Irreversible river water quality and the concept of the reference condition

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In the Water Framework Directive (WFD), ‘water quality’ now refers to a comprehensive assessment of the state of aquatic ecosystems (whether fluvial or lacustrine), which are evaluated by their deviation from a pre-determined historically-based reference condition. However, the WFD does not consider theoretically whether water quality can be expected to recover to a historical condition; it simply assumes that it is possible for quality to be reversed. The main aim of this paper is to ask, in the particular case of the river system, whether its quality is practically reversible or not. By examining empirical evidence and external stresses, we argue that river water quality is more likely to be irreversible. Consequently, there is a dilemma: historical reference states are insufficient if river water quality is irreversible, but a clear quality management goal is needed. To resolve this problem, we suggest that future monitoring practice may need to pay more attention to the river aquatic ecosystem dynamics.

Key words: rivers, water quality, reference condition, irreversibility, Water Framework Directive, species interaction, ecosystem dynamics

Introduction

River ecosystem quality has declined globally because of anthropogenic stresses (Meybeck and Helmer 1989; Malmqvist and Rundle 2002). Policies have accordingly been developed in the last few decades to protect and restore river ecosystems, and the EU Water Framework Directive (WFD) is an example of good practice in this regard, designed for all types of water body in the EU including rivers (European Commission 2000). The EU WFD substantially changed the concept of water quality from a chemically-based one to an overall, multi-criteria quality evaluation of each water body, which is an approximately homogeneous sub-area of a river basin and its channels. The WFD regards the aquatic ecosystem as an environmental good to be sustained and restored where necessary, and not just as a resource to be exploited (Vighi et al. 2006). The concept of a reference condition was introduced to identify the characteristics of this environmental good, and to set recovery goals.

Nevertheless, there have been critiques of the principles underlying the WFD (e.g. Hughes et al. 2008; Richards and Hughes 2008), notably that there is no objective rationale for selecting any given prior state as a reference condition for rivers. Compared with for rivers, the definition of reference conditions for lakes may be more straightforward, as they may have a relatively continuous, dated sediment record to provide validation. However, Bennion et al. (2011) argue that even a sediment-defined reference condition for lakes may still not be appropriate because of the dynamic nature of lake ecosystems, and they believe

whether this or any other temporally defined reference should be used as a target for restoration depends principally on whether it is ecologically achievable by removing the relevant stresses and/or by appropriate management intervention. (2011, 542)

The aim of this paper is to analyse whether it is appropriate to regard a reference condition (or any status determined relative to a reference condition) as a recovery target, and particularly to ask whether river water quality is reversible or not. We argue that, while it may be theoretically possible for water quality to recover towards a historical condition if all external stresses are abated, in practice it is more likely to be irreversible. We base this conclusion on an examination of a meta-analysis of empirical evidence. There are few empirical examples

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that show successful and predictable recovery after stress mitigation, and in many cases it is impossible to eliminate or mitigate external stress in appropriate ways. In these latter cases, an alternative explanation is needed for any observed improvement in a water quality index. However, there remains a dilemma if a historically-based reference condition (or target) is shown to be insufficient, given the clear need for a policy and practice that encourages improved water quality. To square this circle, we conclude that a methodology based on monitoring aquatic ecosystem dynamics may prove a valuable alternative to the current practice.

The concept of water quality

The concept of water quality is surprisingly fluid. Before the 1980s, it was generally the case that only selected physical and chemical indicators were considered in water quality monitoring, and indeed ‘quality’ was effectively defined by the physicochemical characteristics of water. Commonly-used indicators include(d) pH, temperature, turbidity, dissolved oxygen (DO), nitrate-N, phosphate, chemical oxygen demand (COD) and biochemical oxygen demand (BOD). Because these indicators are easily measured, physicochemical water quality was used to evaluate the impacts of human activities on ecosystems as an alternative to comprehensive biological assessment (Karr 1981). However, the physicochemical water quality concept has its disadvantages. For example, it is insufficient to meet the need to protect the communities of some aquatic organisms effectively, such as fish resources (Karr 1981). Although physicochemical parameters may be easily measured, they vary temporally in complex ways that mean that to understand their effects requires a rigorous spatio-temporal sampling regime (Calow and Petts 1992). However, these shortcomings can be rectified by using biological indices, because they directly reflect the health of aquatic organisms and are more stable than the physicochemical parameters. For example, indicators representing the health of fish communities can be directly used for fish resource monitoring (Karr 1981; Jennings 2005). In recent decades, many methods and techniques have been developed to assess structure, composition or function of communities of aquatic organism directly, and these have been applied in water quality monitoring (Ziglio et al. 2006).

Thus, in the WFD, the term ‘water quality’ no longer refers only to the physicochemical characteristics of water, but to a comprehensive assessment of the state of the aquatic ecosystem covering physicochemical, biological and hydromorphological aspects of water bodies, including rivers (Figure 1). The biological component is in
fact the priority element that must be considered in defining the quality status of a river reach or a lake for the purposes of the WFD (European Commission 2000). The definition of ‘water quality’ has expanded from the ‘quality of environmental water’ to the ‘quality of the aquatic ecosystem’ (Vighi et al. 2006; Kernan et al. 2010). In the rest of this paper, we will use the term ‘water quality’, but we will always mean this in terms of a multi-criteria evaluation of the three sets of element defined in Figure 1; the river morphology and its physical habitat, the river ecology and the water chemistry. There are important theoretical implications of this contemporary, comprehensive concept of water quality in rivers; notably, with such a multi-criteria assessment of quality, it is always likely to be more difficult to restore to any pre-determined reference state than is the case with a univariate assessment.

The philosophy of the water quality recovery programme implicit in the WFD is one that evaluates deviation in the quality status of a water body from a pre-determined historically-based reference condition, and assumes that recovery to a quality level closer to that of the reference condition is feasible (European Commission 2000). Whether the water quality can ever be expected to recover to a historical condition has never been fully addressed; the WFD procedures simply assume that it is theoretically possible for water quality to be reversible. Nevertheless, this question is crucial to water quality management. If the assumption is incorrect, it seems insufficient to set targets that are defined relative to a reference condition.

Reference-based water quality standards

The reference condition is an essential concept in the WFD. It is specific to different river types, which are classified primarily according to their hydromorphological characteristics (Boon et al. 2010). For each river type, the reference condition is defined as the status with ‘no or minimal anthropogenic stress’, although this is not necessarily a ‘pristine’ condition (Wallin et al. 2003). The time point represented by the reference condition can vary significantly. However, in most cases, it represents a condition before major anthropogenic impact, such as before European settlement in Australia and North America, or before intensive agriculture in Europe (Stoddard et al. 2006; Wallin et al. 2003). Water quality is then defined as a certain level of deviation from the reference condition (see Figure 2(a)).

According to the Common Implementation Strategy (CIS) guidance on monitoring (European Commission 2003), an Ecological Quality Ratio (EQR) is defined as the ratio between the value of the observed biological parameter for a given surface water body and the expected value under reference conditions. The ratio shall be expressed as a numerical value between 0 and 1, with high ecological status represented by values close to one and bad ecological status by values close to zero (European Commission 2003).

This water quality parameter is then divided into five water quality states: high, good, moderate, poor and bad. The WFD has the ambitious aim that by 2015 all ‘natural’ water bodies in the EU should achieve ‘good’ status. This is achieved by identifying the drivers that have caused the stresses that have resulted in the state of the aquatic system being driven to a lower class than the reference condition, and then developing programmes of measures that will abate or mitigate the effects of those drivers. If good status is not achieved by 2015, river basin management plans will be reviewed and updated every six years thereafter, until a final deadline of 2027 (European Commission 2000). The reference condition is therefore used as the ‘ultimate’ recovery target, and all measures are established to achieve at least ‘good’ status.

Water quality condition versus stress

A two-dimensional stress-status model is usually assumed to represent water quality changes. The idea of this model is that an external stress (which usually arises from anthropogenic activities) is the cause of water quality degradation (see Figure 2(b)). Water quality may deviate progressively from the reference condition if the stress increases. Recovery programmes therefore enhance water quality by eliminating or mitigating the stress. Theoretically, there are two main possibilities when the stress is abated gradually. One is that the water quality may recover towards the reference condition, although this recovery may not follow the pathway of degradation in reverse. Second, the water quality may be trapped in an alternative state that is distinct from the pre-degraded (reference) condition (Gunderson 2000; Schröder et al. 2005). There seems a lack of evidence to show that water quality can indeed be restored by appropriate recovery programmes, although some researchers offer positive opinions about this potential. By contrast, meta-analyses do provide evidence that recovery towards a pre-defined state is relatively rare.

For example, one review of 240 individual studies argues that ‘most ecosystems globally can, given human will, recover from very major perturbations on timescales of decades to half-centuries’ (Jones and Schmitz 2009). To learn whether ecosystems had recovered, Jones and Schmitz relied on the authors’ own expert judgements. There are 44 of these 240 cases that concern freshwater habitats and include biological elements as response variables. Within these 44 cases, only 12 ecosystems are
claimed by the authors to have fully recovered (Table 1). Even in these cases it is debatable whether the cases illustrate reversible water quality. Furthermore, most of these studies were of lake rather than riverine ecosystems (since more work has been done on lakes than on rivers); nevertheless, in this meta-analysis, the conclusions suggest a lack of convergence towards a reference state. In another similar survey, Roni et al. (2008) reviewed 345 stream restoration studies and argued that it is difficult to reach a firm conclusion on the effectiveness of stream rehabilitation, because of ‘limited information provided on physical habitat, water quality, and biota’ and ‘the short duration and limited scope of most published evaluations’ (2008, 856). In addition, Palmer et al. (2010) reviewed 78 independent stream or river restoration projects in order to determine the response of invertebrate taxa richness to the restoration treatment. Although most projects successfully increased habitat heterogeneity, only two of these cases showed significant improvement of biodiversity and had recovered to a level similar to that in reference reaches or sites (Palmer et al. 2010); this finding is reinforced by that of Smith (2003) in another study discussed in the following section.

Before judging whether water quality is reversible or not in individual cases, there are at least two questions to be answered. First, what are we trying to recover? Since a comprehensive concept of quality is employed, referring to the quality and state of the physical habitat and ecosystem, not just a selection of physicochemical characteristics, recovery of water quality status is equivalent to the recovery of the physical, biological and chemical attributes of the whole aquatic ecosystem. Second, what is the meaning of recovery? To assess whether recovery has happened, the ‘recovered’ water quality is compared with the reference condition of an equally multi-criteria pre-disturbance state. Without this comparison, some

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**Figure 2  Water quality degradation-recovery models**

Notes: (a) Water quality condition definition. Higher water quality implies smaller deviation from reference condition; (b) potential degradation-recovery pathway in two-dimensional stress-condition model; (c) a three-dimensional stress-condition model. Solid circles indicate the ‘real’ condition and shaded circles indicate projections of solid circles. The three solid circles represent three states of water quality: 1, reference condition; 2, degraded condition; 3, condition approaching the reference condition after recovery.
improvements in quality may not be judged to be a ‘recovery’. According to these standards, each of the 12 ‘successfully recovered’ freshwater studies in Jones and Schmitz (2009) has at least one of two inadequacies: (1) that a limited set of objective response variables recovered to some degree, rather than the whole ecosystem and (2) that the assessment was not based on a comparison of the state with pre-disturbance data (it only compared with pre-restoration data, or made no direct comparison at all).

Although in these cases the direct anthropogenic stresses had been abated, there is limited evidence to demonstrate recovery of water quality. Considering that there have also been other endemic and generalised stresses, such as land-use change (Allan 2004), invasive species and climate change.
change, recovery towards the reference condition is rather unlikely. An example of the severe difficulty of designing measures to recover ‘good’ status closer to the reference condition is that of invasive species, whose impacts will affect the recovery pathway and outcome. The appearance of invasive exotic species can fundamentally alter species composition and ecosystem processes, through trophic alterations, genetic impacts or the introduction of disease (Taylor et al. 1984), or the loss of one or more native species (Lodge et al. 1998). For example, invasive species constitute one of the most prevalent threats affecting native fish and molluscs in the United States and Canada (Dextrase and Mandrak 2006). Although eradication of invasive species may provide considerable benefits for native species, the loss of natural members of the species pool may make the balance of other ecosystem components irrecoverable (Zavaleta et al. 2001). The additional potential impact of climate change is also of relevance. The effects of climate change pervade all aspects of aquatic ecosystems, including the physicochemical (e.g. water temperature and dissolved oxygen), biological (e.g. metabolic rates of organisms) and hydromorphological dimensions (e.g. hydrological connectivity of slopes and channels) (Whitehead et al. 2009; Wilby et al. 2004). Climate change seems in large degree, and on relevant time scales, impossible to abate as part of the measures for achieving recovery. The programmes of measures at the disposal of environmental agencies are applicable at reach, catchment and regional scales, but cannot affect the entire earth system. If climate change is a ubiquitous and continuing component of anthropogenic stress, there is no possibility of recovering a prior state.

Two-dimensional projection of multi-dimensional water quality states

Using a programme of measures to shift the quality status of a riverine water body from a lower level to a higher level will therefore almost inevitably lead to a state that differs from the historic reference condition defined for it. It seems possible, indeed likely, that there is a third possible consequence of stress abatement in addition to the two identified above: that a water quality state is practically irreversible, but is in a continual state of flux, and any likely future state of water quality is unlikely to be found in history.

This concept may be depicted by recognising the multi-dimensional character of the river water quality concept. A two-dimensional stress-condition representation (Figure 2(b)) can be regarded as a projection of a higher-dimensional system, which for simplicity we can consider initially to be three-dimensional (see Figure 2(c)). In this model, the true water quality condition has two dimensions, (1) the measured water quality indicators and (2) other unmeasured aspects of water quality. Water quality indices and the monitoring programmes that support them merely capture the former dimension and overlook the latter. In the two-dimensional representation, the measured water quality condition is viewed as a theoretical equivalent of the true water quality. Sometimes, the water quality indicators do indicate improvement after a recovery programme, and the recovery pathway seems, in two dimensions, to reverse the degradation pathway and approach the reference condition (Figure 2(b)). However, this may not mean a recovery to the true historical condition. The degradation and recovery may have distinctly different pathways, if viewed in higher dimensions. The water quality status projected onto the water quality index dimension may appear to be very close to the reference condition, but actually they may not be alike in multi-dimensional physico-ecological reality. As an example, consider the study by Smith (2003), which examined the recovery of the benthic macroinvertebrate community in a small stream. Mean total density and taxonomic richness were used to evaluate the recovery. Although these two metrics reached levels comparable with those in the lower range for the reference state, the taxonomic composition changed during the process of recovery, and differed from the reference condition. Thus, it is difficult to conclude that the benthic macroinvertebrate community had recovered to its historic reference condition (Smith 2003, see Table 1). As a further example, Weber and Peter (2011) reviewed 40 selected fish assemblage recovery studies to assess the role of indicator selection in river recovery outcomes. Biological indicators were classified into nine types according to different biological hierarchy and ecosystem attributes. It was found that the result of recovery effectiveness was highly heterogeneous within different types of indicator. Recovery was evaluated by measuring selected recovery indicators, and was considered to have occurred when indicator values reach predefined goals (Weber and Peter 2011); however, the selected indicators only reveal part of the story.

A dilemma and management implication

If the water quality is practically irreversible, it is not helpful to use historical references as the management goal for the water quality standard, and a dilemma appears. On the one hand, the historical reference state is unrealistic; but on the other hand, a clear goal for water quality management is needed. It is nevertheless important to recognise this dilemma, since it exposes the fact that an approach built around historical reference states may generate unrealistic expectations for water quality improvement (Dufour and Piegay 2009).

Specific historic states are thus insufficient to provide analogues for either present or future states; and the irre-
The increased species richness helps to enhance logical structure – improving the desired species richness. The first step is to restore the ecosystem to its historical state. In practice, there is an order in achieving these two endpoints. The structural endpoints and functional endpoints. The network analysis, which has been developed for several decades, may be a promising method to cope with species interaction, or ‘assembly rules’, in ecosystems (Lake et al. 2007).

Species interactions may also help us to understand the functional aspects of ecosystems. It may be more complicated and expensive to assess the functional aspect of ecosystems, but advantages are also apparent. Functional indicators show a lower spatio-temporal variance between replicates than structural indicators, and they provide a better description of ecosystem health (Weber and Peter 2011; Bunn and Davies 2000). Ecological network analysis, which has been developed for several decades, may be a promising method to cope with species interaction (Fath et al. 2007; Christian et al. 2009).

There are mainly two kinds of restoration endpoint, structural endpoints and functional endpoints. The former emphasise species richness, while the latter focus on food web structure and the roles of crucial functional groups for material processing (Palmer et al. 1997). If water quality deterioration cannot be reversed, the structure of an ecosystem cannot be expected to be reversible; but this may not be entirely true of the ecosystem function. Recovery of ecosystem functions does not necessarily need exactly the same structure as occurred in a historically-based reference condition or quality target. Instead, more information is needed on the tendencies and dynamics of water quality, and more attention should be paid to underlying ecological function, and to the processes driving changes in the value of a water quality index, rather than to any specific target value of that index.

Investigating species interactions as well as using functional indicators may be a promising means of detecting water quality dynamics. According to the contemporary (WFD) concept of water quality, biotic components of ecosystems (rather than the conventional physicochemical properties) play a central role in water quality assessment; and the biotic components usually cover more than one type of organism. However, the interactions of these organisms have been neglected; they merely provide entities to be enumerated. It is not just the list of individual species, but the species interactions (or the trophic structure) that contribute to the ecosystem resistance and resilience. Moreover, it is the species interactions, in conjunction with external stress, that co-determine the ecosystem dynamics. The development of a community is largely shaped by species interaction, or ‘assembly rules’, in ecosystems (Lake et al. 2007).

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