Biology-based approaches to unravel multiple stressor impacts on aquatic ecosystems

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CHAPTER 1

General Introduction
A journey in time

About two centuries ago, the Dutch landscape looked very different from today: water flowed through a varied mosaic delta-landscape, including natural areas, grasslands, vast heather, swamp and marsh areas, alternating with villages and larger settlements (Knol et al., 2004). Although the landscape in these days was already strongly shaped by mankind, including deforestation, drainage, digging of canals and peat, and small-scale agriculture, surface waters bodies like ditches, lakes, streams and fens were still inhabited by a wide diversity of organisms. A well-known image of the aquatic life around 1900 stems from the school panels of M.A. Koekkoek, showing the colourful combination of organisms which might meet the interested eye that looks above and below the water table (Figure 1).

Since then, the Dutch above- and underwater landscape has changed dramatically. Anthropogenic activities have affected the state of waterbodies in various ways, for instance by large-scale agriculture and the associated increased runoff of nutrients and toxic substances to the water, urbanisation to host a growing population with increased sewage effluent, and structural changes to the morphology of waterways to increase their drainage capacity for water safety (Allan and Castillo, 2007). Consequently, the aquatic environment became a less suited place for pristine aquatic life. The current degraded state of Dutch waterbodies is

Figure 1. An impression of Dutch surface waters and the surrounding landscape about 200 years ago. Based on paintings of Van de Sande Bakhuyzen and the illustration by M. A. Koekkoek.
Chapter 1

characterized by an altered hydrology and poor habitat and water quality, leading to poorly functioning ecosystems, and the subsequent absence of species that are sensitive and characteristic for pristine water bodies (Feld et al., 2011) (Figure 2). This raised the awareness to halt further ecosystem degradation and to restore ecosystems to recover biodiversity.

However, in the landscape of the future, it will not always possible to return to the situation of about 200 years ago, because many interventions cannot easily be reversed. Nevertheless, in the last decades, numerous efforts have been undertaken that aimed to decrease the negative influences of human activities and to improve the structure and functioning of aquatic ecosystems. Yet, these restoration measures remained often ineffective (dos Reis Oliveira et al., 2020; Palmer et al., 2005). This may be attributed to a lack of knowledge of measure-effect relations and a lack of considering multiple stressors acting on larger scales (dos Reis Oliveira et al., 2020; Palmer et al., 2010). An increased insight in the way negative factors interact and jointly affect aquatic ecosystems on different scales might therefore contribute to effective restoration in the future, striving for a landscape in which diversity is preserved in a densely populated country.

How then will this future situation look like? Below, I will envisage the key aspects of aquatic ecosystems that changed over time and give an impression of possible future developments that may lead to the restoration of ecosystems and the recovery of biodiversity (Figure 3).

Figure 2. An impression of the current state of Dutch surface waters and the surrounding landscape.
From multiple stressors to an unstressed future

When an environmental or biotic variable extends beyond the range of its natural variability, this variable can be defined as a stressor, causing reduced fitness of organisms. This natural variability includes both the size and the frequency of the abiotic or biotic variable (Resh et al., 1988; Townsend and Hildrew, 1994). A stressor, acting on the inhabitants of aquatic ecosystems, can originate from natural processes as well as from anthropogenic activities (Rykiel, 1985), and relates to the abiotic environment, e.g. chemical, morphological or hydrological stress, or the biotic environment, e.g. invasive species, diseases or parasites. Often, stressors do not come alone but occur simultaneously. Human induced changes in abiotic conditions that result in multiple stress include an increased nutrient and toxic load due to agricultural activity, organic pollution and siltation by waste water effluent discharge, a decrease of structural heterogeneity and a loss of habitats by channelisation, extreme peak discharges and erosion due to land use changes or a loss of connectivity by, among others, dams and weirs (Figure 2).

In general, most human induced changes take place simultaneously and consequently, in 60% of the western Europe rivers multiple stressor combinations have been reported (Birk, 2018; Schinegger et al., 2012). Hence, multiple stress is currently common in most aquatic
ecosystems (EEA, 2012; Schäfer and Piggott, 2018). Moreover, multiple stressors act over multiple but often different spatial and temporal scales (Allan, 2004). The inflow of nutrients and agricultural pesticides is typically linked to the growing season and to heavy rainfall over extensive areas. Contrastingly, thermal pollution by industrial outflow has a more local impact during low flows, and morphological alterations causing a loss of connectivity can pose a stress on an entire water body or complete ecological networks throughout the year (Rasmussen et al., 2013).

In addition to this scale-dependency, stressors that are simultaneously present may have interactive effects, since the combination of stressors acting on a local assemblage may cause effects that are stronger (synergistic), equal (neutral) or weaker (antagonistic) than expected based on single stressor-response relations (Piggott et al., 2015). For instance, the effects of low dissolved oxygen concentrations on the drift response of organisms may be amplified by low flow velocities, suggesting that the tolerance to one stressor is reduced by another (Calapez et al., 2017).

Previously, the research on the effects of multiple stressors has often been approached from an abiotic viewpoint, with a focus on physical-chemical water quality assessment. However, this is an incomplete characterisation of the multiple stress situation, as it disregards the translation of physical-chemical changes into actual impacts on biota. Organism responses are indicative of the overall status of ecosystem health, as these integrate the environmental conditions over time, thus serving as a more appropriate endpoint for assessment (De Pauw et al., 2006; Hering et al., 2010). Moreover, another need to depart from biology originates from the notion that we do not yet fully comprehend how environmental, geographical and biotic drivers of species assemblages interact, as their effects can vary between various ecosystems and species assemblages (Lake et al., 2007; Matthaei et al., 2004).

From a biological viewpoint, understanding how combinations of stressors influence the ecological status of freshwater ecosystems remains challenging. So far, the search for understanding stressor-response relations has been approached in several ways. Using empirical techniques, the effects of stressor combinations have been studied in controlled laboratory-based experiments (de Brouwer et al., 2017; Heugens et al., 2006; Verberk et al., 2013), in field mesocosms (Calapez et al., 2017; Davis et al., 2018; Elbrecht et al., 2016) and in actual streams (Townsend et al., 2008). These studies all contributed to the understanding of how aquatic ecosystems are affected by environmental stress, but their applicability is limited to the specific stressors, organisms and environments of interest and extrapolation to diverging field conditions remains difficult (Jackson et al., 2016a). Hence, multiple stressor effects as they occur in the degraded Dutch aquatic landscapes still remain largely unknown and therefore need clarification.
Nonetheless, we can take the opportunity here to imagine a situation in which a large part of these stressors has been tackled. A possible future situation shows surface waters that are allowed space in the landscape (Figure 3). Shores are less fixed, and concrete and steep banks and borders are replaced by gradual land-water gradients that give access to species that need the land phase for a part of their life cycle and vice versa, simultaneously allowing the stream to flood and feed the groundwater system. Agriculture uses a precisely defined sufficient amount of fertilizers and limits runoff to surface waters by using advanced drainage systems (Blann et al., 2009; Schoumans et al., 2014). Both lotic and lentic waters in agricultural surroundings will be delimited by riparian buffer zones, that intercept excess nutrients before these reach surface waters. Such zones will, at the same time, provide increased shading and the input of coarse organic matter, the first being more important in streams and the latter in stagnant waters. Point sources originating from sewage treatment plants and industry are relieved of harmful substances, to the level that the water can be discharged to surface waters without adverse effects. Connectivity between water systems is increased, obstructions and dams are diminished. Green zones further increase connectivity over land for organisms with a terrestrial life phase. These gradual land-water gradients also provide habitat for additional species and further increase biodiversity.

To effectively move towards such a future, we need to increase our present understanding of the contribution of multiple stressors to habitat deterioration and diversity declines, the nature of the interactions between the multitude of these simultaneously acting stressors and their scale- and context-dependency, in order to choose long-term successful and sustainable restoration measures.

**From degraded lowland streams to catchment-wide restoration**

The study of multiple stressor-response relations is strongly scale-specific, because each stressor acts on a different spatial and temporal scale, and because their combined effects are specific to a biogeographical region and water type. Therefore, studying effects of multiple stressors should also be focused on a specific water type and biogeographical region. Because Dutch lowland streams are especially affected by multiple stressors due to their position in a densely populated and intensively used landscape, this water type has been selected as model ecosystem for the present study. The main characteristic of lowland streams is the moderate dynamic flow velocity, but a range of other environmental conditions and dimensions in space and time also apply (Verdonschot, 2000a). Stressors specific to this water type include channelization and embankment for increased discharge efficiency, drought, inflow of excess nutrients and a loss of shading, connectivity and characteristic
morphology. Subsequently, only an estimated 4% of the lowland streams in the Netherlands is still in its near-natural state (Verdonschot, 2000a).

Ideally, in the future, the multiple stressors affecting lowland streams have been resolved. The gradients and interactions with the surrounding landscapes have been restored. It is acknowledged that the landscape drives the stream (dos Reis Oliveira, 2019; Hynes, 1975): the upstream parts of the stream will be characterised by swampy and marshy conditions, and more downstream, riparian wetland forests border the channel. In specific areas, the stream is allowed to flood the surrounding area. With these modifications, catchments are better capable to store water and consequently, stream ecosystems will be more resilient to droughts and floods. Furthermore, the wetland areas provide a number of ecosystem services. Legacy pollution is history and additional pollution eliminated.

To know how to reach this aspired future situation with an improved ecological status, in particular for lowland streams, it is needed to consider the context-specificity of multiple stressor-response relations.

**From stressed organisms towards diverse, well-functioning macroinvertebrate assemblages**

Macroinvertebrates are an important group of organisms in aquatic ecosystems. In their various roles and feeding groups, they contribute to the functioning of aquatic ecosystems (van der Lee, 2020; Vannote et al., 1980). With abundant species distributed over multiple trophic levels and environments, macroinvertebrates can be used to indicate specific habitat conditions on multiple scales (De Pauw et al., 2006; Rosenberg and Resh, 1993). In addition, they are relatively easy to sample and indicative of specific aquatic habitats for at least a part of their lifecycle. Therefore, they are a suitable group to indicate the impact of multiple stressors, and as such they can be used as a proxy for ecological quality (Birk et al., 2012; De Pauw et al., 2006; Wright et al., 1997).

Macroinvertebrate assemblages under stress contain less taxa indicative of a specific water type. Highly tolerant ubiquist species are present, and disturbed waters are more similar in species composition, despite their original environmental differences. In a possible upcoming scenario, the composition of the macroinvertebrate assemblage will change in response to improving environmental conditions. A decreasing influence of stressors will permit the presence of more characteristic and sensitive species, the specialists. Yet, other changes will remain present. For instance, certain invasive species will settle in the Netherlands permanently. Accordingly, this will influence the interactions between organisms and
the functioning of the ecosystem, due to deviating behaviour, preferences and traits.

To work towards diverse and well-functioning species assemblages, we need to increase our insight into species-specific stressor-response relationships as well as the response of entire macroinvertebrate assemblages to changes in the environment, resulting from both increased stress as well as from restoration measures. It should be realized that each species evolved under certain natural conditions and that these conditions thus provide the outline for the future restored circumstances.

**Aim and objectives**

To select the appropriate measures to effectively move towards an unstressed future for aquatic ecosystems, we need to unravel the contribution of multiple stressors to the status of aquatic ecosystems. Here, it is argued that this may be achieved by departing from a biotic rather than an abiotic viewpoint. This leads to the following aim of this thesis:

*To explore biology-based approaches to unravel multiple stressor impacts on aquatic ecosystems.*

This aim translates into the following objectives (Figure 4):

1) To explore the building blocks and limitations for simulating macroinvertebrate responses to multiple stressors.

2) To define the appropriate context for a biology-based expression of ecological quality.

3) To develop tools for simulating macroinvertebrate responses to multiple stressors.

4) To integrate the obtained findings and to give an outlook for an improved understanding of multiple stressor effects.
Outline of the thesis

To gain insight into the possibilities for simulating macroinvertebrate responses to multiple stressors, we evaluated the available methods and their potential for improvement (Objective 1, Chapter 2). Using a conceptual model, we described a means to simulate macroinvertebrate-based ecological quality considering multiple stressors acting on multiple scales. This includes formulating a context for the expression of ecological quality by departing from biology, and the subsequent usage of tools for simulating multiple stressor impacts building on this context.

The second objective was addressed by expressing the ecological quality departing from species distribution data. In Chapter 3 a community classification was made which builds upon a hierarchical clustering based on similarity in species composition. The defined clusters of sites provide a context for the expression of ecological quality, which needs to be carried out for a specific region and water type. To gain insight into the characteristics of the clusters defined in Chapter 3, multiple ways to express species diversity were evaluated (Chapter 4), comparing a context-specific and country-wide application of these metrics.
To achieve the third objective, we studied how macroinvertebrate responses to multiple environmental stressors could be simulated within the previously defined context. Building on the conceptual setup described in Chapter 2, in Chapter 5, a cumulative approach was adopted to quantify the impact of multiple environmental stressors acting on macroinvertebrates in lowland streams, accounting for impacts on multiple spatial scales. The developed method may help to diagnose the causes of deterioration and to identify the most stringent stressors. To further investigate the suitability of different techniques for studying responses to multiple stressors, a network approach was adopted in Chapter 6, to simulate the ecological status using a Bayesian Network. This method can potentially be used to compare the effects of stream restoration scenarios on the macroinvertebrate-based ecological quality.

Finally, I concluded this thesis with a synthesis (Chapter 7). Here, the biology-based approaches to express and simulate ecological quality are discussed. In addition, an outlook is given for moving towards an improved understanding of multiple stressor effects in the future, by building on advancements in ecological theory, the development and use of appropriate methods and techniques and the subsequent application of this knowledge in water management.