.008

Risser PG, Rice EL (1971) Diversity in tree species in Oklahoma upland forests. Ecology 52:876–880

Romero KC et al. (2017) Lentic water quality characterization using macroinvertebrates as bioindicators: an adapted BMWP index. Ecol Indic 72:53–66. https://doi.org/10.1016/j.ecolind.2016.07.023

Roozbahani MM, Nabavi SMB, Farshchi P, Rasekh A (2010) Studies on the benthic macroinvertebrates diversity species as bio-indicators of environmental health in Bahrekan Bay (Northwest of Persian Gulf). Afr J Biotechnol 9:8763–8771. https://doi.org/10.5897/AJB10.1049

Rosenzweig ML (1995) Species diversity in space and time. Cambridge University press, New York, NY

Ross SM, McManus I, Harrison V, Mason O (2013) Neurobehavioral problems following low-level exposure to organophosphate pesticides: a systematic and meta-analytic review. Crit Rev Toxicol 43:21–44. https://doi.org/10.3109/10408444.2012.738645

Sanders HL (1968) Marine benthic diversity: a comparative study. Am Nat 102:243–282

Sanders T, Liu Y, Buchner V, Tchounwou PB (2009) Neurotoxic effects and biomarkers of lead exposure: a review. Rev Environ Health 24:15

Schäfer RB et al. (2011a) A trait database of stream invertebrates for the ecological risk assessment of single and combined effects of salinity and pesticides in South-East Australia. Sci Total Environ 409:2055–2063

Schäfer RB et al. (2011) Effects of pesticides monitored with three sampling methods in 24 sites on macroinvertebrates and microorganisms. Environ Sci Technol 45:1665–1672. https://doi.org/10.1021/es103227q

Schäfer RB et al. (2013) How to characterize chemical exposure to predict ecologic effects on aquatic communities? Environ Sci Technol 47:7996–8004. https://doi.org/10.1021/es4014954

Schäfer RB, Caquet T, Siimes K, Mueller R, Lagadic L, Liess M (2007) Effects of pesticides on community structure and ecosystem functions in agricultural streams of three biogeographical regions in Europe. Sci Total Environ 382:272–285. https://doi.org/10.1016/j.scitotenv.2007.04.040

Schäfer RB, von der Ohe PC, Rasmussen J, Kefford BJ, Beketov MA, Schulz R, Liess M (2012) Thresholds for the effects of pesticides on invertebrate communities and leaf breakdown in stream ecosystems. Environ Sci Technol 46:5134–5142. https://doi.org/10.1021/es2039882

Schäfer RB, van den Brink PJ, Liess M (2011b) Impacts of pesticides on freshwater ecosystems Ecological impacts of toxic chemicals 2011:111-137. https://doi.org/10.2174/978160805121210138

Schmidt TS, Van Metre PC, Carlisle DM (2018) Linking the agricultural landscape of the midwest to stream health with structural equation modeling. Environ Sci Technol 53(1):452–462

Schulz R, Liess M (2001) Toxicity of aqueous-phase and suspended particle-associated fenvalerate: Chronic effects after pulse-dosed exposure of Limnephilus lunatus (Trichoptera). Environ Toxicol Chem Int J 20:185–190. https://doi.org/10.1897/1551-5028(2001)020%3C0185:toapas%3E2.0.co;2

Shahid N, Liess M, Knillmann S (2019) Environmental stress increases synergistic effects of pesticide mixtures on *Daphnia magna*. Environ Sci Technol 53(21):12586–12593

Sharma RC, Rawat JS (2009) Monitoring of aquatic macroinvertebrates as bioindicator for assessing the health of wetlands: a case study in the Central Himalayas, India. Ecol Indic 9:118–128. https://doi.org/10.1016/j.ecolind.2008.02.004

Sharma M, Sharma S, Goel V, Sharma P, Kumar A (2008) Water quality assessment of Ninglad stream using benthic macroinvertebrates. Life Sci J 5:67–72. http://lsj.zzu.edu.cn/. Accessed 19 Feb 2020

Sharma MP, Sharma S, Gael V, Sharma P, Kumar A (2006) Water quality assessment of Behta River using benthic macroinvertebrates. Life Sci J 3:68–74. http://www.lifesciencesite.com/lsj/life0304/life-0304-14.pdf. Accessed 19 Feb 2020

Shimba M, Jonah F (2016) Macroinvertebrates as bioindicators of water quality in the Mkondoa River, Tanzania, in an agricultural area African. J Aquat Sci 41:453–461. https://doi.org/10.2989/16085914.2016.1230536

Stoddard JL, Herlihy AT, Peck DV, Hughes RM, Whittier TR, Tarquinio E (2008) A process for creating multimetric indices for large-scale aquatic surveys. J N Am Benthol Soc 27:878–891. https://doi.org/10.1899/08-053.1

Svensson O, Bellamy AS, Van den Brink PJ, Tedengren M, Gunnarsson JS (2018) Assessing the ecological impact of banana farms on water quality using aquatic macroinvertebrate community composition. Environ Sci Pollut Res 25:13373–13381. https://doi.org/10.1007/s11356-016-8248-y

Thiere G, Schulz R (2004) Runoff-related agricultural impact in relation to macroinvertebrate communities of the Lourens River, South Africa. Water Res 38:3092–3102. https://doi.org/10.1016/j.watres.2004.04.045

Tomanova S, Moya N, Oberdorff T (2008) Using macroinvertebrate biological traits for assessing biotic integrity of neotropical streams. River Res Appl 24:1230–1239. https://doi.org/10.1002/rra.1148

Uherek CB, Pinto Gouveia FB (2014) Biological monitoring using macroinvertebrates as bioindicators of water quality of Maroaga stream in the Maroaga Cave System, Presidente Figueiredo, Amazon, Brazil. Int J Ecol 2014:1–7. https://doi.org/10.1155/2014/308149

Van der Oost R, Beyer J, Vermeulen NP (2003) Fish bioaccumulation and biomarkers in environmental risk assessment: a review. Environ Toxicol Pharmacol 13:57–149. https://doi.org/10.1016/s1382-6689(02)00126-6

Varnosfaderany MN, Ebrahimi E, Mirghaffary N, Safyanian A (2010) Biological assessment of the Zayandeh Rud River, Iran, using benthic macroinvertebrates. Limnol Ecol Manag Inland Waters 40:226–232. https://doi.org/10.1016/j.limno.2009.10.002

Voshell JR (2002) A guide to common freshwater invertebrates of North America. 40:40–2780. https://doi.org/10.5860/choice.40-2780

Wan H, Chizinski CJ, Dolph CL, Vondracek B, Wilson BN (2010) The impact of rare taxa on a fish index of biotic integrity. Ecol Indic 10:781–788. https://doi.org/10.1016/j.ecolind.2009.12.006

Wang L, Robertson DM, Garrison PJ (2007) Linkages between nutrients and assemblages of macroinvertebrates and fish in wadeable streams: implication to nutrient criteria development. Environ Manag 39:194–212. https://doi.org/10.1007/s00267-006-0135-8

Wendt-Rasch L, Pirzadeh P, Woin P (2003) Effects of metsulfuron methyl and cypermethrin exposure on freshwater model ecosystems. Aquat Toxicol 63:243–256. https://doi.org/10.1016/s0166-445x(02)00183-2

Weston DP, Poynton HC, Wellborn GA, Lydy MJ, Blalock BJ, Sepulveda MS, Colbourne JK (2013) Multiple origins of pyrethroid insecticide resistance across the species complex of a nontarget aquatic crustacean, Hyalella azteca. Proc Natl Acad Sci 110:16532–16537. https://doi.org/10.1073/pnas.1302023110

Whittaker RH (1972) Evolution and measurement of species diversity. Taxon 21(2/3):213–251

Wijeyaratne W, Pathiratne A (2006) Acetylcholinesterase inhibition and gill lesions in Rasbora caverii, an indigenous fish inhabiting rice field associated waterbodies in Sri Lanka. Ecotoxicology 15:609–619. https://doi.org/10.1007/s10646-006-0101-5

Willming MM, Qin G, Maul JD (2013) Effects of environmentally realistic daily temperature variation on pesticide toxicity to aquatic invertebrates. Environ Toxicol Chem 32:2738–2745. https://doi.org/10.1002/etc.2354

Zacharia JT (2011) Ecological effects of pesticides. Pesticides in the modern world-Risks and Benefits, IntechPublisher, 129–142

Zhou D, Zhang H, Liu C (2016) Wetland ecohydrology and its challenges. Ecohydrol Hydrobiol 16:26–32. https://doi.org/10.1016/j.ecohyd.2015.08.004

Zhou Q, Zhang J, Fu J, Shi J, Jiang G (2008) Biomonitoring: an appealing tool for assessment of metal pollution in the aquatic ecosystem. Anal Chim Acta 606:135–150. https://doi.org/10.1016/j.aca.2007.11.018