THE USE OF MATHEMATICAL MODELS TO SUPPORT THE IMPLEMENTATION OF THE WATER FRAMEWORK DIRECTIVE IN IRELAND.

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INTRODUCTION

EC Directive 2000/60/EC establishing a framework for Community action in the field of water policy, commonly known as the Water Framework Directive (WFD), requires development and implementation of a range of technical tasks that relate inter alia to characterisation of catchments, monitoring procedures, establishing relationships between catchment pressures and impacts on aquatic systems, and remediation measures where water bodies are considered to be at risk of failure to achieve their environmental objectives. The technical requirements of the WFD that necessitate scientific support are outlined mainly in Article 5 (Characteristics of the River Basin District) and its associated Annex II, Article 8 (Monitoring of water status) and its associated Annex V, Article 11 (Programmes of Measures), Article 16 (strategies against pollution of water) that addresses listed substances, and Article 17 (strategies to prevent and control pollution of groundwater). Detailed analysis of catchment characteristics, assessment of risk to surface and groundwaters, further analysis of existing information and collection of new data are all needed to support the implementation of the WFD. However, there is still much to understand about the relationships between the catchment and the movement of pollutants, and the response of the aquatic ecosystem to anthropogenic impacts. Internal catchment processes, dominant pathways of pollutant load and hydromorphology are all important for the response of aquatic biological communities to pressures that arise within the catchment. Understanding these relationships is, further, restricted by the inherent complexity of natural systems. The simplification of that complexity through the identification of key variables and prediction of responses is a valuable tool. Such modelling is a likely feature of implementation of all of the technical Articles that support the overall objectives of the WFD.

Environmental management operates within a conceptual "DPSIR" framework, comprising Drivers, Pressures, State, Impact and Response. While it is common to view this as a unidirectional circuit, it can also be visualised in the opposite direction linking across categories, in order to identify specific management options, or as means of applying diagnostic tools, as used in Artificial Intelligence models (Fig 1). The links among the DPSIR framework equates to an assessment of risk of enhanced pollutant mobility and impact on the quality elements included in Annex V of the WFD. Incorporation of hydromorphology allows type-specific responses among water body types. This encapsulation of the needs of the WFD is shown in (Fig 2). It also guides where mathematical modelling may be useful to estimate and predict physico-chemical and biotic response to anthropogenic pressures.

This framework guided a six-month desk study (Irvine et al., in press) that reviewed the application of mathematical modelling to support the implementation of the WFD. The report addresses general

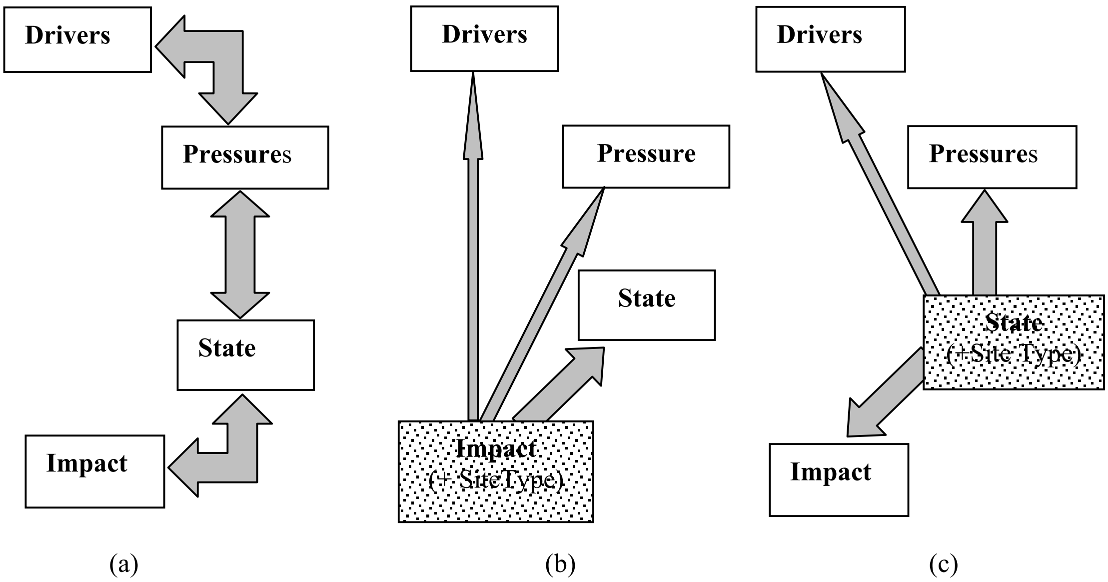

Figure 1. Some possible applications of AI-based models, showing in (a) how predictions and diagnoses can be achieved using a single BBN model, and in (b) and (c) how they can be achieved using two different pattern recognition models, one based on patterns in the Impact (i.e. biology) and site type data, and the other based on patterns in the State (i.e. chemistry) and site type data.

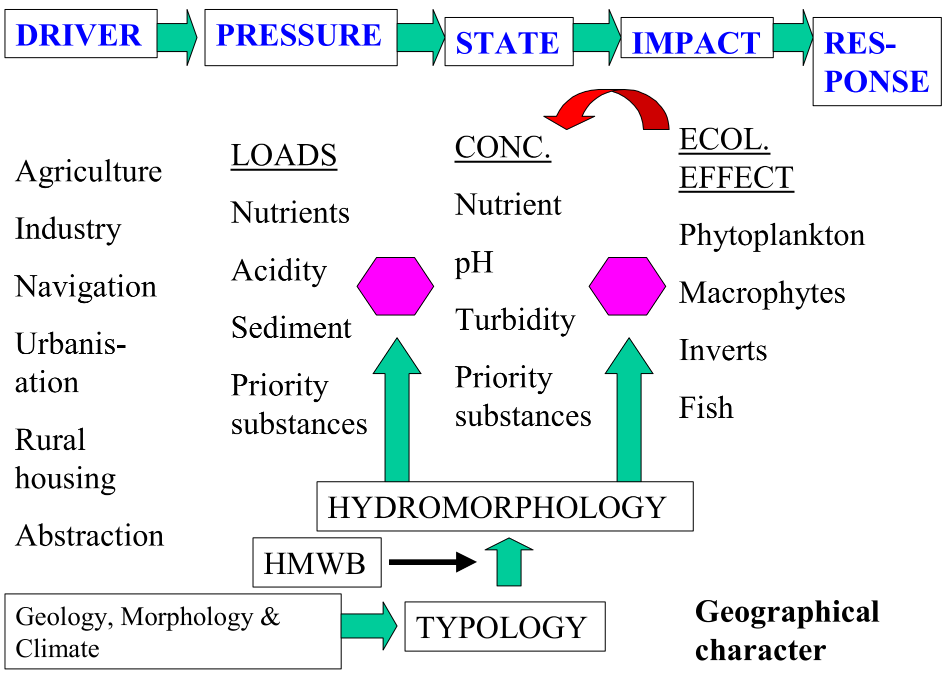

Figure 2. The Driver-Pressure-State-Impact-Response model of catchment management, with examples within the sequence. Shaded hexagons represent application of mathematical models. See text for further detail.

considerations important for application of modelling in the implementation of the WFD and, through numerous examples, details of modelling approaches used in the catchment as a whole, and in rivers, lakes, transitional and groundwaters. Coastal waters are addressed only briefly. The report is supplemented by an extensive annex that details individual models and sources of further information. The work complements a range of larger EU projects that address modelling in support of the WFD (Table 1).

Table 1. Current E.U. funded projects examining application of mathematical modelling to the implementation of the Water Framework Directive. The first four projects listed are within a larger cluster caller Catchmod (http://www.info.wau.nl/eesd1_1/)

Title of project	Website
BMW	http://www.vyh.fi/eng/research/euproj/bmw/homepage.htm
EUROHARP	http://www.euroharp.org/index.htm
HARMONIQUA	http://www.harmoniqua.wau.nl/
HARMONIT	http://www.harmonit.org/
PAEQANN	http://www.fundp.ac.be/sciences/biologie/urbo/paeqann.html
STAR	http://www.eu-star.at/frameset.htm
REBECCA	http://www.environment.fi/syke/rebecca

This paper summarises some of the main findings of the project. It can not, because of limitations of space, be a comprehensive review or address all sectors where modelling can help support the WFD. The paper is structured to provide: 1) an overview of the application of Geographical Information Systems to modelling; 2) hydromorphology, that affects both the movement of pollutants and their impact on biota; 3) pressure-state models, with particular regard to the movement of nutrients; 4) state-impact models relevant to the biotic elements listed in Annex V of the WFD; and 5) discussion of the principles that are required for application of all models and their role as decision support tools. Description of individual models is kept to a minimum and the interested reader is referred to the main report (Irvine et al., in press).

Application of Geographical Information Systems to modelling.

Geographical Information Systems (GIS) provide the obvious structure for visualisation of catchments, as required for Characterisation under Article 5 of the WFD, and as an investigative tool for changes in catchment landuse and pollutant emissions. The coupling of GIS and mathematical modelling is used increasingly to interrogate catchment data sets and is well developed to assist catchment characterisation in Ireland. It has extensive potential for use in identification of hydrological pathways and their morphological alteration. Linking such pathways with information on pollutant loads will be of major importance in the identification of pressures and their impacts, and as a guide to management. In Ireland this is especially important for the management of diffuse pollutant loads from land to water and can be used to help link the needs of the WFD with those of reform of the Common Agriculture Policy. It is anticipated that the resolution of datasets within the drainage network will support different scales of investigation and data aggregation. Determination of the appropriate aggregation should be based both on the level of analysis required (e.g. screening or investigation) and on the characteristics of the datasets that describe a particular 'interfluve' zone (the area between identifiable channels). As a support to pressure-state models, GIS can encompass a broad range of models relating to movement of water, and associated particles or solutes. It can assist in optimising monitoring networks. Its application to state-impact modelling is less obvious, but has clear potential to identify and map spatial networks important for biotic response to pressures. This would include the linking of catchment characters with biotic community structure and response to catchment derived pressures.

Hydromorphology

Hydromorphology determines the rate of movement of material through waterbodies and the habitat structure of waterbodies. Existing models based on hydraulic equations, and used with hydrological inflow series and channel cross-sectional data, can predict water levels, flow velocities and scour. However, modelling of river and floodplain hydromorphology at scales appropriate to that of the

WFD (years to decades) requires further development. Hydromorphological models, and management, for rivers also need to incorporate a wider dimension than the river channel alone. River habitats depend on floodplain processes; and habitat diversity of natural floodplains depend on river dynamics (Richards et al., 2002). The River Habitat Survey (Raven et al. 1997; Fox et al. 1998), while not a mathematical approach, provides a methodology to guide the modelling of hydromorphology. Recent development of models for use in lakes in Finnish (Hellsten et al., 2002) and U.K (Black et al., 2002) lakes follow work in the US on Indicators of Hydrologic Alteration (IHA, Richter et al, 1996). There is clear potential for the extensive current and historical data of the Irish OPW to be "mined" in order to develop a similar system.

PRESSURE-STATE MODELS

Hydrological and water quality models.

Implementation of the WFD requires an understanding of the entire hydrological cycle. There has been an extensive history of modelling of water movement from the predominantly terrestrial zone (the interfluve) to first order, and higher, water channels. Catchment models are distinguished by a) the precision of the spatial units used in analysis as being lumped or distributed and b) the precision of the events modelled over time as being a single or continuous event. Models range from highly detailed process-type models that account for spatial and temporal patterns to simple empirical "black-box" models that estimate net nutrient movement. It is notable that the development of "black-box" models evolves towards greater complexity and that of "process" models to greater simplicity. The most complex distributed models generally require information on topography, channel network, spatial distribution of soil types/properties and of land use/cover and management practices. Many such models are already linked to GIS and permit the detail that might be required (under Article 8 of the WFD) to target operational and investigative monitoring. The Système Hydrologique Européan and related models are probably the most widely known example of a distributed model (Abbott et al., 1986). Process-based semi-distributed models such as HBV (Bergström & Forsman, 1973) and TOPMODEL (Beven & Kirkby, 1979; Beven, 2001) are simpler, and require less intensive data input, than fully distributed ones. They assume a similar response among categories of grid cells that allows integrated modelling.

Within river channels and estuaries, use of computer models to estimate flushing and residence times range from using gross estuary characteristics to detailed hydrodynamic and solute transport models that define water body structure. An industry standard water quality model is the CE-QUAL2E (Brown & Barnwell, 1987) model that can also simulate a range of chemical variables. It assumes steady-streamflow and steady-effluent-discharge. Other well used models such as the Danish developed MIKE11 are better able to simulate transient conditions.

Increasing emphasis on the importance of diffuse nutrient loads to surface waters, highlights the importance to develop models that can simulate cumulative inputs and losses of nutrients in Irish rivers. However, given the difficulty of developing process models for that purpose, it is unlikely that models applicable for widespread use in Ireland will be forthcoming in the near future. Simpler nutrient models such as SIMCAT, developed by the UK NRA, that address point sources are generally applicable only if point sources dominates total nutrient loads. Recent and current upgrading of many SWT plants in Ireland will reduce the contribution of many sewage treatment plants to total phosphorus (P) load. Modelling may, of course, still have an important role in determining whether investment in P-removal technologies is required in order to meet compliance targets.

Modelling diffuse movement of nutrients

In Ireland, modelling of nutrient emissions from land to water has been subject to a great deal recent research (see Jennings et al., (2003) for review of subject). This arises both from 1) the need to implement the WFD and further understand the relationships between inputs of P and nitrogen (N) to land and their movement through catchments and 2) address the assertions by sectors of the agricultural industry that the extent of diffuse movements of nutrients is overstated by the EPA, Teagasc and the scientific literature.

As part of an EPA/Teagasc project on the effect of agriculture on water quality there are a number of modelling activities that include comparison of the performance of process distributed distributed models (HSPF, SWAT and SHETRAN) for estimation of loss of P from the catchments of the Clarianna (Tipperary), Dripsey (Cork) and Oona (Armagh). The models will be compared with empirical, "regression" type models (see below). Testing of the mid-range model GWLF (Haith et al., 1992) has, independently, occurred in the catchment of Lough Leane, Killarney under the EU funded CLIME project. These studies are of direct relevance to implementation of the WFD, in particular to the requirements under Articles 4, 5, 8 and 11.

While there is often a focus of phosphorus movement to inland freshwaters and nitrogen to coastal waters, both can be important in either situation. P and N flux, however, differ sufficiently from each other to merit separate modelling and management considerations. The management and understanding of the mobility of both nutrients is important for the implementation of the WFD.

Point and field scale models of N-movement (e.g. CREAMS (Knisel, 1980; Leonard & Ferreira, 1984)) are primarily of research interest for understanding the processes and not applicable to the catchment scale. Large scale catchment models (e.g. AGNPS (Young et al., 1989), N-LES (Simmelsgaard et al., 2000), and SOILN (Eckersten & Jansson, 1991)), estimating N loss to surface or groundwaters have applied both a nutrient export coefficient and more process type approach. Modelling of N runoff and impact has been progressed by the INCA (Whitehead et al., 1998a, b) model, which simulates flow, nitrate-nitrogen and ammonium-nitrogen and tracks both terrestrial and river flow pathways. The model is dynamic and can simulate daily variations in flow and nitrogen following a change in input conditions and, at longer timescales, investigate change in land use. Further development of nitrogen leaching models, especially in Irish grasslands is required. The INCA model was developed specifically with the Water Framework in mind and its application to Irish rivers should be investigated. Development of a 'sister' phosphorus model INCA-P is in progress.

"Black-box" empirical catchment models

Empirical modelling that estimates pollutant loads from catchment geology, topography and landuse offer an attractive management tool that does not involve either long-term and intensive chemical and hydraulic measurements or detailed understanding or measurement of catchment processes. Tests of empirical nutrient-load models have often found that, while nutrient exports across a range of water bodies are ranked correctly, model predictive power can be modest. Nevertheless, the development of simple empirical relationships between key features in the catchment and water body nutrient status merit further development, as export coefficients can provide a very cost-effective tool to support catchment management.

Recent work in the U.K. has developed an empirical modelling of diffuse P export (Heathwaite et al., 1997) with a conceptual framework of three layers- storage, mobilisation and hydrological connectivity-for which the data input of each can be expanded and refined as knowledge and information become available. The model is a synthesis of three existing modelling approaches and is designed to support management options. The SPARROW model (Smith et al., 1997) developed by the US Geological survey uses spatially referenced regressions of pollutant transport to predict water quality metrics as functions of river channel and catchment descriptors, and incorporates both point and diffuse pollutant loads. The SPARROW model employs a somewhat similar conceptual model as Heathwaite et al., 1997 by recognising the importance of spatial heterogeneity and weighting of zones of influence (Soranno et al., 1996; Cressie & Majure, 1997). Other, conceptually simple, approaches for modelling landuse effects on water quality are by use of multiple regression (e.g. Håkanson & Peters, 1995). In Ireland, Daly et al. (2002) used multiple regression to estimate mean loads of phosphorus to rivers based on soil properties and land management. Predictive strength of models is, however, important for management. Håkanson (1999) for example, suggested that regressions with $r^2 < 0.75$ could be considered effectively useless for lake management.

Modelling nutrients in lakes

Modelling nutrients and particulate transport in lakes has usually employed “Vollenweider” type models of mass balance (Vollenweider, 1968; Vollenweider & Kerekes, 1980; OECD, 1982). While these models provide useful summaries of average concentrations, they do not account well for seasonal variation in phosphorus flux; bioavailability of TP; internal loading of phosphorus; and patterns of phosphorus retention in lake water through seasonal mixing and stratification. Seasonal factors have major implications for the modelling of phosphorus in lakes and, more critically, the biotic response. Internal release of phosphorus from sediments further complicates interpretation of mass-balance models, particularly in nutrient enriched lakes prone to stratification.

STATE-IMPACT MODELS

Effect-Load-Sensitivity

To understand the link between State and Impact of a pollutant, it is necessary to demonstrate reliable dose-response relationships. This drives the determination of Effect-Load-Sensitivity (ELS) models (Håkanson, 2001). Categorising Critical Loads and Maximal Allowable Loads drive water quality monitoring programmes in the U.S. and are of fundamental importance for the implementation of Programmes of Measures under the WFD. State-Impact models are applicable for all biological elements listed in Annex V of the WFD; although development of models for prediction of ecological elements has been far less extensive than those relating to hydrology and nutrients. This reflects both a traditional emphasis on “water quality”, but also inherent difficulties owing to spatial and temporal heterogeneity, food-web effects and the frequent lack of linear state-impact responses of biological elements.

Phytoplankton

The response of phytoplankton to given concentrations of TP is variable, both among lakes and within years. Sub-annual time increments are especially important for predictions of phytoplankton production and standing biomass. New developments, such as Lakeweb (Håkanson & Boulion, 2002) and the PROTECH family of models (Reynolds et al., 2001) have progressed the development of model capability, but are not yet applied widely to support management. Simple Vollenweider and multiple regression models to predict response of algae populations in lakes to changes in nutrient loads could be applied without undue difficulty, given estimates of loads and hydromorphology, but are more appropriate for application to specific lakes rather than on a regional scale.

Macrophyes and phytobenthos

The WFD requires that macrophytes and other phytobenthos be used for the classification of surface waters. General models for predicting macrophyte distribution and community structure are not well developed, although there has been extensive work on studying the effects of pressures, particularly nutrients, on macrophyte communities. The use of general models for robust prediction of periphyton biomass is uncertain. Complex ecological interactions among components of the phytomacrobenthos (macrophytes, epiphytes and epibenthos), the phytoplankton, littoral invertebrates and zooplankton act against widely applicable use of mathematical models to help with WFD implementation. Site specific models in Ireland, for application to investigative monitoring and Programmes of Measures, require further research, although development of simple regression models linking periphyton with physical and chemical variables would be a relatively simple, and perhaps useful, endeavour.

Macroinvertebrates

The use of macroinvertebrates as indicators of river quality has a long history (Metcalfe, 1989). This has included development of simple metric scores (as utilised by the Irish EPA for river quality assessment) and, more recently, application of multivariate techniques (Reynoldson et al., 2000; Smith et al., 1999; Wright, 2000). The USEPA apply a variety of metrics for classification of river water quality (Barbour & Yoder, 2000). The biometric approach includes criteria for reducing the number of metrics to the most relevant core group to be aggregated into a single quality score. Multimetric assessment can, however, provide a low predictability of correctly assessing impairment of a site (Resh et al., 2000) and use of both multimetric and multivariate approaches provides for a better methodology. Multimetric and multivariate classification tools require comparison and further evaluation of their application to the WFD.

Fish

Linking fish habitat preferences to river hydraulics has been done by a number of models (e.g. PHABSIM (Bovee,1982), RHABSIM (Payne, 1994), RHYHABSIM (Jowett, 1989) and EVHA (Ginot, 1998)). While such models can be useful in determining the response of fish to discharge and features of the habitat, and can incorporate hydraulic simulation models to predict availability of suitable habitat, they are often site specific and require precise topographical and discharge measurements. Recent work (e.g Lamouroux & Capra, 2002), that predict fish habitats from hydraulic geometry appear suitable for application across geographic scales and models relating fish communities to impacts have a high potential for application in Ireland.

Ecosystem models

Models that describe or predict ecological response of single biotic “compartments” such as phytoplankton or invertebrates, to driving variables, such as nutrients, have had some success because they are conceptually simple and are often site-specific. The use of ecological models, that link components of the ecosystem and incorporate food-web effects, is not widespread although used increasingly as research tools. Models that account for interactions across trophic groups are, however, likely to be required increasingly in freshwater and coastal management. Recent developments of ecosystem modelling include the Lakeweb model (Håkanson & Boulion, 2002), ECOPATH (Christensen & Pauly, 1993) and, increasingly, use of Artificial Intelligence (Walley & Fontama, 1998). Artificial Intelligence has high potential for the interpretation of biological and environmental data. River Pollution Diagnostic System (RPDS) based on pattern recognition (Walley & O’Connor, 2001) and River Pollution Bayesian Belief Network (RPBBN) based on plausible reasoning (Walley et al., 1992) are recently developed models that can provide important support to the implementation of the WFD, with respect to identifying ecological status. Models that examine non-linear response and complex dynamics (e.g. Scheffer et al., 1993) within aquatic ecosystems require further research and development.

MODELS AS DECISION SUPPORT TOOLS

Mathematical models applied as part of the implementation of the WFD require technical and users decision support. This necessitates the computing skills to run, where needed, complex models and to make informed decisions on model choice; and for the development of integrated management frameworks involving effective communication and discussion among modellers, managers and stakeholders. Without these links optimum use of models to guide management can not occur. There is a need for common understanding and expectation of model reliability. Quantification of natural states and processes include uncertainty, which can be accentuated in models that link processes together and incorporate insufficiently validated assumptions. The robustness of application of models to catchment management requires an awareness of model uncertainty, but this should not prevent model use. There is little doubt that models will be extremely valuable in the assessment of risk of water bodies failing to meet environmental objectives and in targeting monitoring and Programmes of Measures. It is, however, important that policy-makers and end-users appreciate the uncertain nature of the natural world. Otherwise there can be unrealistic demands for certainty of model outputs and distraction among stakeholders about definitions of the problem to be solved (Westervelt, 2001).

Simple management orientated models using functional or empirical relations can appear more feasible, if less accurate, options that complex ones. The simpler models can, however, lack the mechanistic detail of the process models and may provide less insight to the required, and targeted, solutions of any particular problem. The choice to use simpler models over complex ones requires careful consideration, and there is no point in applying a simple model if it is inadequate for the task at hand. Many complex models that address water quality and quantity have undergone considerable development over the last twenty years to provide “user friendly” front ends. On the other hand, there is no guarantee that a complex model provides a better, or more reliable, output than a simple one. A key point in the application of mathematical models to support the implementation of the WFD is that they should be useful and relevant to management objectives, which themselves need to be well defined.

CONCLUSIONS AND SUMMARY

Models that support implementation of the WFD are likely to be of particular importance for: (1) identification of risk to ecological quality from catchment pressures and which should form part of the GIS-supported Characterisation process under Article 5; (2) description of hydrological regimes and estimation of annual nutrient loads; (3) assistance with elucidation, assessment and choice of Programmes of Measures, which necessitates a case-by-case approach; and (4) definition of spatial and temporal resolution of monitoring systems for identification of hydromorphology, and chemical and ecological status.

Further developments of modelling are required to assist with: (1) determination of reference conditions and, subsequent, estimation of departure from reference state for ecological classification; (2) use of artificial intelligence techniques for assisting with determination of ecological status; (3) identification of appropriate temporal and spatial scales to model impact of catchment processes on pollutant loads; (4) modelling frameworks for selection and integration of models; (5) development of decision and user support, to include enhanced communication for widespread understanding and use of models and dialogue among stakeholders; and (6) modelling of ecological systems response to State changes and management measures.

For models to be applied successfully there is also a need to appreciate that:

(1) Models are, by nature, simplifications of reality;
(2) Management objectives need to be defined clearly to guide model use;
(3) There are no universal models, and selection of appropriate models for specific tasks is critical;
(4) All models require initial conceptualisation in order to provide a logical sequence of connections between compartments;
(5) All models have strengths, weaknesses and uncertainties which need to be understood in model choice and application;
(6) Simple models are, generally, more likely to be used and understood than complex ones, but great care is needed to avoid inappropriate model use. Complex models applied with the necessary expertise or user support can be far superior where there is a need to address spatial and temporal complexities;
(7) All models, and the measurements used to calibrate and validate them, have errors which need to be quantified and reported; and
(8) Catchment and hydrological models are generally more well developed, and with greater consensus of applicability to the WFD, than ecological models.

Finally, as identification, prevention and reduction of impact are the pillars of the WFD, there needs to be a greater emphasis on the development and application of ecological models to support implementation. This will certainly necessitate not only application of mathematics and computer science but well structured research that improves our understanding of the response of ecological communities to anthropogenic impacts.

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