Towards a hydroinformatics framework to aid decision-making for catchment management
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ABSTRACT

What is the role of hydroinformatics in improving the balance between profitable rural landscapes and environmental quality? Growing recognition of the need for integrated approaches to land and water management, taking account of socio-economic development and environmental considerations, has given rise to concepts such as sustainable development and integrated River Basin Management. Models and information systems have a place in integrated land–water management, but only if researchers and practitioners engage with wider concerns and work across disciplines. Thus a balanced approach to decision-making is proposed involving partnerships between stakeholders and researchers in the natural and social sciences, using quantitative and qualitative tools. Involvement of stakeholders tied to all scales is essential to building successful partnerships and thus the importance of public engagement is emphasized.

A multi-scale land and water management framework is proposed that attempts to capitalize on current expertise. The place of hydroinformatics tools such as models, GIS and flow visualization software is discussed and a number of specific tools are presented including a novel decision support tool: the Decision Support Matrix. The use of conceptual models to aid communication is discussed and two attempts to apply the framework from projects in the UK and the Western Balkans are presented.

Key words | decision support matrix, hydroinformatics, management, partnerships

INTRODUCTION

In recognition of the profound changes that have taken place in the “relationship between the human world and the planet that sustains it”, in 1983 the United Nations proposed strategies for sustainable development. This was intended to lead to ways of improving human well-being without having adverse effects on the environment and to address potential conflicts between environmental considerations and economic development. In 1987 this approach resulted in the publication by The United Nations Commission of “Our Common Future” (Brundtland 1987) which was followed by the Earth “Summits” of 1992 and 2002 and, in turn, a comprehensive programme of citizen participation through Agenda 21.

In parallel with these developments, there has been increasing awareness of the need for an integrated approach to the management of water resources and the land, largely driven by the world-wide trend in the deterioration of water quantity and quality standards and in increasingly limited access to water. This recognition has given rise to the concept of Integrated Water Resource Management (IWRM). IWRM involves the co-ordinated planning and management of land, water and other environmental resources for their equitable, efficient and sustainable use (Calder 1999). Following the philosophy of IWRM, the Water Framework Directive (WFD) will require all Member States of the European Union (EU) to divide their land area into river basin districts and to prepare management plans for these river basins, enshrining in European legislation the principle of Integrated River Basin Management (IRBM), including a statutory requirement for public participation.
This is intended to encourage a holistic approach to the management of river basins, taking account of the interdependence of human and natural factors within the basin. River basins and catchments are dynamic living areas that can include human habitation and infrastructure such as roads and railways as well as forests, agriculture, grassland and wildlife. Decisions related to one part of a basin or catchment thus should be informed by knowledge of the consequences for the whole system.

The above concerns give rise to the questions of what tools can play a part in environmental management in the real world, and what is the role of hydroinformatics in improving the balance between economic development and environmental quality. At a time of growing demand for water, the gap between science and practice is widening (Miller & Gray 2008) and calls are made to the scientific communities to produce research that addresses societal needs. In the disciplines related to hydroinformatics there is an ever-increasing abundance of data and sophistication of models (Gourbesville 2009), yet it is rare that modellers stand back and consider how these models and data can support decision-making. We need to ask some hard questions about the quality of data, how our models function and what role models can play in dealing with problems in the real world (Quinn et al. 2005; Jakeman et al. 2006; Solomatine & Ostfeld 2008; Abbott & Vojinovic 2009; Díez & McIntosh 2009; Villa et al. 2009). We have to think about whether existing hydroinformatics tools are appropriate for integrated land and water management and about what new tools we might need to aid communication between researchers and stakeholders. If there is to be a place for hydroinformatics in decision support in the context of rural development, be it in the developed or developing world, it has to be within an iterative framework that includes serious engagement with stakeholders at all scales (Thorkilsen & Dynesen 2001; Abbott 2007; Hewett et al. 2009).

This paper proposes a multi-scale framework for decision support in land and water management (see Figure 1). It suggests how the variety of disciplines essential to effective land and water management can be brought together and discusses the significant part that hydroinformatics can play in such a framework. The importance of public engagement and the range of modelling, data and policy support tools that are needed are discussed, and some examples of hydroinformatics tools appropriate to different scales are presented.

Our proposed framework deals first with the land use in the area of a research catchment which usually has an area between 1 m² and 1 ha. Stakeholder workshops are held in order to understand the current local land use and the knowledge, concerns and interests of stakeholders at a variety of scales. Physical parameters relevant to the research catchment, such as flow and water quality, are monitored, ideally along with some monitoring on the larger catchment within which the research catchment is located. The importance of monitoring and data management is emphasized, with emphasis on the need for high-quality data and the importance of data integration.

The framework suggests that hydroinformatics tools can play a role in decision support by informing decision making, providing best practice guidance, and enabling effective communication between stakeholders. The role of visualization and communication tools is also highlighted, with a focus on the importance of clear and accessible communication in decision support.

Figure 1 | A multi-scale framework for decision support in land and water management.
situated. This data and knowledge is fed into physically based models which reproduce measured data and can subsequently be used to model what happens if there is a change in land use. Economic analysis should also be performed at this scale to generate a detailed picture of what is happening in the research catchment. Recognising a degree of uncertainty in scaling up, this research-scale knowledge is used to get an indication of the likely physics and economics at the larger catchment scale and models are used to predict what happens at this scale. While it is possible to use the same models at both scales it is often apposite to use simple meta-models that mimic the dynamics of the physically based models at this larger scale and the output of these models is translated into risk indicators which are input to a Geographical Information System (GIS). Here researchers have to rely on observation, experience and judgement as the scaling-up procedure inevitably introduces a degree of uncertainty that is hard to quantify.

In order to bridge the gap between the information generated and policy makers, decision support tools, such as the Decision Support Matrices (DSMs) presented in this paper, are created. Such tools aim to allow for strategic planning at the catchment scale. Risk indicators generated by the meta-models coupled to a GIS can be used at this stage to target priority areas. In order that the policies developed are implemented, these tools need to assist in persuading land managers and farmers to improve farming practice. One aspect of this is to show them that small changes in practice can lead to large improvements in the environment and need not have an adverse affect on their income. Stakeholder workshops and discussion can be used to provide feedback into visualization, communication and decision support tools and to encourage a sense of ownership of ideas amongst rural communities and institutions. Ultimately any change in land use feeds back into what is done in the research catchment which is then simulated using the physically based models, closing the loop.

**WATER FRAMEWORK DIRECTIVE**

In Europe the introduction of the Water Framework Directive (WFD) is one of the most significant reforms ever undertaken in relation to water quality management legislation. Its overarching theme is integrated water management at the level of the river basin. Its principal objectives are to restore and enhance bodies of surface water to achieve and maintain “good ecological status”, reduce pollution in water courses and preserve protected areas. It requires good status, defined according to chemical, biological and physical measures, to be achieved by 2015. Negative human impacts on the water environment from specific places such as farms, mines or factories, and sources such as road networks, must be identified and a programme of measures established to address those impacts.

The WFD deals with the management of water bodies on a river basin basis. As competent authority for the WFD in the UK, the Environment Agency is responsible for the production of River Basin Management Plans (RBMPs) every six years and for the co-ordination of the programme of measures required to meet objectives. Through RBMPs decisions will be made at the basin level about measures to tackle pollution of water courses. Here it is clear that understanding the physical processes within a river basin will be an important component in deriving RBMPs. However, this is far from being the whole story as there is a statutory requirement for public involvement in the development of RBMPs within the WFD. However, only three forms of stakeholder engagement are referred to in the WFD:

1. access to background information,
2. consultation in the planning process, and
3. active involvement of interested parties in all aspects of the implementation of the WFD.

This represents a serious limitation in the legislation as the term “public participation” refers to a much wider range of stakeholder engagement approaches than is required by the directive (Berardi 2002). We would argue that there is a need to engage with a wide variety of participatory methodologies. In the context of agricultural development specifically useful lessons can be learned from the experience of Carberry, McCown and others in Australia (see, for example, Carberry et al. 2002, 2005; McCown 2002).

Here the results of research and communication of those results to the public will be a key to success and we are confident that some existing hydroinformatics tools...
(e.g. hydrological models, GIS), used in conjunction with some new ones (e.g. the conceptual models and decision support matrices discussed below) have an important part to play.

When environmental concerns or potential hazards are perceived by resident communities the procedure for getting these issues acted upon is often unclear. Time and financial resources are needed for actions. Participatory environmental initiatives rely on individual citizens committing time and energy to projects, often with no clear outcomes. The WFD is a significant opportunity to engage communities in the process of making plans for river basin management and giving fuller consideration to community concerns and local environmental perceptions. It may provide a key to stakeholder participation in environmental actions dealing with issues that concern resident communities, noting scientific, technical, planning, administrative and economic implications. Opportunities exist through engaging the public in the river basin plan-making process to address concerns of “democratic deficit” in the environmental decision-making process. Full participatory programmes offer the opportunity to promote environmental awareness and scientific understanding and to develop mutual understanding through discussion and experiment. Participation can contribute to building and reinforcing a sense of community. Partnership between local people and statutory authorities can build trust through an open and transparent plan-making process. Public confidence can be enhanced through a wider awareness of the issues and processes involved.

With this backdrop in mind the key questions arise: How can the necessary partnerships be developed? What is the role of research in this process? How can the problem of disparate scales implicit in integrated land and water management be dealt with? In this paper we share our experiences of applying the multi-scale framework and propose it as one way of bringing together researchers and stakeholders in collaboration to solve practical problems related to agriculture.

PARTNERSHIPS AND THE ROLE OF RESEARCH

It is clear that periods of public engagement must be accepted as an integral part of developing IRBM from the outset. Thus it is necessary to bring together the many research disciplines required at the catchment scale with stakeholders. Meetings of researchers and end users at the local, national and international scale have to be part of the process. A great deal of work has been done in using hydroinformatics tools to facilitate dialogue between stakeholders, in particular in the area of large civil engineering projects. An impressive example of this is the bridge and tunnel link between Denmark and Sweden (Thorkilsen & Dynesen 2001). In the course of this project innovative tools were developed to aid communication between formal and informal stakeholders and inventive use was made of ICT, all of which can provide useful lessons for building successful partnerships. A useful discussion of this project can be found in Abbott (2007) who also points to how the knowledge and understanding gained in such projects are relevant in the developing world.

Figure 2 illustrates our vision of a balanced approach to integrated land and water management involving partnerships between natural scientists, economists, sociologists, agronomists, end users such as farmers, residents, local traders, tourists and local councils, national bodies such as the National Farmers’ Union, the EA, Department for Environment, Food and Rural Affairs (Defra) in the UK, or equivalent organisations in other countries, and international bodies such as the European Commission. The “cooking pot” in the centre of the figure is intended to reflect the importance of discourse across disciplines and with end users in the process of arriving at a local catchment/river basin plan.

In the box entitled “Water and Environment” it is clear that a partnership of scientists, ecologists and engineers must be created to establish the current water quantity and quality regime for an area (which should be fed by an informative GIS). In many countries, especially developing countries, there may not be expertise in all the fields required and thus transfer of knowledge will play an essential role in making this approach workable. It is important to capitalise on the great improvements that have been made in hydro-ecological understanding (Acreman 2001) and Earth Systems Engineering and Management (Allenby 2000; Quinn & Hewett 2003). It is also important to take on board the widespread recognition of the need for a broader approach to research related to water resources,
combining knowledge and methods from a range of disciplines in the natural and social sciences (Naiman 1994; Thorkilsen & Dynesen 2001; Aylward 2005; Quinn et al. 2005; Abbott 2007; Hewett et al. 2009). Figure 2 thus reflects the importance of natural scientists working closely with social scientists—in particular with economists and sociologists, who have the tools to design surveys, interpret data, understand and communicate stakeholders’ concerns and perform action research which results in changes in practice.

Finally, Figure 2 supports the concept of mutual partnerships between the professional and research scientific disciplines. The researchers are forced to work together at the strategic scale of the river basin, both exchanging concepts and skills while studying local catchment properties and learning from end users directly. Local stakeholders are tied to the river basin scale as well as the regional, national or international scale. While there is clearly an input from regional, national and international drivers, those components must be translated into a local framework first. The key innovation is to place all the research and local end user needs into the “cooking pot” where all the issues can be simmered for a suitable period of time. This means much more than paying lip service to participation and involves real engagement with the concerns and needs of stakeholders. The key here is the willingness of all parties to listen to each other; there should be no dominant ingredient within the cooking pot and no matter how long and difficult the process is, any product from the pot will be a jointly owned, viable vision for the local catchment. As such, any proposed land use planning and policy can be created and enforced by the local community. With these points in mind we would recommend holding most or all of the stakeholder meetings close to the relevant farms. We have found this valuable in helping to build trust in the research team’s commitment to the area and in improving the likelihood of farmers attending.

**SCALE ISSUES**

There are a range of scales which must be considered within an integrated approach to land and water management in parallel with two sets of factors which we argue have the greatest influence on successful implementation (see Figure 3). Firstly, there are conflicting interests at play at the individual, community, regional, national and international scale and thus dealing with the human dimension at all scales is essential. Secondly, there are hydrological
processes that impact on the river basin at the plot, hillslope and catchment scale and thus an understanding of the issues related to scaling up results is equally important (Beven 1993; Blöschl 1997). It is essential to understand the links between any local activity and its impact downstream. The issues are where, when and how human activities interact with hydrological processes and the impacts they have on water quantity and quality throughout a catchment.

It is widely recognised that environmental measurements cannot be scaled-up directly (Beven 1989). The types of measurements taken at a point (1 m²), may differ radically from measurements made at the hillslope scale (1 ha), in small catchments (1 km²) or in large catchments (1,000 km²). However, some environmental measurements can be made accurately at all scales, for instance the water balance and nitrate balance, and these can form the basis of a combined monitoring and modelling strategy for addressing scale issues. In principle, synchronous determinations of the water and nitrate fluxes made at the point, plot, hillslope, catchment and basin scales offer the best hope of understanding scale-dependent effects and determining modelling strategies appropriate to specific scales of application. Equally, modelling studies using existing GIS data and multiple time series data is giving excellent insights into multi-scale modelling approaches to suit many ecological and environmental issues. The hydrological community is awakening to the needs of humans and the environment (not just reservoirs’ provision and irrigation schemes). The International Hydrology Program will, in the future, seek to blend hydrological research with management as reflected in the new UNESCO HELP (Hydrology, Environment, Life and Policy) programme which is seeking to address sustainability issues through catchment studies. The establishment of environmental observatories has great appeal for the hydroinformatics community but once again the tools and technologies often outstrip our ability to deliver environmental solutions to end users (Abbott & Vojinovic 2009; Quinn et al. 2009).

**FRAMEWORKS FOR ANALYSIS AND DECISION SUPPORT**

The Sustainable Livelihoods (SL) approach has been widely used over the last decade in development planning and interventions. In keeping with the concept of sustainable development, SL is intended to promote poverty reduction alongside protection and better management of the environment, but with the emphasis placed on people rather than resources (Carney 1998; Hewett & Hope 2002). In the late 1990s the UK Department for International Development (DFID) developed the SL framework to conceptualise economic, social and environmental influences and interactions, shown in Figure 4 (DFID 1999).

Another framework that has become popular in environmental management and sustainable development, especially in the context of water resource management, is that of the Driving force–Pressure–State–Impact–Response (DPSIR) framework (see Figure 5 (after Giupponi 2002)). The origin of DPSIR lies in the social sciences in the late 1970s when the “stress–response” model for information organisation of Rapport & Friend (1979) was developed for environmental reporting. This later evolved into a number of forms such as the Pressure–State–Response (PSR) framework developed by the Organisation for Economic Co-operation and Development (OECD) (1994, 1998) and the Driving force–State–Response (DSR) model of the United Nations Commission on Sustainable Development (UNCSD 1996) and the DPSIR framework itself, adopted by the European Environment Agency (EEA) (1999). Further description of the development of the DPSIR framework can be found in Wieringa (1999).

The DPSIR methodology attempts to describe the cause and effect relationships between interacting components of a system, be it social, economic or environmental. It consists of using sets of indicators to represent different

![Figure 3](https://iwaponline.com/jh/article-pdf/12/2/119/386438/119.pdf)

**Figure 3** | Factors influencing successful integrated land and water management.
Driving forces of environmental change, such as farming practices and industrial production, are the cause of pressures on the environment, such as discharges of nutrients or industrial waste. These pressures affect the state of the environment as reflected in, for example, water quality. Any changes in state have impacts on, for example, human health, the economy and ecosystems and there is a corresponding societal response, such as policy and planning measures, to deal with those impacts (e.g. watershed protection). The DPSIR framework has been adopted by a whole range of agencies such as the UK’s Department for Environment, Food and Rural Affairs and Eurostat.

Frameworks such as those discussed above can be very useful as “thinking tools”, but what is often missing is a set of tools with which to analyse the interactions suggested by the Figures (Quinn et al. 2005). It is all too easy to be glib with such approaches. Conceptualising the links between things using a series of boxes with arrows joining them is easily done. Turning this into some useful analysis is not. The problem is, as soon as there are more than two or three factors to consider, the number of potential links becomes very large and even drawing all the possible connections between different factors becomes overly complicated, let alone analysing them all (see Figure 6). The real challenge is in moving from a “thinking tool” to a set of appropriate analysis tools or models. Some researchers have tried to move from the DPSIR framework to decision support tools (e.g. Giupponi 2002) and have thought carefully about the need and role of models in implementing policy (see, for example, Rekolainen et al. 2003) and these are welcome developments. However, there is a tendency to overplay the centrality of models in bringing about improvements to the environment and to do little more than touch on consultation and engagement.

As we have indicated above we consider that building the appropriate partnerships has to be an integral part of any framework which hopes to bring about change. Hydroinformatics has a key part to play in conceptualising and visualising problems, quantifying the effects of proposed changes and providing evidence for policy initiatives, but the cooking pot has to be part of the loop if we want to see changes in practice implemented. We thus propose an iterative framework which takes account of scaling issues and uses existing knowledge, experience and tools (Figure 1). The scaling and management framework we propose is only one possible mode to drive the process forward. It is clearly not the only possibility, but is an approach that can commence now as all of the tools within the framework already exist, which is important in the context in which we work: in situ solving practical problems that exist now. The framework reflects scaling and uncertainty issues and includes a range of modelling and decision support tools. The example shown is based primarily on a nutrient pollution project but has

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**Figure 4** | Sustainable livelihoods framework (DFID 1999).

**Figure 5** | The DPSIR framework.
many generic aspects common to other issues related to integrated land and water management.

In Figure 1 the framework is represented as a loop around which it is necessary to move in order to develop improvements in land management, taking account of scaling and uncertainty issues and including a range of hydroinformatics tools. In the centre of Figure 1 is a research catchment (the “kidney” shape in dark grey) operating at what we have described as the research scale, which also operates as a local demonstration site. This could be the scale of a farm or even of an individual field. A number of parameters are monitored at this scale to provide time series of, for example, water quality and quantity. In the figure some monitoring is also indicated downstream on the larger catchment. On the left of the figure we have stakeholder workshops (represented by the cooking pot). These initially provide essential information on the current local land use which, along with the monitored data, feed into research scale physical models and economic analysis. Scaling up is then performed taking us over to the right-hand side of Figure 1.

At the policy scale (the catchment, regional and national scale), direct engagement is made with policymakers to establish their understanding of the problems including uncertainty. Measured data, models and analysis are used to generate indicators of environmental risks and of economic performance which can be represented in a GIS. Figure 7 shows a risk indicator map for phosphorus loss as an example. Decision support tools are developed to show the nature of problems associated with specific land management practices and to suggest strategies that will help to resolve problems.

The GIS, results of models and other decision support tools are used to inform decision-making at the regional or national level, resulting in catchment scale planning. If the partnerships are functioning as they should, the policymakers using the tools will make plans that both encourage best management practice within agri-environment schemes, new regulation and legislation, and are realistic in terms of the interests of stakeholders.

It is then necessary to scale down in order to implement plans. Visualisation and communication tools, including the decision support tools developed at the large scale, are used to inform stakeholders of the findings of research, and workshops are used to plan actual changes in land use based on those findings. The GIS and models should give good indications of where to target first so that strategic plans can be formulated. Thus, as we downscale from the political scale, a series of land management options can be considered and prioritised in space and time and these in turn feed into action plans. Key environmental strategies such as tackling hot spots of pollution and the creation of riparian management schemes (buffer strips, wetlands and exclusion of animals) can begin immediately. This can provide significant benefit quickly and can demonstrate to the end users that policy is benefiting their own environment. At this stage it is often the researchers who learn more than the stakeholders do and this crucial education can be fed back into the models and decision support tools. Finally any changes in land management are fed back into physical and economic models, taking us on another iteration round the loop.

The loop represented in Figure 1 is a conceptual model of the process discussed throughout this paper, which has the partnerships discussed above at its heart. The point of representing the framework as a loop is to emphasise the continuing nature of the process. Going round the loop once or even twice is unlikely to lead to great improvements in land management. Rather it is only by continuing to nurture the partnerships discussed above that improvements will take place. It should be noted that, although the stakeholder workshops are shown only on the left of the loop, this in no way indicates how often they should take place and is not intended to suggest that they are
only part of the implementation stage. In practice the greater the involvement of end users in the various stages of the process, the more likely that improvements in practice will result.

**CASE STUDIES**

As stated above there is a need to communicate the results of research to end users and allow the stakeholders (farmers, industry and local government) to take ownership of problems. Thus we propose using a set of tools that demonstrate key land use changes and reassure end users that it will not have any adverse effects on their income. Two projects will be referred to in discussing these tools, which represent initial attempts to apply the framework described in this paper.

The first is SEAL, a multi-disciplinary EPSRC-funded research project concerned with assessing the pressures on land and water resources due to recycling of sewage sludge to land in the UK (http://www.lec.lancs.ac.uk/cswm/seal/). The work in SEAL consisted of using models and measurement to generate data on a research catchment which was used to get an indication of the movement of nutrients at the larger catchment scale. In order to communicate the outputs of the research and engage with the knowledge and concerns of stakeholders a Decision Support Matrix (DSM) was created (Hewett et al. 2004, 2009) which is designed to provide advice to both catchment scale strategic planners and individual farmers. Risk indicators generated by the models coupled to a Geographical Information System (GIS) were used to help prioritise particular areas. Stakeholder workshops and discussions were used to provide feedback into education and decision support tools and to encourage a sense of ownership of ideas amongst rural communities and institutions. SEAL has been completed and contains most of the elements we propose in our framework for decision support, but did not have an economic component (Hewett et al. 2009).

The second, Waterweb, is concerned with water resource strategies and drought alleviation in Western Balkan agriculture (Jacobsen et al. 2004). There are a number of elements to the research involving monitoring and modelling water quantity and quality, evaporation regimes and rainfall patterns, together with trials on water and nutrient use to test deficit irrigation techniques with maize, grapevine, potato, tomato and quinoa (Davies et al. 2000; Bacon 2002). A GIS has been developed to categorise two regions near Belgrade, Serbia and Ovce Pole, Republic of Macedonia and this will be further developed into a Land–Water–Economic Information System (LWEIS). The LWEIS will include a policy analysis matrix derived from commodity-based spreadsheets, which examines private and social profitability of different farm systems (see, for example, Yao 1997). Waterweb is in its early stages and represents an opportunity to apply the framework in a development context.

The examples discussed here involve three strategies making use of:

1. research catchments that exhibit problems and the possible solutions to those problems;
2. models and GIS-based flow visualization tools to assess runoff and potential pollution (up and down scaling); and
3. the DSM approach which is used to show the nature of the specific problem, the uncertainty associated with it, and to suggest management strategies that will start to resolve environmental problems.

Now we shall introduce some existing tools to show how they can be used within our multi-scale framework. It should be noted that there are alternative models that could be used within such a framework, but we have deliberately chosen simple models as this underpins the philosophy of communicating simple messages wherever possible.

**RESEARCH CATCHMENTS**

The purpose of using a research catchment is to establish the problems that are likely to occur on the larger catchment within which it sits and to investigate potential solutions to those problems. It also acts as a demonstration site for proposed interventions to solve problems. It is important to choose sites that are fairly typical so that any scaling up that is done is likely to be representative. Extensive monitoring and detailed mapping of individual fields is performed at these sites.
In SEAL the focus was on nutrient losses from farms and how different practices regarding use of fertilisers can impact on waterways. A large demonstration farm in the south of England provided the principal site for the study as the practice there was thought to be representative of much of the intensive arable farming carried out in the UK.

The farm covers an area of close to 4 km² and grows a range of crops such as oil seed rape, drum wheat and winter wheat. Soils range from sandy loam to clay loam and the underlying geology of the area is Upper Chalk overlain by glacial sands and gravel. The site has a shallow slope with an average gradient of 3%. The average annual rainfall for the area is typically 600 mm. Flow and water quality were monitored at a number of points on the farm over three years and these data were used to calibrate research scale models. Digital terrain data were obtained using a Leica Global Positioning System (GPS) and these form the basis of a digital elevation model (DEM) of the farm.

Figure 8 shows a DEM of one of the fields on this farm which we shall use as a case study to illustrate how the hydroinformatics tools were used. We shall refer to this field henceforth as SEAL Field 1. The field has a large ditch running along its east side which was surveyed in detail, shown on the right of Figure 8 and the bottom of this ditch, found at the bottom right of the figure, was an important monitoring point for flow and water quality.

In Waterweb there are four main research sites, three in Serbia and one in the Republic of Macedonia, each with a different research emphasis. Figure 9 shows maps of Serbia and the Republic of Macedonia with the approximate location of the research sites marked with diamonds. The first, which we refer to as Research Farm 1, lies to the south east of Belgrade, and is owned and run by the University of Belgrade. A number of experiments are taking place on this farm, including monitoring of water quantity and quality and experimental irrigation techniques for grapevines. Research Farm 2 is a large commercial arable farm in the Srem region at which a range of crops are grown, including lucerne and maize. Here the emphasis is on nutrients...
moving from the farm into waterways and on the economics of farming at this scale. One large field is being used for commercial production and provides the focus for the research. Water table levels and soil moisture content at a range of depths are monitored at a series of points on this field to provide a detailed picture of subsurface flow. The third is a market gardener in the Srem region at which deficit irrigation experiments are taking place on tomatoes. Finally the site in the Republic of Macedonia is near to the village of Sveti Nikole in the Ovce Pole region, see Figure 9. This is a drought region and the primary focus is on growing quinoa as a potential commercial crop. A number of plots have been sown with different varieties of quinoa to see how they perform in drought conditions and piezometers, profile probes (for measuring soil moisture) and a flume are being used to build a picture of the hydrology of the site. Research sites 1, 2 and 4 have been surveyed in detail to provide data for DEMs that provide the base maps for the GIS within the LWEIS and will be used for modelling purposes. Policy analysis matrices (PAMs) for crop production, which analyse profitability using conventional methods versus different irrigation systems are being developed for each site using data collected from on-farm surveys.

**TIME-DEPENDENT SIMULATION MODELS**

Physically based models can be used effectively at the research catchment scale in combination with experiments where the acquisition of data is appropriate to the structure of the model. There are a wide range of physically based models available that are appropriate for this purpose. For example, the hydrological models EPIC (Williams et al. 1990), INCA (Whitehead et al. 1998; Wade et al. 2002a,b), SWAT (Arnold et al. 1998), MACRO (Jarvis 1995) and DAISY (Hansen et al. 1990) are suitable for modelling local runoff and the movement of nitrates and phosphates. Problems of parametrising physical models at the catchment scale, due to heterogeneity and uncertainty, are reported elsewhere (Beven 1995; Franks et al. 1997). At the hillslope or small catchment scale, many modellers may decide that quasi-physical, semi-distributed models are more appropriate (Beven et al. 1995), but even quasi-physical models may not be applicable at the larger catchment scale.

We argue that the use of meta-models that can mimic the output of physically based models is most appropriate for use at the larger catchment scale. In particular, we propose using a subset of meta-models that have been described as Minimum Information Requirement (MIR) models (Quinn et al. 1999; Quinn 2004). In the MIR approach the simplest model structure is sought such that the MIR can mimic the output of the physical or quasi-physical models used at the plot/field scale or hillslope scale and route this flow to the catchment scale. Thus, respect is paid to the physical factors that influence nutrient transport, but only the MIR models are used for communicating key catchment scale effects. We propose that the scaling up of cause-and-effect relationships can be achieved by combining the outputs from physically based models applied at the research scale and an MIR model that routes and mixes flow downstream so that simulations can be made at any scale. MIR models work well with catchment scale GIS data. In essence, the GIS data correlates with higher and lower risk land uses and runoff zones. These maps of likely pollution and runoff risk are often called “indicator” maps and are a vital tool in the IRBM process, where prioritisation of problem areas and strategic planning is needed.

In the examples discussed in this paper TOPCAT N-P is used to simulate events at the research scale (Hewett et al. 2004; Quinn 2004; Quinn et al. 2008). TOPCAT N-P consists of three MIR models, the hydrological flow path model TOPCAT, which is a MIR version of the model TOPMODEL (Quinn & Beven 1993), a nitrate MIR model and a phosphorus P-MIR which emulate output of the physically based model EPIC (Williams et al. 1990). The physically based models were first used to produce time series of flow, nitrate and phosphorus at the plot scale. A simple mathematical function was then determined that mimics those results for the majority of the simulations, providing the MIR models. The physically based models were set up for many agricultural and meteorological scenarios, including long time series (eight years of daily data), differing crops and soil types plus different application rates and fertilizer timings. In all the cases simulated it is possible to emulate the N and P losses by using simple effective modelling parameters (Quinn et al. 1999). These factors relate mainly to the volume and type of nutrient added and
the propensity of the nutrient to leaching and, for the case of the P-MIR, the entrainment of nutrient into the overland flow. Leaching and overland flow rates were generated by the hydrological flow path model (Hewett et al. 2004; Quinn 2004; Quinn et al. 2008).

INCA (Integrated Catchment) is a physically based model designed to investigate the fate of nutrients in aquatic and terrestrial environments (Whitehead et al. 1998; Wade et al. 2002a,b). The model incorporates both dynamic and stochastic elements and is semi-distributed, with nitrogen and phosphorus fluxes produced as daily time series, outputs assessed as either probabilistic or percentile values and spatial variations in land use categorised into land use classes. The model has a GIS interface, nutrient input model, hydrological model, catchment nutrient process model and a river nutrient process model. A semi-distributed GIS interface is used to represent percentage changes in land use cover, together with a land classification scheme based on a simplified version of the Centre for Ecology and Hydrology land cover map of Great Britain, using six land classes. Hydrology is simulated using a two-box model with soil- and ground-water components: each river reach is then modelled using a mass-balance approach to inputs, storage and outflow. Catchment nutrient process mass balance differential equations in the soil and ground water are solved simultaneously with the equations of flow.

The dynamic nature of the model means the day-to-day variations in flow, N and P fluxes and concentrations can be investigated following a change in inputs such as atmospheric deposition, sewage discharges, biosolid or fertiliser application. The phosphorus version of INCA (INCA-P) was extensively modified in the course of SEAL with the incorporation of key processes in the catchment including adsorption and desorption onto sediments, immobilisation of phosphorus into a non-soluble mineral form, uptake by plants and leaching from the catchment. All the processes are soil-moisture- and temperature-dependent. The in-stream component of the model simulates sedimentation, equilibrium with soluble phosphorus in the water column, macrophyte, epiphyte and phytoplankton growth. Velocity flow relationships are incorporated to allow residence time calculations. The model also allows for sediment bed exchange of phosphorus with the water column. INCA-P generates graphical time series outputs on a reach-by-reach basis or as a profile down the river system together with all relevant statistics.

In the SEAL project TOPCAT was used in combination with the INCA model. TOPCAT was used to simulate the flow and nutrient transport at the demonstration farm in order to better understand which modes of transport were dominant when there is a storm event (Hewett et al. 2009). Since the purpose of using TOPCAT in this way was to focus on events, the model runs were performed with an hourly time step, providing detailed time series such as the flow simulation shown in Figure 10. Daily Hydrologically Effective Rainfall (HER) data was also generated for input to INCA simulations, providing a degree of integration between the hydrological models. INCA was run with a daily time step at the whole catchment scale to investigate flow, nitrate and ammonia phosphorus dynamics. Having established the key process parameters at the large scale, the model was also applied at the research scale to the demonstration farm.

Figure 10 | TOPCAT flow simulation with an hourly time step.
VISUALISATION AND COMMUNICATION TOOLS

Three types of visualisation and communication tools are proposed for use in our framework:

1. conceptual models,
2. flow visualization tools,

We have found conceptual models to be powerful tools in communicating with stakeholders. Presenting concepts in the form of simple diagrams or pictures is extremely effective in communicating an understanding of processes and the findings of research. The first such model, shown in Figure 11, was developed in order to conceptualise some of the catchment processes and activities influencing water quantity and quality modelled using TOPCAT. Farming activity is illustrated by showing livestock (in this case sheep) on the land and a tractor spreading sewage sludge for arable farming. The figure also includes two mechanisms by which nutrients are transmitted to waterways following rainfall: overland flow carrying sedimentary phosphorus from Critical Source Areas and nitrates and soluble P leaching into the soil being transmitted via subsurface flow.

A series of conceptual models have also been developed to communicate good and bad practice in relation to the risk of nutrient export and flood risk (Hewett et al. 2004, 2009; Posthumus et al. 2008). These were used extensively in stakeholder workshops to simulate discussion of current practice and to elicit suggestions for improved land management both from a nutrient export and flood risk perspective. Figure 12 shows a set of examples developed for consideration of flood risk in livestock farming.

Next we present a simple conceptualisation of the research taking place in Serbia within Waterweb (Figure 13). This model was used in the first stakeholder workshop related to the project held in Serbia in 2005. In Figure 13 we see the two major rivers that run through Belgrade; the Sava and the Danube. Belgrade and Novi Sad, the two large cities in the region, are shown along with a representation of the hills that lie to the south of the Sava River and those near to Novi Sad. The three Serbian research sites described above are shown in the figure. Belgrade’s reliance on groundwater for its water supply is represented and this draws attention to the fact that the market gardener is drawing water from the same source, highlighting a potential conflict of interest. The diagram is intended to be simple as the idea is to continue to develop the conceptual model throughout the course of the project and to use it as a tool for communicating the aims of research to stakeholders and for incorporating their suggestions into the model and into the research itself.

We now move on to TopManage, a tool for simulating and visualising flow accumulation based on simple hydrological flow path concepts and a high resolution GIS-based terrain analysis toolkit (Hewett & Quinn 2003, 2004; Heathwaite et al. 2005). The terrain analysis theory used in TopManage is based on the multiple flow
direction theory of Quinn et al. (1991). High resolution data is first acquired to produce a Digital Terrain Map (DTM) of a single field which is input into a Digital Elevation Model (DEM). TopManage then allows man-made features to be added to the DEM to allow the impact on flow accumulation to be approximated and visualised. Thus any overland flow known to occur or any man-made features controlling runoff can be presented to the farmer or land use planner visually. TopManage can be used as a key tool to use in conjunction with demonstration sites and models (Heathwaite et al. 2005; Hewett et al. 2009). Figure 14 shows a DEM of SEAL Field 1 at the demonstration farm prepared for TopManage analysis on a 5 m grid and a flow accumulation
map where the darkest areas are the wettest. This field characterisation provides excellent information on where best to target interventions.

The maps generated by TopManage show how flow is entering the channel and what pollution it might be carrying. Equally, a series of local interventions that alter flow paths can be proposed and simulated. These interventions can help disconnect polluting flow from ditches, and redirect flow to storage ponds or wetlands. Perhaps a series of strategically based buffer zones and ponds can be recommended (see, for example, Hewett et al. 2004, 2009; Heathwaite et al. 2005). The area occupied by these features should be small and the financial viability of the food production system should not be compromised. Further to this, it is possible, given current technologies, to trap nutrients and sediments and recycle them to the land.

In all cases, the uncertainty of the predictions is very high and the implications of this are explained in full. Therefore a series of shrewd assumptions are made. For example, for the case of an arable farmer in the UK we assume that it will rain heavily during the winter period on bare soil that has received fresh nutrient loading. Therefore the principal design component is management of the worst case scenario since our aim is to design a robust landscape. Thus pollutant load reduction, good soil management and practical interventions to show how flow is be altered, stored and buffered can all be proposed. Any smaller events should take care of themselves, as the system of protection is over-designed deliberately to allow for uncertainty.

**DECISION SUPPORT MATRICES**

The catchment and farm scale GIS and models discussed above are relatively simple and are designed to provide workable support tools. However, they may still be inappropriate to regional or national decision-makers. Therefore DSMs are developed for this specific role. These may be considered as decision support systems (DSS) under the broadest definition of the term (Power 1997). According to Alter’s taxonomy for DSS a DSM, or at least its interactive (spreadsheet-based) version, would fall in the category “suggestion model” in that it leads to a suggested decision for a fairly well-understood task (Alter 1980). However, recognising the poor uptake of DSS by farmers historically (see, for example, McCown 2002) DSMs are designed to be very simple tools intended for use by the non-expert. They are not a DSS in the generally understood sense of the term as they represent only one tool of many to aid decision-making within our framework. Rather we argue that the framework itself should be considered as the DSS.

To date there are three DSMs relevant to this paper; a nitrate tool called the Nitrate Export Risk Matrix (Quinn 2004), the Phosphorus Export Risk Matrix, (PERM) (Hewett et al. 2004, 2009; Heathwaite et al. 2005) and the Floods and Agriculture Risk Matrix (FARM), recently adopted by Defra (O’Connell et al. 2005). DSMs are intended to allow certain land units and land management practices to be investigated in terms of runoff and pollution or flood risk and to

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**Figure 14** | 5 m DEM of Field B prepared for TopManage analysis (left) and flow accumulation map (right) where the darkest areas are wettest (reproduced from Hewett et al. 2009).
highlight obvious problems of current practice on vulnerable runoff systems.

A DSM is not a single tool, but is a set of tools that fulfil different functions, consisting of:
1. a discussion tool used within stakeholder workshops,
2. a set of conceptual models for visualising good and bad land management practice,
3. a matrix onto which the results of simulations can be mapped,
4. an interactive DSM containing a series of questions related to farming practice which, when answered, provide a mapping of the risk level associated with that practice.

Stakeholder workshops should play a key role in the development of DSMs. For example, the initial PERM developed within SEAL was simply a conceptualisation of the DSM as a cube as shown in Figure 15 onto which the risk of phosphorus export could be mapped. The PERM shown here is designed for arable farming and targets the farm scale as the key scale where the greatest impact on P loss can be achieved. It is assumed that farms and catchments can be treated in the same way, i.e. hillslopes feeding channel networks.

At this stage the choice of the three axes breaks down the risk into different categories to help decide on remediation options to decrease risk. In the case of the PERM these are flow connectivity, fertiliser application, and soil management and soil type (Figure 15). Individual fields which were part of the SEAL study were discussed in the workshops and the level of risk on the matrix was decided by a vote. These discussions also informed the choice of examples of good and bad practice which were incorporated into the interactive PERM (Hewett et al. 2004, 2009).

Many farming practices at present are targeted at crop and soil management to provide high yields while minimising soil nutrient surplus. What is often not considered is how nutrients reach the larger receiving channels. In developing the PERM the aim was to communicate how runoff mobilises available nutrients and how it moves them on through the fields to ditches and ultimately to the larger receiving waters. Assuming that the soil type within a specific field is relatively homogenous, a two-dimensional PERM, which can be visualised as the front face of the cube shown in Figure 15 or the square matrix shown in Figure 16, can be used. This assumption is a pragmatic response to dealing with soil spatial heterogeneity, allowing the approach to be further developed.

The risk of nutrient export can often be assessed by asking informed questions relating to farming intensity and practice. This information, combined with the concept of runoff management, points towards straightforward mitigation strategies. With this in mind an interactive 2D PERM was developed within SEAL to enable farmers and land use planners to assess the risk of P loss from their land and to explore options to reduce phosphorus loss (Hewett et al. 2004, 2009).

The interactive PERM consists of the examples of good and bad land management practice discussed above, which are plotted as high and low risk on the 2D matrix, and two sets of questions related to (a) flow connectivity and (b) fertiliser application and soil management. It reflects both the P available to transport processes and the mechanisms by which the flow propagates through and off the farm. Hence, the PERM identifies a range of viable mitigation strategies to control, intercept, buffer and remediate polluting runoff. The management of P losses is depicted in a simple form despite the complexity of the P problem. The farmer or land use planner answers the questions according to the current land use for a particular field or set of fields, providing a plot of the current risk level and then can change the answers to the questions to assess how changes in practice may increase or decrease the risk of P loss from the field. A plot on the bottom left-hand corner of the matrix represents the lowest risk and the top
right-hand corner the highest risk. **Figure 16** shows a screen dump of the interactive PERM where the answers have resulted in a medium to high risk on both axes. A full set of questions in the interactive PERM can be found in Hewett et al. (2004).

During development of the PERM, the questions related to P export were presented, discussed and revised in the course of the stakeholder workshops. This step-by-step development of a DSM in various forms, rather than presenting an interactive tool in the first instance, is recommended as it is highly engaging and provides a sense of ownership in the finished product.

**DISCUSSION**

The multi-scale framework for decision support described in this paper is underpinned by an understanding of how scale issues affect land management, from the individual plot through hillslopes and catchments to whole countries. A key feature of the framework is that knowledge and expertise related to specific scales all influence decisions about changes in practice. Partnerships between researchers and stakeholders (represented by the cooking pot in Figures 1 and 2) are essential components of the framework and thus building trust is key to successful implementation. One of the primary functions of the scale-appropriate models and decision support tools within the framework is to aid communication between partners. The specific hydrological models used in this case study can be readily interchanged with others—what is important is the approach to solving practical, immediate problems *in situ*.

The rationale behind the approach described was a pragmatic response to the need to solve real water quality problems in both the SEAL and Waterweb projects. It was therefore essential from the outset that we worked with policy makers and farmers, that we made best use of whatever data was available (at whatever scale) and that we collected whatever data we could within the project. We do not claim that our approach is the only way to address the problems associated with IRBM and implementation of the WFD, but that it does provide a useful conceptualisation of what we attempted to do in the projects discussed. We have attempted to emphasise two key aspects of the work: engagement with stakeholders at all scales and the crucial role that hydroinformatics tools (models, GIS, DSMs) played in the loop. We feel that the strength of the scaling loop shown in **Figure 1** is that it allows researchers and
stakeholders to enter the loop and contribute actively to planning land and water management. It allows contributors to benefit from the knowledge and skills available within the loop, gaining awareness of issues arising at each scale. The result is an intimate link between what is happening at different scales and between different actors.

It should be noted that the case study drawn from the SEAL project represents the first application of the approach. As such the specific tools developed are tied to large scale arable farming in the south of England. However, in generic form the framework could be applied to any catchment and any environmental problem. Unfortunately if used elsewhere it would be necessary either to adapt existing tools or insert new tools into the framework at various points, build up the knowledge base for local conditions and the type of farming, and build the necessary relationships with stakeholders. This is time-consuming, but an essential part of the framework as we envisage it.

To date one clear limitation to the approach is that only farmers who have been directly involved in stakeholder workshops have used the DSMs and, more importantly, have implemented mitigation measures on their farms as a result of being “in the loop”. However, we do consider we have had a measure of success in that a long term relationship was formed with the farmer who owns the SEAL demonstration farm as well as a number of other farmers in the area. At present the farmer is putting in features to mitigate nutrient export and reduce flood risk at his own expense and is still monitoring flow and water quality well beyond the life of the research project. We thus expect tangible runoff management to occur as a result of the work.

In Waterweb, although the project has now been running for three years we are still on our first circuit of the loop. There are a number of reasons for this. One is that there is a long learning curve associated with the knowledge transfer element—understanding of GIS, hydrological monitoring and modelling by the researchers in the study countries needs to reach a certain level before much progress can be made. Language is, of course, another barrier in that communication with stakeholders loses its immediacy when it is mediated by translation. There is also a notable difference in farmers’ attitudes in that awareness of environmental issues is much more pronounced in the UK context. Finally, there is much more awareness and adherence to legislation in the UK which makes for a very different culture and mentality in the farming community. All these elements highlight how, even with experience gained in applying this approach in one country, there are many factors that mitigate against applying it successfully in another, especially in the short term, and this is especially relevant in the context of developing countries.

CONCLUSION

Increasing awareness of the need for an integrated approach to managing water resources has given rise to the concepts of IWRM and IRBM. This underpins recent European legislation, such as the WFD, which includes a statutory requirement for public participation. While there are clearly weaknesses in the legislation we consider it an opportunity to develop a balanced approach to water management involving partnerships between stakeholders and researchers in science, engineering, economics and sociology. Periods of public engagement are an essential ingredient to building successful partnerships and have to involve stakeholders tied to all scales of water management, from the individual farmer or local trader through to decision-makers at the national level.

We argue that knowledge of hydrological processes and how they change with scale is also essential to effective land use and water policy. A multi-scale land and water management framework is proposed for in situ problem solving that capitalises on current hydrological expertise and input from the social sciences and stakeholders. The models and tools within the framework are interchangeable and have been chosen for their simplicity and thus potential to aid communication. Stakeholder involvement is an essential part of the loop for generating robust decisions. The key strength of the framework proposed is that the types of tool presented already exist and are readily useable, meaning that the approach can be implemented immediately.

Tools like TopManage and DSMs can be used within stakeholder workshops, where the scientists, the professional bodies (councils and water authorities) and the local end users (in this case land owners and farmers) can meet. The tools are based on field studies and
hydrological theory but also reflect factors observed by the local stakeholders and, in more general terms, by local policy-makers and planners. However, just reflecting local processes is not enough. The stakeholders must be encouraged to take part in creating the future land use policy that ultimately satisfies their own needs and the policy-makers’ requirements. Simple viable interventions such as minimising poor farm practice, moving to best farm practice (maybe with an incentive) and local hydro/engineering interventions such as creating ponds, buffer strips and wetlands can be added to reduce pollution, reduce flood risk and increase biodiversity, demonstrating that problems can be solved. None of the above list should impact on farmer incomes but should greatly improve the local environment for all.

Once a future plan is agreed, trial areas of change can be proposed (perhaps within the research catchment or environmental observatory). Physically based models can be used to study the local impacts of changing land use. Meta-models and modified risk indicators can reflect this at the catchment scale (uncertainty included). Visualisation tools and conceptual models can be used to communicate research findings to stakeholders. In the long term, a push for environmental land management is obvious even if the uncertainty of the impacts cannot be quantified in detail. The policy-maker must be given confidence that practical land use change can be created and that the benefits will be positive.

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