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An Integrated Approach of Multi-Community Monitoring and Assessment of Aquatic Ecosystems to Support Sustainable Development

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Received: 1 June 2020; Accepted: 1 July 2020; Published: 12 July 2020

Abstract: Aquatic ecosystems are one of the most threatened ecosystems in the world resulting in the decline of aquatic biodiversity. Monitoring and the assessment of aquatic ecosystems are necessary to protect and conserve these ecosystems as monitoring provides insights into the changes in the aquatic ecosystem over a long period of time and assessment indicates the status of these ecosystems. This paper presents an overview of different methods for the hydromorphological, physical–chemical and the biological monitoring and assessment of surface waters. Furthermore, recently developed monitoring and assessment methods are discussed to support sustainable water management and contribute to the implementation of the Sustainable Development Goals 6 (SDG6 related to clean water and sanitation) and 15 (SDG15 related to terrestrial and freshwater systems) of the United Nations. However, many other SDGs are dependent on freshwater, such as food (e.g., SDG2) and climate-related SDGs. We presented an innovative concept for integrated monitoring and assessment. The main new elements are the monitoring of all communities and the use of integrated socio-environmental models to link these communities to ecosystem interactions and functions as a basis for determining their relation to the SDGs. Models can also allow to determine the effects of changes in SDGs on the different elements of the concept, and serve in this manner as tools for the selection of an optimal balance between the SDGs in the context of sustainable development.

Keywords: river; lake; trade-offs; integrated assessment; integrated monitoring; Sustainable Development Goals

1. Introduction

Aquatic ecosystems are one of the most threatened ecosystems in the world [1,2] due to overexploitation, water pollution, flow modification, habitat destruction or degradation and invasion by exotic species [1,3–5]. As a result, declines in aquatic biodiversity are far greater than those in the most affected terrestrial ecosystems [1]. Since biodiversity is linked to ecosystem processes and the resilience of ecosystems to environmental change, alterations in biodiversity can have profound consequences for the services that humans derive from ecosystems [6,7]. It is therefore of paramount importance to protect and conserve aquatic ecosystems.

Monitoring and the assessment of aquatic ecosystems are necessary to protect and conserve these ecosystems. In particular, monitoring provides insights into the changes of aquatic ecosystems over a long period of time while assessment indicates the status of these ecosystems [8,9]. It is also critical for providing an evidence-based documentation of the state of water bodies as a result of human disturbances and interventions. Furthermore, monitoring and assessment programmes provide insights into which strategies and management actions are effective in reducing or preventing further water degradation [10]. They are important in facilitating the decision-making of water managers, supporting the policy development of policymakers and provide information to stakeholders which may encourage them to participate in the decision-making and implementation process [11]. They can also be used as a basis for adapting the implemented actions and at the same time evaluating these actions. Lastly, monitoring and assessment programmes aid in identifying cost-effective solutions to water degradation and provide information to achieve the efficient and optimal use of water resources (Figure 1) [12]. Thus, monitoring and assessment programmes are essential towards the sustainable development and management of water resources to realize the clean water and freshwater biodiversity-related goals of the United Nations [13].

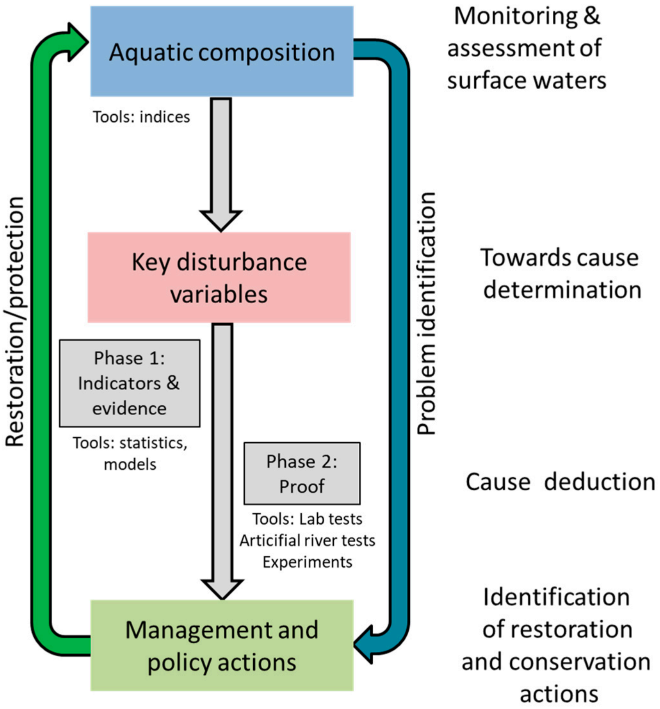

Figure 1. Diagram illustrating the cycles of monitoring and assessment programmes—management and policy action of water bodies towards sustainable development and the management of water resources (adapted from Forio et al. [12]).

This paper presents an overview of different methods for hydromorphological, physical–chemical and biological monitoring and assessment of surface waters. Each component (i.e., hydromorphology, physical–chemical water characteristics and biology) of a water body is described and their relevance in the monitoring programmes is discussed. Recently developed monitoring and assessment methods are elaborated. Lastly, the integrated monitoring and assessment of aquatic ecosystems is discussed and we presented an innovative concept of an integrated approach to support sustainable development.

2. Hydromorphological Monitoring

The monitoring of the physical habitat or the hydrology and geomorphology (referred as hydromorphology) of water bodies is of paramount importance for the ecological integrity of rivers and streams, and in the context of river restoration and management [14–16]. Hydromorphology has been identified as an essential component in the integrated assessment and management of river ecosystems [17,18]. It was shown that certain activities can directly or indirectly impact river habitats. These activities are land drainage, flood defence, channel realignment, river regulation, water abstraction, inter-basin water transfer, navigation, urban and industrial development, the construction of transport links, intensive cultivation, livestock overgrazing, coniferous afforestation, forest clearance and open-cast mining and quarrying. Subsequently, these activities can cause a loss of channel habitat, wetland loss, over deep channels, increased spate frequency, higher flood peaks, increased bank erosion, increased siltation, increased nutrient input, artificial flow regime, reduced flow and dried up channels [12,19–23].

There have been several protocols on hydromorphological characterization [24]. The features examined during a survey are predominant valley form, predominant channel substrate, predominant bank material, flow types and associated features, channel and bank modification, bank face and bank top vegetation structure, channel vegetation types, bank profile, bankside trees and associated features, channel habitat features, artificial features, features of special interest and land use [19]. These protocols are provided in the reports of Raven et al. [19] and Parsons et al. [14]. The field sheets can be modified according to the purpose of the hydromorphological monitoring and assessment.

3. Physical–Chemical Monitoring

Human activities have been modifying the chemical composition and physical characteristics of water bodies over the past century. In particular, concentrations of chemical pollutants such as pesticides, trace metals, endocrine disruptors, organic pollutants, pathogens and nutrients have increased in rivers [25,26]. These pollutants can cause direct physiological effects, indirect food chain effects, increased primary production, algal blooms, toxic effects to humans and biota, toxic effects through biomagnification and interference with naturally produced hormones [25]. It has been shown that the physical and chemical properties of water sustain ecosystem processes and functioning, the goods and services that ecosystems provide and the ecological processes that support the organisms [27]. Thus, changes in the physical and chemical characteristics of water can lead to an alteration in ecosystem functioning and the related ecosystem services.

The physical characteristics of water which are commonly monitored are water temperature, conductivity, light penetration, particle size of the suspended and deposited material, dimensions of the water body, flow velocity and hydrological balance while the chemical quality of water is usually determined through the analyses of nutrient concentrations, dissolved oxygen concentration, pH of water, chemical oxygen demand, biological oxygen demand, pesticide concentrations and trace metal concentrations [28]. Some of these analyses can be performed in the field. For example, water temperature and dissolved oxygen are best determined in the field. This can be made possible through the use of electronic equipment such as dissolved oxygen probes and an electronic thermometer. For most chemical parameters, water samples are collected and are brought to the laboratory for analysis. The methods of collecting, preserving and analysing water samples should be performed using the standardised procedure. However, it should be noted that the physical and chemical characteristics of water can have high temporal variability [29,30]. That is, measurements can be highly variable within a day, month, season, and year. Detailed protocols and methods of analysing the chemical composition and physical characteristics of the water can be found in Bartram et al. [28].

4. Biological Monitoring

Organisms are one of the indicators used to determine ecosystem health and integrity [31]. They are an important tool for detecting the changes in the ecosystems [32]. Thus, biotas are essential in monitoring aquatic ecosystems. Among the often monitored biotas are macroinvertebrates, fish, diatom and macrophytes [33,34]. Below is the list of organisms that are used in monitoring aquatic environments.

4.1. Aquatic Invertebrates

Aquatic macroinvertebrates are good indicators of aquatic ecosystems because they are affected by the physical, chemical, and biological conditions of the water body; they are also ubiquitous and abundant in an aquatic ecosystem; some macroinvertebrate taxa are sensitive to pollution while others are very tolerant; they integrate environmental conditions over a long period of time; they play an essential role in the ecosystem functioning and food web; they may show the impacts of habitat loss not detected by traditional physical and chemical water quality assessments, they are relatively easy to sample and identify [10,35] and; they can be indirectly affected by stream hydromorphology [12,21,36]. However, the limitations of macroinvertebrates include the difficulty in quantitative sampling because of their non-random distribution in the river bed; insects may not be found at a certain period of the year because of their seasonality; and finally, the incidence and frequency of occurrence of some taxa may be restricted geographically [10,37–39].

4.2. Fish

It is assumed that certain fish species and assemblages are sensitive to subtle environmental changes [40]. Furthermore, the application of fish in environmental monitoring and assessment have advantages: they are present in all aquatic ecosystems; they are affected not only by biotic, physical and chemical factors, but also by hydromorphological characteristics and the continuity of rivers and streams; most fish are easy to identify and they can be immediately released back into the water body after being sampled and identified; fish assemblages often include species that belong to different trophic levels; they integrate environmental alterations over a long time interval wherein fish structure and populations change as a response to disturbances; they also integrate these responses over different spatial scales; many fish species are suited to ecotoxicological tests; and there is broad public awareness of the role of fish in aquatic ecosystems and its economic value, which allows the easier enforcement of monitoring activity [41]. Limitations of using fish in monitoring and assessment are that unbiased sampling may be difficult to achieve in some cases such as in large rivers; sampling may be biased by the mobility of fish according to seasonal, daily or occasional patterns; and lastly, some fish species can actively avoid environmental disturbances [41].

4.3. Amphibians, Reptiles, Birds and Mammals

Amphibians, reptiles, birds and mammals are important in both the aquatic and terrestrial ecosystems, because they are often key elements to the trophic web [42]. In particular, they can potentially control other pest species through predation. They can also affect ecosystem structure through soil burrowing and aquatic bioturbation. They also contribute to the ecosystem functions such as decomposition and nutrient cycling [43]. In particular, amphibians are globally threatened and are rapidly declining in comparison with birds and mammals [44]. This is primarily caused by the disappearance, modification and disintegration of habitats, environmental degradation and increasing anthropogenic disturbances [44,45]. Thus, monitoring amphibians, reptiles, birds and mammals is of paramount importance from both biodiversity and ecosystem functioning perspective.

4.4. Macrophytes

Macrophytes play an important role in determining the structure and functions of aquatic ecosystems [46–48]. They also influence nutrient cycling, biotic interactions and assemblages. Moreover, they respond slower than algae but faster than invertebrates and fish to alterations in nutrient concentrations in the water bodies [47]. Their plant tissues can also bioaccumulate toxins, which are linked to the organic matter content, acidification, and buffering capacity of sediments [46]. In particular, submerged macrophytes are dependent on sunlight penetration [46,47,49]. Thus, an increase in water turbidity may result in the loss of this macrophyte. The occurrences of macrophytes also decline as the altitude increases [50]. This has to be taken into account when monitoring macrophytes, especially in high-altitude regions.

4.5. Diatoms

Diatoms are single-celled phytobenthic algae (class Bacillariophyceae) and are ecologically significant in aquatic ecosystems due to their dynamic position at the trophic web as primary producers [51]. They are known to be sensitive to environmental pollution (e.g., nutrients) in aquatic ecosystems. Furthermore, diatoms are easy to sample in shallow waters and are widely diffused. They also quickly respond to changes in environmental conditions [52]. However, diatoms have high seasonal variability and are affected by climatic events, as well as nutrient and light availability [49]. The morphological identification of diatoms can be relatively difficult as this may require a lengthy processing procedure and time and can be also subjective [53].

4.6. Phytoplankton

Phytoplanktons, also known as microalgae, are the important components of rivers as they are the primary producers. They can be an early warning indicator of changes in aquatic environments. In particular, they indicate eutrophication in water bodies [54]. However, their quantitative and qualitative networks are limited to large rivers. Furthermore, they have high inherent spatial and temporal variability and the determination of phytoplankton assemblages can be complex [49]. The response of phytoplanktons to eutrophication can cause chains of negative effects. For instance, an increase in their abundance contributes to the turbidity of water and subsequently results in the decreased colonisation depth or withdrawal of macrophytes. These alterations can result in negative socio-economic consequences [54]. For instance, the excessive growth of harmful algal blooms may impact food safety [55]. Algal blooms can also kill fishes and other marine life, thereby reducing fish catch [56].

4.7. Zooplankton

Zooplanktons are small animals (microscopic or can be seen by the unaided eye) that freely float in the water column of oceans, lakes and ponds. Their distribution is primarily determined by water currents and mixing [57]. They are reported not only as a valuable indicator of ecological status but also their sedimentary remains provide useful information on the state and modifications of the ecosystem over a period of time [58]. Specifically, they indicate eutrophication and predation, change in climate and contribute to the understanding of ecosystem structure and functioning [58].

4.8. Microorganisms

Microorganisms (bacteria and fungi) are generally highly sensitive to environmental disturbances. Particularly, they grow and multiply quickly, and respond not only to low levels of pollutants but also to other physical, chemical, and biotic environmental alterations. They are responsible for the numerous productivity processes and nutrient cycling in aquatic systems, but they are also linked to many diseases of another biota. Thus, they play a key role in detecting and characterizing changes in a system as well as the safety of water usage for consumption and recreation. However, to understand their responses to environmental perturbations, a complementary use of analytical and molecular indicator tools aids in exploring the promising potential of microbes as a bioindicator [59].

4.9. Overview of the Common Sampling Methods Used in Biotic Monitoring

Numerous sampling methods have been developed in recent decades. These methods were developed based on the characteristics of the water body, objectives of the monitoring, availability of funds and personnel, climatic conditions and applicability of the method. Table 1 presents an overview of the commonly used sampling methods used in monitoring. Other methods can be found in Bartram et al. [28] and Ziglio, et al. [60].

Table 1. Overview of the common biological monitoring methods.

Biological Communities	Sampling Methods	Strengths	Weaknesses	References
1. Macroinvertebrates	Kick-net method using hand net attached to a stick (c. 500 µm mesh)	Cheap and simple.	Only applicable in shallow river beds, lake shores.	Bartram et al. [28], Friedrich et al. [61]
	Artificial substrates (e.g., glass slides plastic baskets)	Semi-quantitative compared to other methods. Minimum disturbance to the community. Cheap.	"Unnatural habitat", therefore not truly representative of natural communities. Positioning in water body important for successful use.	Bartram et al. [28], Friedrich et al. [61]
	Grab (e.g., Ekman, Peterson, Van Veen)	Quantitative sampling. Minimal disturbance during sampling.	Expensive. Requires winch for lowering and raising. Mobile organisms avoid sampler.	Bartram et al. [28], Friedrich, et al. [61]
	Dredge type	Semi-quantitative or qualitative analysis which depends on the sampler.	Expensive. Mobile organisms may avoid the sampler. The natural spatial orientation of organisms is disturbed.	Bartram et al. [28], Friedrich et al. [61]
	Corer (e.g., Jenkins or made in-house)	Discrete. Quantitative sampling possible.	Expensive unless made in-house. A small quantity of sample can be taken.	Bartram et al. [28], Friedrich et al. [61]
	Surber method	Quantitative sampling. Simple.	Applicable in shallow river beds. Requires certain flow velocity.	Storey et al. [62]
2. Fish	Fish net/trap	Cheap. Minimal fish destruction.	Selective. Qualitative unless mark-recapture techniques are used.	Bartram et al. [28], Friedrich, et al. [61]
	Electro-fishing	Semi-quantitative. Minimal fish destruction.	A selective technique according to current use and fish size. Safety risk to operators if not carried out carefully. Expensive.	Bartram et al. [28], Friedrich et al. [61]
	Fyke nets	Cheap. Can provide information on the fish direction.	Some species may not be represented in the sample. Not suitable for areas with strong currents.	Davies et al. [63]
3. Amphibians, reptiles, birds and mammals	Nocturnal stream search/visual survey	Cheap. Robust at varying weather conditions and during the range of summer, or breeding season. Robust across a range of forest types and riparian condition.	Time-consuming fieldwork.	Parris et al. [64], Hunsaker and Carpenter [42]
	Amphibian pitfall traps with drift fences	Lesser effort in the field for sampling amphibians.	Can be only applied in the terrestrial ecosystem. Time-consuming to establish the traps.	Parris et al. [64]

Table 1. *Cont.*

Biological Communities	Sampling Methods	Strengths	Weaknesses	References
	Automatic tape recording (anuran calls, bird sounds, . . .)	Robust at varying weather conditions and during the range of summer, or breeding season. Robust across a range of forest types and riparian condition. Require less effort than nocturnal stream search.	Listening to the tapes from the recorders is time-consuming, however artificial intelligence (AI) applications offer options for automated identification.	Parris et al. [64]
4. Diatoms	Scrubbing of rocks and other hard substrates	Cheap and easy.	Not possible when the site does not have rocks or hard substrate.	Kelly et al. [65]
	Scrubbing of artificial substrate	Cheap and easy.	Duration of the incubation of the artificial substrate may affect the colonization of the diatoms.	Kelly et al. [65]
5. Macrophytes	Collection by hand	Cheap.	Qualitative only.	Bartram et al. [28], Friedrich et al. [61]
6. Phytoplanktons	Plankton net	Cheap and simple. High density of organisms collected per sample. Large volume or integrated samples are possible.	Qualitative unless calibrated with a flow meter. Selective according to mesh size. Possibly damage the organisms.	Bartram et al. [28], Friedrich et al. [61]
	Bottle samples (e.g., Friedinger, Van Dom, Ruttner)	Quantitative. Enables samples to be collected from discrete depths. No damage to organisms.	Expensive unless manufactured "in-house". Low density of organisms per sample. Small total volume sampled.	Bartram et al. [28], Friedrich et al. [61]
7. Zooplanktons	Plankton net (e.g., simple conical tow net, Hensen net, Apstein net, Juday net)	Cheap and simple. High density of organisms per sample. Large volume or integrated samples possible.	Numerous factors can affect the monitoring: mesh size and material, the volume of water filtered, closing devices, measurement of the depth of sampling, speed of tow, avoidance, and escapement.	UNESCO [66]
8. Microorganisms	Corer (for sediment) or bottles (for water column)	Discrete. Quantitative sampling possible.	Only part of the microorganisms can be grown on media. Culture-based methods take a long time to obtain results (several days). Molecular methods are fast but are still expensive.	Bartram et al. [28], Friedrich et al. [61]

5. Assessment Methods

5.1. Hydromorphological

Hydromorphological assessment evaluates and classifies both the hydrological and geomorphological conditions of an aquatic ecosystem. Among the hydromorphological assessment approaches used are the Morphological Quality Index (MQI), the Morphological Quality Index for monitoring (MQIm), and the Geomorphic Units survey and classification System (GUS) [15]. Specifically, the MQI evaluates, classifies, and monitors the morphological state (i.e., good, poor). Moreover, the index considers not only the basic channel forms but also includes a series of indicators directly linked to the functioning (e.g., continuity in the sediment and wood fluxes, bank erosion, lateral channel mobility). The index also accounts for the temporal component and reference conditions which are defined based on dynamic processes and functions. However, MQI may not be suitable for monitoring short-term changes in channel conditions. On the other hand, MQIm evaluates the tendency of morphological conditions (enhancement or deterioration). The index takes into account small changes and short time scales (i.e., a few years). MQIm is relevant for the environmental impact assessment of interventions (e.g., including flood mitigation, restoration actions). Lastly, GUS supports the overall morphological analysis of a given reach. In particular, the index can be used in characterizing the reach morphology and can detect small scale (temporal and spatial) morphological changes induced by human interventions or restoration actions. Other assessment methods include (1) German Länder-Arbeitsgemeinschaft Wasser (LAWA) overview method [67], which serves as decision support for the implementation of the European Water Framework Directive [17], (2) on-site survey for urban rivers [68], which addresses urban river assessment and restoration and the (3) the Hydromorphological Index of Diversity (HMID) [69], which measure the structural diversity represented by the flow and depth in a river reach [70]. Further information on the hydromorphological assessment methods can be found in Belletti et al. [71] wherein the authors reviewed different methods which are classified into four categories namely the physical habitat assessment, riparian habitat assessment, morphological assessment and the assessment of hydrological regime alteration.

5.2. Physical and Chemical Assessment Methods

The physical and chemical quality of water can be assessed by comparing their measurements with the natural concentration in surface waters and guideline limits as presented in Chapman [72]. These guideline limits depend on the purpose of water usage. For instance, the EU recommended a dissolved oxygen concentration between 5–9 to support fisheries and aquatic life [72]. Likewise, the chemical and physical measurements provide information on how polluted the water is. For example, surface waters often have a nitrate concentration of less than 1 mg/L NO_3^{-1}-N to about 5 mg/L NO_3^{-1}-N. Thus, concentrations higher than 5 mg/L NO_3^{-1}-N may indicate pollution by fertiliser run-off or human or animal waste [72]. Recent insights, however, have shown that physical and chemical conditions in water can be highly variable, both in time and space. Therefore, more and more complex systems of environmental standards have been implemented to deal with the dynamics as well as particular chemical conditions of the different types of surface waters.

The physical–chemical measurements can be integrated into a single index of pollution indicating the state of the water body (e.g., polluted, moderately polluted, good quality). Among these indices are the Prati Index [73], the Water Quality Index [74], the Lisec index [75] and Index of organic pollution (IPO) [76]. In particular, the water quality can be evaluated using three kinds of Prati: the Prati-oxygen, basic Prati, and total Prati. A basic Prati index is calculated based on the oxygen saturation, the chemical oxygen demand and the ammonium content, while the total Prati is derived from 13 different chemical parameters of water [73]. Likewise, the WQI provides a single value to infer the quality of water based on a list of chemical parameters. This single value indicates the water's suitability for various purposes such as drinking, irrigation, and fishing [74,77]. For further information on other water quality indices, they are elaborated in Abbasi and Abbasi [78].

5.3. Biological Assessment Methods

One of the methods to assess ecosystem health is through indicator taxa. They are species or higher taxonomic groups whose parameters, such as density, presence or absence, or infant survivorship, are used to determine the state of the ecosystem [79]. Indicator taxa provide (early) warning signs of environmental impacts, directly indicate the cause of change, provide continuous assessment over a wide range and intensity of stresses, are cost-effective to measure, and can be relatively easy to identify [80]. For example, metal pollution can be inferred from the abundances of mayflies and heptageniids [81].

It has been shown that biodiversity is linked to ecosystem health and services [82]. Thus, estimating the diversity based on taxonomic groups in an aquatic ecosystem may indicate the state of the ecosystem. For instance, perturbations in aquatic ecosystems can lead to a reduction in diversity. Accordingly, numerous diversity indices have been developed to assess the aquatic ecosystem [10]. Common diversity indices are species richness, Shannon's diversity, Simpson's diversity, Simpson's dominance, Simpson's evenness, and Berger–Parker dominance [83]. Advantages of diversity indices are they are easy to use and calculate, applicable to different kinds of water bodies and taxonomic groups, have no geographical limitations and are therefore relevant for comparative purposes. However, the main limitation of the method is no clear endpoint or reference level [10].

Numerous water quality indices based on biota (e.g., macroinvertebrates, fish, diatoms) have been developed in recent decades [78,84]. Many of these indices provide an estimation of not only the ecological status of an aquatic ecosystem but also its condition and health. Many of them designate the water whether it has bad or good quality. Common water quality indices based on macroinvertebrates are Biological Monitoring Working Party (BMWP), Average Score Per Taxon (ASPT), South African Score System (SASS) and Multimetric Macroinvertebrate Index Flanders (MMIF) [10,84]. Likewise, the indices based on fish were developed: the European Fish Index (EFI+), Ajust de l'Índex d'Integritat Biòtica (IBICAT2b) [85], River–Reservoir Fish Assemblage Index (RRFAI) [86] and the index of biotic integrity based on fish assemblages [87]. Similar methods also start to find their way to other communities such as birds and need more emphasis for amphibians, reptiles and mammals, since these indices are often a basis for decision-making in water management, and communities that are not included are often neglected in protection and restoration management.

6. Recent Developments in Monitoring and Assessment Methods

6.1. Remote Sensing

Satellite remote sensing is a cost-effective monitoring approach which predicts changes in plant species composition. This is due to the fact that this method allows for a thorough spatial coverage of the Earth's surface over a short period of time and can also provide repeated measures allowing to investigate the temporal variations in species composition and biodiversity [86]. However, additional environmental variables (e.g., climate, soil types, topographic variables, biotic interactions) must be considered when using remotely sensed variables. Furthermore, sensitivity studies derived from remote sensing need to be taken into account to understand the shortcomings and effects of different data collection processing and models [88,89].

6.2. Continuous, Real-Time Monitoring System

Concerning the physical–chemical monitoring, the continuous real-time monitoring system (CRTMS) has allowed to measure the physical and chemical characteristics of water more efficiently over a longer period of time. It consists of a transmission system, data receiver and sensors (with or without samplers) that measures water properties (e.g., multiprobe, passive sampler) [90,91]. However, CRTMS has diverse applications, type of sensors, data-handling processes as well as the concepts to combine several measurements [91]. In particular, the passive samplers—a possible component of CRTMS—collect and detect the target analyte (e.g., organic micropollutants) in situ. Passive samplers usually combine sampling, selective analyte isolation and pre-concentration thereby eliminating the need for an energy supply and allow the entire sampling set-up to be simplified and miniaturised [92]. CRTMS are increasingly applied for measuring the effects of abrupt changes, allowing the measurement of contaminant concentrations that vary over time [91,92]. A disadvantage of their samplers and sensors is the possible growth of biofilm on unprotected surfaces submerged in water. Furthermore, colonizing organisms may damage the surface of membranes [90]. Besides, many on-line sensors are less precise and accurate in comparison with laboratory instruments, thus, the reliability of the measurements needs to be checked [91].

6.3. Citizen Science

Citizen science is a monitoring approach which involves volunteers (i.e., nonprofessional scientists) and can be described as public participation in scientific research [93,94]. This approach has an advantage of an increased scale of field studies with continent-wide, centralised monitoring efforts and also enables to conduct large and coordinated field monitoring which can produce large datasets. However, the potential for errors and biases are not well known [95].

6.4. Trait-Based Monitoring and Assessment

Environmental assessment based on traits of biota has been increasing in recent decades [37,96,97]. The traits are characteristics of organisms and are divided into two categories: biological and ecological attributes. Biological traits refer to the physiological and behavioural characteristics of an organism (e.g., body size, life cycle duration, the resistance or resilience potential of organisms, respiration mode, feeding habits, reproduction mode) while ecological traits refer to the habitat preferences of organisms (e.g., preferences for bottom substrate, current velocity, temperature, pH and salinity) [98,99]. It was reported that the traits of organisms are linked to environmental alterations and disturbances [97]. Furthermore, trait-based monitoring and assessment programmes provide a mechanistic understanding of compositional changes and ecological functioning of aquatic ecosystems because organisms' traits are connected to ecosystem functions [100].

6.5. eDNA

Environmental DNA (eDNA) and metabarcoding are advanced monitoring approaches that have recently been developed and can complement or replace morphological identification for use in biological assessment [101] and the (early) detection of invasive species [102]. DNA-based identification is clearly advantageous for fish monitoring because eDNA approaches offer a suitable and reliable sampling method, as they have a high probability of detecting fish species, and at the same time, the approach avoids costly and destructive sampling [101]. Dealing with the abundances of organisms is a major challenge of this approach. Furthermore, there is a need to adjust the biological-based water quality assessment methods, to incorporate the data obtained from the DNA-based monitoring methods [101].

6.6. Animal Tagging, Camera-Based Methods and Hydroacoustics

Other emerging monitoring approaches include animal tagging, camera-based methods and hydroacoustics. Animal tagging makes use of (electronic) tags which are surgically implanted to the animal(s) under study. The tagging data is subsequently transmitted to a satellite or data receivers. This monitoring approach provides information on the seasonal movements, distribution and environmental preferences of these species [103]. Likewise, camera-based monitoring has been increasingly applied and developed in aquatic systems. This approach offers the cost-effective observations and measurements of organisms and their interactions underwater. Moreover, this method is non-destructive and is also reliable in recording an organism's behaviour, communities and habitat preferences [104,105]. Hydroacoustics is based on the physical properties of sound in water, which is a non-invasive monitoring method and provides observation of fish populations over a long period of time [104].

Its foremost challenge is their inability to identify the species. However, a solution to this limitation is the development of an acoustic camera which improves image resolution whilst providing information on fish morphology and swimming behaviour [106]. Most of these methods have found their way in the observation and behaviour analysis of larger types of animals such as fish, birds, reptiles and mammals, however, more and more smaller animals are also being tagged or captured by camera-based methods. Further technological development of tags and cameras, and in particular their energy supplies as well as data transfer and data storage will lead to more applications in the future.

7. Integrated Monitoring and Assessment: A Concept to Link Aquatic Ecosystems to Sustainable Development

The aquatic ecosystems consist of interactive elements such as climate, geological structure (e.g., rocks, sediments), water (chemical and physical characteristics of water), hydromorphology and organisms. Thus, to obtain a holistic picture of aquatic ecosystems' status, these elements must be integrated and evaluated as a whole. A conceptual example can be found in Goethals and De Pauw [107], wherein they suggested the development of an integrated ecological river assessment. Another example is the integrative assessment of hydropower plants as reviewed in Nguyen, et al. [108]. It is not only important to integrate species occurrence, but also the visualization of species interactions allowing to gain insights into energy transfer, nutrient cycling and the effects of invasive species. This will moreover provide insight into the stability of the ecosystem and its potential shift towards another state. Through the integrated approach, different environmental elements can be fed in a model (e.g., numerical models, process-based models, statistical models, spatial models) to determine the associations between these elements and ascertain the cause and the effect of an environmental impact or anthropogenic activity. An example is presented in the study of Holguin-Gonzalez, et al. [109] wherein they assessed the effectiveness of different wastewater treatment/disposal strategies based on the receiving water's ecological aspects. They integrated a mechanistic hydraulic and physical–chemical water quality model with aquatic ecological models (i.e., habitat suitability models predicting the occurrence of macroinvertebrates and ecological assessment models determining a biotic index score). The findings of their study demonstrated that this integrated modelling approach provided an added value for decision support in river management. This approach illustrates holistic insights into aquatic ecosystem management and policy. Integrated monitoring and assessment is moreover crucial in the evaluation of trade-offs and synergies among the Sustainable Development Goals (SDGs) [13,110,111]. In this respect, modelling tools are necessary to find a balance between ecosystem uses [111]. Based on these elements, we provide an innovative concept for integrated monitoring and assessment (Figure 2). The main new elements are the monitoring of all communities and the use of integrated socio-environmental models to link these communities to ecosystem interactions and functions as a basis for determining their relation to the SDGs. Models can moreover allow to determine the effects of changes in SDGs on the different elements of the concept, and serve in this manner as tools for the selection of an optimal balance between the SDGs in the context of sustainable development.

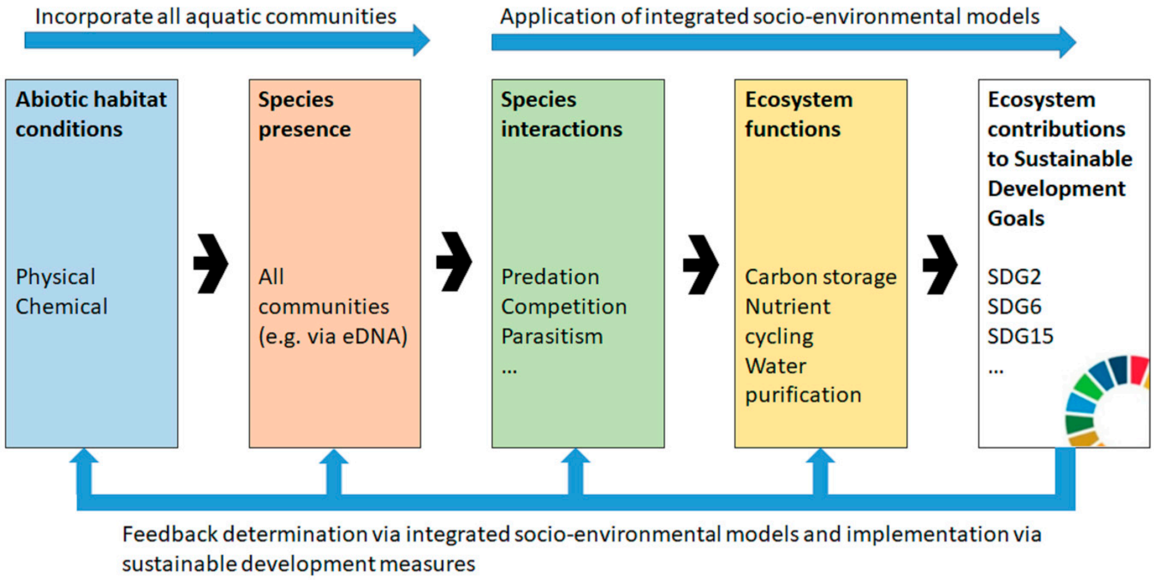

Figure 2. Conceptual diagram for the integrated monitoring and assessment approach to support the selection of an optimal balance between the Sustainable Development Goals (SDGs).

Author Contributions: Conceptualization, P.L.M.G.; writing—original draft preparation, M.A.E.F.; writing—review and editing, M.A.E.F., P.L.M.G.; supervision, P.L.M.G. All authors have read and agree to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: This paper was conceptualised in the context of the VLIR Biodiversity Network Ecuador, Watermas project (Project 586345-EPP-1-2017-1-DE-EPPKA2-CBHE-JP) and the CONSEA project (Project 573515-EPP-1-2016-1-FR-EPPKA2-CBHE-JP). Marie Anne Eurie Forio is supported by the Crosslink project which is co-funded by BiodivERsA and The Research Foundation of Flanders (FWO, project G0H6516N).

Conflicts of Interest: The authors declare no conflicts of interest.

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