Towards appropriate emphasis on regulation of the hydrological regime in integrated river basin management

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Abstract

Abstraction licensing in England and Wales has been steadily evolving over the last 50 years to increase the consideration of ecological response in licence determination. The recent implementation of the Water Framework Directive (WFD) reinforces this by putting ecology at the centre of the decision-making process for regulatory activities like abstraction licensing. The WFD requires that as well as understanding the supporting hydrological regime for the target ecology, any decisions on investment in restoring and maintaining this regime must also consider the range of other pressures that might be affecting the ecology. The WFD river basin planning process must ensure that money is targeted at the most cost-effective areas for remediation. This paper briefly outlines the approach developed in England and Wales to achieve the objectives of the WFD from the point of view of the hydrological regime. It also discusses some of the sources of information as well as emerging tools that might help support the decision-making process when hydrology is considered in context within the River Basin Plan.

Introduction

In England and Wales the widespread regulation of abstraction to protect surface water flows was introduced in 1963 with the Water Resources Act. At first, this was mainly about protecting existing water users and was based on simplified water balance calculations that could be made using records from flow gauging stations and licensed quantities. Many methods were developed but quite often they concentrated on protecting the 95th percentile low flow.

Over time, there was increased recognition of the need to understand the requirements of the water-dependant ecology, along with the need for objectives to protect these that could be used in licensing. Initially, these were taken into account through an assessment of local impacts during the licence determination; however increased computing power and the ability to estimate flows in ungauged catchments made it possible to build the best of these approaches into the nationally consistent Catchment Abstraction Management Strategy (CAMS) process. The CAMS process was always intended to anticipate the requirements of the WFD and included an ecological river flow objective (as a flow duration curve) to set the amount of water that must remain in the environment. To further improve decision-making, CAMS also introduced a concept of Environmental Weighting to reflect differences in the sensitivity of habitats and communities to hydrological change. The CAMS process has proved to be well designed as a major part of the River Basin Planning process for Water Resources in the Water Framework Directive; only minor changes have been made in the light of the recent implementation of the Directive.

Over a similar period as the first cycle of CAMS (2000–2007), the Habitats Directive Review of Consents process has been undertaken. This process has been looking at all the Environment Agency's plans, permissions and projects (including abstraction licenses) to determine the risk they place on European designated sites. Once the level of risk is determined, changes must be made to permissions to protect the designated features of interest. The Habitats Regulations 1994 have turned regulatory impact assessment on its head by requiring a competent authority to demonstrate there is no risk to the site integrity before the permission can be affirmed (for existing permissions) or issued (for new permissions). This process has put the spotlight on hydroecology, particularly uncertainty in the links between hydrological pressure and ecological impact, and contributed greatly to the shift towards ecologically based objectives in water resources management.

The value of water as a resource is increasing together with rising demand; at the same time a better understanding through economics of the balance between licensing water and the 'value' of the environment is emerging. The WFD puts great emphasis on the role economics should play in resolving conflicting priorities within a process of integrated river basin management. Uncertainty over the potential pressure from climate change and the need for redevelopment and increased housing stock in certain areas has indirectly benefited ecology as it is increasingly realised that the reduction of hydroecological uncertainty through commissioning new science or targeted monitoring is often a more cost-effective approach than imposing precautionary restrictions on abstraction licences. Exactly how to model or predict how an ecological community may respond to different pressures is an area that needs further development.

Protecting and improving the environment where abstraction is currently thought to be unsustainable will be costly. For England and Wales, the programme for Restoring Sustainable Abstraction (RSA) has an estimated total cost of £448 million, while the estimated range of costs to meet the WFD environmental objectives by 2027 could be between £3 billion and £20 billion (EA/DEFRA, 2007). In reality, this much would never be spent as the estimates do not take into consideration the need to maintain public water supply or issues of affordability. However, the potential size of these costs underlines the continuing need to reduce any sources of uncertainty in the decision-making process; to better identify where the environment is more resilient to hydrological pressure and where ecological systems will not recover from stress caused by abstraction.

A nationally consistent process of water resource management that locally optimises the balance between environmental needs and those of water users is increasingly being realised. However, fully integrated river basin management that puts hydrology in context with all pressures acting on the environment (Logan, 2001) is partly constrained by the legacy of separate regulatory processes evolving over many years — both in organisational structures and in the funding mechanisms that pay for the work. Catchment Management Plans and Local Environment Agency Plans developed over the last 15 years have worked at drawing these processes together within the development planning framework. Over the next two years, the collation of the first river basin plans will test a new approach in objective setting for water resources management — putting greater emphasis on ecological needs and trying to strike a cost-effective balance between measures to target the hydrological regime and those targeted at other areas like water quality. This paper sets out some of the sources of information and approaches that may help realise this.

Background

The hydrological regime and morphological processes combine to form the hydromorphological quality element in the WFD. This immediately recognises the intimate interdependence of hydrology and morphology when considering the potential effects of human activity on water-dependent ecology. The past reliance on flow duration curve derived thresholds for regulation of water resources has been a vast simplification because the ecology responds not simply to flow, but rather to the combination of changes in both flow and channel form. These relationships are further complicated by numerous other pressures and physical variables such as changing water quality, temperature, climate, upstream influences and instream vegetation.

A central objective of the Water Framework Directive is the achievement of Good Ecological Status (GES). The hydromorphological quality element has an indirect link to GES: it is described in the Directive as being only a supporting element. The hydromorphological conditions must be at a level that supports GES — however GES itself is determined using biological and physicochemical indicators. This approach, with hydrology being a supporting element, reflects the complexity of factors contributing to hydroecological relationships. The associated uncertainties make it inappropriate to specify a nationally fixed flow threshold describing the hydrological regime that would directly determine whether GES has been achieved. However, as an aid to water resource management and to build a current consensus on the hydrological regime that supports GES, flow 'standards' have been developed as part of a UK-wide project WFD 48 (Acreman *et al.*, 2006a). A Ministerial decision has been made to adopt these standards in England and Wales (DEFRA, 2008). These 'standards' have been interpreted for England and Wales within the update to the Resources Assessment Methodology of CAMS where they are known as Environmental Flow Indicators (EFIs). Similar to the first cycle of CAMS, these EFIs also depend on the assessed sensitivity of the ecology to abstraction. Use of these updated tools and the information gained from the first cycle of CAMS have allowed the identification of parts of the country potentially exposed to higher levels of departure from a natural hydrological regime as a result of net abstraction pressure. Within these areas the weight of evidence that these hydrological pressures are in fact expressed as changes in the ecology will be examined — changes significant enough to result in a risk to achieving the WFD objectives. This evidence can then be used to prioritise further investigations on what might be the most appropriate mitigation measures.

The biological and physicochemical indicators used directly in the status classification provide the first and major piece of evidence that the ecology is under stress. However, investigations must also consider the range of pressures affecting the ecology and determine which are having the greatest impact locally so that the money available for measures can be most effectively targeted.

The Water Framework Directive makes allowance for strategically important uses of water through the designation of Heavily Modified Waterbodies (HMWBs). The modification can be as a result of direct morphological intervention (e.g. channelisation) or indirectly through changes in the hydrological regime (e.g. interbasin transfers of water to support downstream abstraction for public water supply). This approach is being used to ensure that major elements of the water resources infrastructure are recognised for their contribution to sustainable development; ensuring that everything is being done to improve the associated ecology without significantly restricting the original purpose they were designed for. In these areas the hydromorphological pressure is clear and ecological effects probable, however the need to continue to use these waterbodies for specific and justified purposes means that it is no longer appropriate to assess ecological status on the basis of departure from a natural reference condition. For the first river basin plan, the classification of HMWBs concentrates on the presence/absence of appropriate mitigation measures rather than EFIs or indicators of ecological status.

Methods of assessment

The management of most water abstraction problems in England and Wales is not based on explicit, quantitative representations of the risk pathway from physical cause to ecological effect (i.e. between pressure and impact). Most decisions use expert judgement underpinned by appropriate modelling, data and investigations.

Site-based hydrology and habitat-hydraulic methods such as PHABSIM (Elliot *et al*., 1996) do provide a more scientifically grounded means of making such hydroecological assessments, but only after detailed, resource-intensive site investigations. Acoustic Doppler Current Profilers (ADCPs) can acquire the sort of detailed site data used in PHABSIM much more quickly and easily than before and there is untapped potential to use these data in hydroecological decision-making. LowFlows 2000 (LF2000) (Young *et al*., 2003) and Continuous Estimation of River Flows (CERF) (Young *et al.*, 2008) now provide the facility to estimate flow duration and time series hydrology quickly for anywhere in England and Wales; but it has proven difficult to date to make a generalised link between hydrology and ecology using existing tools. This difficulty is holding back the ideal of widely available and applicable hydroecological tools which are scientifically underpinned.

Two new hydroecological tools under development offer the potential to close this gap: 'Determining the Relative Importance of Environmental Data Underpinning flow Pressure' (DRIED-UP) (Dunbar *et al*., 2006) along with Rapid Assessment of Physical Habitat Sensitivity to Abstraction (RAPHSA) (Acreman *et al*., 2006b). Tools developed using Artificial Intelligence techniques and large datasets offer a powerful method of putting a wide range of pressures in the context of their relative impact on the ecology; creating a level playing field on which to make management decisions that put appropriate emphasis on measures which target the hydrological regime.

Acoustic Doppler Current Profilers (ADCPs)

ADCPs complement the development of models that integrate hydrology and morphology more closely. They provide a rapid means to collect large amounts of channel form and hydraulic data, allowing a better characterisation of the hydromorphological processes that the ecology responds to. Their speed and mobility means they can be used for short term investigative monitoring in a way that neither conventional current metering nor more permanent flow gauging could have been used in the past. Their largely non-intrusive nature also means that the very act of monitoring does not add further pressures on fish movements or morphological processes.

The Environment Agency has had experience in the widespread use of ADCPs for a number of years. Generally, they are used as a more convenient method of spot gauging, though they have also allowed measurements at sites that may have been too wide, deep, complex or fast flowing for previous measurement.

Elements of aquatic ecosystems (particularly the more mobile parts like fish) can be affected by catchment-level hydromorphology rather than simply the conditions at a single sample point. While the River Habitats Survey (Raven *et al*., 1998) has a history of reach scale monitoring, it is only the availability of ADCPs that has recently made feasible the widespread matching of these habitat data with in-river hydromorphological data at a similar scale. It is increasingly possible to underpin catchment-level models with comprehensive catchment-level monitoring. This will greatly contribute to making the sort of assessments that the WFD requires at the waterbody level that will result in more integrated catchment management.

DRIED-UP relationships

The Lotic Invertebrate Index for Flow Evaluation (LIFE) method (Extence *et al.*, 1999) provides a direct biological indicator, reflecting invertebrate tolerance to persistent low flows. It is already incorporated in the CAMS process when estimating the overall ecological sensitivity to flow pressure. DRIED-UP (Dunbar *et. al*., 2006) found that the LIFE score derived from autumn biological samples was significantly correlated with the preceding summer flow regime in the river. The DRIED-UP equations suggested that decreases in flow, as summarised by the Q95 over the preceding summer, cause quantified changes in macroinvertebrate community, as indexed by the LIFE score.

Sites were chosen in East Midlands and northern East Anglia that had a good record of biological and hydrological data; they covered a spectrum from semi-natural to those subject to significant morphological or hydrological pressure. The relationships developed were two-level linear regression models that used steady-state inter-site data (such as river type and habitat modification score) and time-varying site data (data for different times at the same site). This form of relationship allowed use of pooled comparisons between sites and local data. The flow statistic used in the relationships was the 95th percentile low flow (Q95) over the preceding summer, normalized for compatibility of the data across sites with different flow magnitudes and regimes.

Although the analysis was based on a limited number of sites, it appeared that morphological habitat modification could influence the relationship between LIFE score and flow, with more modified sites having lower LIFE scores and a steeper slope of response of LIFE score to flow. It also demonstrated that a statistically significant, conceptually valid and quantitative estimate of morphological modification could be incorporated into the model, based upon a widely available measure. This measure was the Habitat Modification Score (HMS) which can be calculated using data from River Habitats Surveys and reflects the number of anthropogenic modifications present in the river channel (Raven *et al*., 1998).

The DRIED-UP relationships use the Habitat Modification Score at a site and normalized preceding summer Q95 to estimate the intercept and the slope of LIFE-flow regime relationships. This provides a means of estimating the expected change in LIFE score arising from a change in flow regime. Confidence intervals may also be calculated.

In addition, DRIED-UP demonstrated that the generalized relationships could be improved by using local biological or hydrometric data. Since the relationships allow better quantification of the relative value of monitoring the morphology, biology and flow, there is the potential to better target monitoring for water resource regulation; perhaps giving priority to the variable that offers the greatest decrease in uncertainty for the least cost.

Water managers can potentially use DRIED-UP relationships to experiment with scenarios to see the effects of an artificially influenced flow regime upon LIFE score. Typically, they might use a naturalised flow regime scenario to estimate the biological impact of a steady abstraction against a natural benchmark regime. The effect of licensed or projected abstraction could be estimated by subtracting it from the natural series. Alternatively, the benefits of reduced abstraction could be estimated, or an allowance made for other effects such as climate change or the volume of consented discharges.

RAPHSA relationships

Like DRIED-UP, RAPHSA demonstrated the controlling influence of local habitat conditions on the hydroecological relationships it identified. RAPHSA was set up as a collaborative project between the Centre for Ecology and Hydrology and the Environment Agency (Acreman *et al*., 2006b). The RAPHSA project investigated the technical feasibility of developing catchment-wide tools for rapid determination of sensitivity of physical habitat to abstraction.

The direct relationship between physical habitat and flow provides a potential tool for assessing the impact on habitat availability of changing the flow regime of a river in a similar way to the potential DRIED UP offers to assessing the impact on the macroinvertebrate community.

RAPHSA investigated how to determine physical habitat-flow relationships without undertaking extensive and site-specific data collection, hydraulic and habitat modelling. The research created a database from 66 detailed physical habitat studies from across the UK. The initial work focused on trying to define relationships between the physical habitat-flow relationships and catchment characteristics. This had limited success because the relationships are driven by the hydraulic structure of the river, and few rivers in England and Wales are natural and free from past engineering. Better success was achieved by relating parameters describing the relationships to attributes of the river channel such as width and depth using multiple linear regression. This would require physical measurement of a new site, with these measurements being entered into the regression model. The best estimates of the relationships came from data sets that included measurements of river velocity in addition to width and depth. Good results were obtained using only a fraction of the data required for a full physical habitat study. Overall, the results demonstrated that the more site data that was collected, the better the estimates of the relationships.

Because physical habitat-flow relationships are specific to a chosen component of the river biota, RAPHSA also looked at more generic variables which also change with flow and which could index sensitivity to abstraction. These included wetted bed width, mean depth and mean velocity.

The output from RAPHSA has been two new tools — the Direct Rapid Assessment of Physical Habitat Tool-kit (DRAPHT) and the Catchment Habitat Assessment Tool (CHAT). The tools differ in their input data requirements, allowing estimates of abstraction sensitivity to be made from catchment characteristics, channel survey or hydraulic model output to provide incremental accuracy for given investment.

For these tools, a flow duration curve needs to be estimated using data from a near-by gauging station or LowFlows 2000. The tools produce estimated relationships between river flow and river width, depth, velocity or physical habitat. The slope of any relationship produced by RAPHSA indicates the sensitivity to abstraction at that flow.

In addition to assessing physical habitat sensitivity to flow change, the RAPHSA approach could also be used in the context of river restoration and engineering works. Measurements of river depth, width and velocity from design models could be used to provide predictions of likely physical habitat in the resulting river channel.

River Pollution Diagnostic System (RPDS)

This tool uses Artificial Intelligence techniques to diagnose the environmental pressures that could be affecting a site, based on its river invertebrate fauna. It is assumed that there is more diagnostic information in the invertebrate data from standard invertebrate samples than can be obtained by conventional biotic indices, in particular the indices that are used to classify ecological quality. Pressure-specific biotic indices are prone to erroneous diagnoses because all indices are affected by pressures other than the target pressure — for example a poor LIFE index can be caused chemical pollution rather than just flow.

RPDS is based on pattern recognition. River invertebrate communities (sampled by standard methods) are classified into 250 different types using machine learning (Walley *et al.*, 2002). These types are then associated with information about the environmental conditions that occur with them. The latest version of RPDS is based on 63 567 biological samples. There is a separate model for spring and autumn (Paisley *et al*., 2008).

To diagnose pressures at a new site, the biological data collected from a standard sample are entered. RPDS allocates this to the closest matching community type based on the composition and abundance of 82 Biological Monitoring Working Party (BMWP) families. The environmental data associated with the samples belonging to this type of community in RPDS's database provides the pressure diagnosis.

The diagnosis includes 42 chemical variables, 23 land use categories (from Land-cover 2000); actual and natural flow from LF2000; interpolated flows from 121 gauging stations indicating drier or wetter than normal conditions in preceding 3, 6, 8, 12 and 24 months, and subjective information about 150 potential environmental stresses (a mixture of activities and pressures).

River Pollution Bayesian Belief Network (RPBBN)

This tool also uses Artificial Intelligence techniques and is primarily for choosing the best combination of chemical objectives to ensure good ecological quality. It was designed for identifying the most appropriate programme of measures to protect river invertebrate quality (Walley *et al.*, 2002). The latest version is based on 40 000 matched samples for biology, chemistry and flow (Paisley *et al*., 2008). The model is restricted to sites controlled by organic and nutrient pressure (i.e. not for sites driven by toxic stresses).

RPBBN predicts the abundances of 82 invertebrate families from combinations of concentrations of orthophosphate, ammonia, dissolved oxygen (saturation), biochemical oxygen demand and total organic nitrogen. It can do this for wetter than normal, normal or dry years. RPBBN also calculates a range of biotic indices from the biological taxa, including ASPT, N-taxa and LIFE.

The RPBBN will be used in reverse to help check the ecological status likely to be achieved as a result of the programmes of measures introduced in the first WFD River Basin plan. The concentrations of chemical parameters predicted by the Environment Agency's Simplified Catchment Model (SIMCAT) will be used and potentially an indication of hydrological stress can be incorporated as well. The ASPT and N-taxa predicted by RPBBN will be used to predict WFD status.

Discussion

The tools and techniques under development give an exciting indication of what may be possible using the resources available for hydroecological decision-making and catchment planning.

Used together, DRIED-UP and RAPHSA relationships present the opportunity to manage abstraction using transparent and quantifiable links between abstraction pressure and ecological impact. They could be applied with little or no site data for generic application and improved for high-value site-specific studies as part of a toolkit of approaches that might include methods such as PHABSIM within the Agency's Resource Assessment and Management (RAM) framework. Moreover, ADCPs offer the potential to collect site data more widely and easily than previously.

DRIED UP and RAPHSA also have the potential to incorporate morphological data and bring river channel modification into routine abstraction management decisions in a quantifiable way that allows direct comparison of the benefits between changes in abstraction or channel form. Alternatively, they might also be used to translate estimated changes in hydrological regime from climate change into ecological impact.

Allied to these methods, the River Pollution Diagnostic System (RPDS) and River Pollution Bayesian Belief Network (RPBBN) may help where DRIED UP, RAPHSA or existing approaches to assessing hydromorphological ecological stresses are skewed by non-hydrological pressures. There is also significant potential for further developing the indicators of the hydrological regime used by the tool, to predict the likely change in WFD status resulting from a broad basket of mitigation measures that include hydrological regime and non-hydrological stresses on the ecology.

There is no doubt that these developments still require a substantial amount of further work. The predictive capabilities of these tools will need to be tested alongside real data and decisions based on these tools will also need to be examined and built back into the development of future tools. There are further questions to address: there is, for example, little yet to determine the importance of floodplain flows, or to distinguish the relative importance of winter and summer abstraction. There are also new issues raised: for example, the linear relationships in DRIED UP suggest that, disregarding the effects of water quality, high flow groups within the LIFE index will be favoured by the volumetric gain from consented discharges by the same magnitude as abstraction favours low flow groups. To date, increases in flow regime have usually been regarded as positive, or at least not detrimental to river ecology. However, Initial Characterisation for the Water Framework Directive suggests that as many or more river stretches are discharge-rich as are over-abstracted. Should the position on artificially higher flows be reviewed?

Together, these new techniques offer the chance to move forward from a reliance on expert judgement and flow-based standards that focus more on the pressure than the impact. They are more closely aligned with the Water Framework Directive requirement of scientifically underpinned, generically applicable techniques that express acceptable standards in terms of the impact rather than in terms of the pressure and allow abstraction licensing decisions to be integrated into a more holistic approach to river basin planning.

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