Short Communication

Monitoring strategies and scale-appropriate hydrologic and biogeochemical modelling for natural resource management: Conclusions and recommendations from a session held at the iEMSs 2008

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\textbf{A B S T R A C T}

This short communication paper presents recommendations for developing scale-appropriate monitoring and modelling strategies to assist decision making in natural resource management (NRM). These ideas presented here were discussed in the session (S5) ‘Monitoring strategies and scale-appropriate hydrologic and biogeochemical modelling for natural resource management’ session at the 2008 International Environmental Modelling and Simulation Society conference, Barcelona, Spain. The outcomes of the session and recent international studies exemplify the need for a stronger collaboration and communication between researcher and model developer on the one side, and natural resource managers and the model users on the other side to increase knowledge in: 1) the limitations and uncertainties of current monitoring and modelling strategies, 2) scale-dependent linkages between monitoring and modelling techniques, and 3) representation of hydrologic and biogeochemical phenomena in model development and practical application for natural resource management.

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1. Introduction

Sustainable natural resource management (NRM) requires integration of many social, political, and economic institutions, which commonly function at different scales. Hence, there are a range of governance authorities and structures for NRM operating form diverse national, regional, and local regulatory frameworks, with varying degrees on integration between them (Ostrom, 1990; Wittmer et al., 2006; Hewett et al., 2009; Volk et al., 2010). Many studies have investigated the complex interactions between natural resource, societal, political, and economic implications of NRM modelling (Newham et al., 2006; Martinez-Santos et al., 2010; Brouwer and Hofkes, 2008; Uthes et al., in press).

With this complexity in mind, this paper focuses only on hydrologic and biogeochemical monitoring and modelling for managing natural resources. In particular, it focuses on sources of uncertainties and data gaps that limit combined monitoring and modelling efforts in practice. The topic was the focus of presentations and discussions in session S5 at iEMSs 2008 in Barcelona, Spain.

2. Natural resource management: interaction between data collection and modelling

Natural resource management is a key element of worldwide sustainable development. Thus, the activities include coordinating, monitoring, analysing, and reporting on water quantity and quality conditions. It also includes setting thresholds for potential threats, i.e. identifying when and where management interventions are needed. Effective NRM requires an evidence-based understanding of the system being managed, including understanding about links between human activities and environmental impacts. It also requires setting appropriate environmental quality targets and identifying cost-effective remediation alternatives.

Hydrologic and biogeochemical simulation models are valuable tools for natural resource decision making and assessment, and planning process. These models are especially useful when they are able to accurately represent landscape processes and the impact of potential management decision at the desired watershed scale (Jakeman and Letcher, 2003; Merrit et al., 2003; Volk et al., 2008, 2009). Accurate simulation, however, relies on monitoring programs to collect hydrologic, meteorological, water quality, and landscape data. The problem is the practical difficulty in designing
appropriate monitoring to adequately represent the spatial and temporal scale of real-world phenomena; therefore, a stronger link between monitoring and modelling efforts to better understand catchment functions has been advocated for some time (Soulsby et al., 2008; Fenicia et al., 2008).

Without effective communication between field researchers, model developers, and decision makers, monitoring strategies often fail to capture relevant, catchment-specific information required to support informed decision making. For example, the variation in nutrient concentrations in storm flow events, may not be adequately captured by measurements collected on a monthly monitoring basis (as opposed to more frequent measurements), but which is often employed by regional water quality sampling programs. Similarly, data that is collected more frequently is typically carried out for acute situations or for only a short period of time and therefore unable to provide a long-term history of data often needed in natural resource modelling (Allan et al., 2006). As illustrated, the choice of monitoring strategy options can affect perceptions of catchment runoff and nutrient dynamics, model calibration and model verification, which in turn influence environmental management decisions.

3. Monitoring

Monitoring data are fundamental for assessment of environmental systems, evaluation of mitigation measures, and calibration and evaluation of simulation models. Given the diversity of environments, it is not surprising that NRM monitoring strategies vary significantly in scope and objectives, geographic focus and catchment complexity, topical interest, financial constraints, and technology used (Soulsby et al., 2008; Tetzlaff et al., 2008). Furthermore, monitoring strategies cover a broad range of spatial scales (plot, field, water body, catchment, large basin), temporal resolutions (storm event, weekly, monthly), and data objectives (inventory, short-term intensive, and long-term). Whatever the monitoring objective, measured data provide imperfect representations of actual conditions (Soulsby et al., 2008). Uncertainty in hydrologic and water quality data is affected by detection levels, spatial resolution, sampling frequency, observational periods, equipment drift, and predisposition to malfunction (see contribution by Ninov et al. (2008) for an example of how flow record errors affected model validation, with similar examples provided by Andréassian et al. (2001, 2003) and Perrin et al. (2007)).

It is well recognised that the inherent uncertainties in observational data must be assessed and quantified for effective decision making and modelling (Harmel et al., 2006, 2009; Liu and Gupta, 2007). Today, practical tools available for estimating uncertainties associated with monitoring data. Specific examples were presented during the S5 in regard to water quality data. Harmel et al. (2008) demonstrated the DUET-H/WQ (Data Uncertainty Estimation Tool for Hydrology and Water Quality) software, which was designed to estimate the uncertainty individual load and concentration values. This tool can be practically applied by NRM agencies and/or by researchers alike and can be used to complement other program evaluation methods, such as cost benefit analysis to optimise sampling design (e.g. see contribution by Erechtchoukova and Khaiter, 2008).

The realization that ‘we often measure what we can and not what we need to measure’ (Beven, 2008; Sivakumar, 2008) is closely related to the question of how much data are needed to gain key insights about hydrologic or biogeochemical processes (Dunn et al., 2008; Burt et al., 2010) for decision making. While technological limits exist, many have been and will be overcome in the future with monitoring techniques such as satellite and air-borne remote sensing (e.g., to examine the energy balances, surface hydrology, land use, vegetation indices, snowpack extent, surface temperature, vapour fluxes, soil moisture, and precipitation etc.; e.g. Creutin and Borga, 2003; Wagner et al., 2007) and smaller scale air-borne laser-based LIDAR (Light Detection and Ranging) observations (e.g., to more precisely describe surface topography, flow pathways, saturated areas) (Tenenbaum et al., 2006). Recently developed geophysical methods in combination with natural and artificial tracer techniques can better determine subsurface structures (Uhlenbrook et al., 2008), monitor residence times, mixing of old and new water, water table levels, and saturated areas (Uchida et al., 2005; Tetzlaff et al., 2008). Similarly, new sensors make possible continuous, real-time monitoring of water quality parameters, such as nutrients (Bende-Michl et al., 2010).

Session contributors demonstrated the potential of new monitoring techniques in the areas of developing numerical models, testing intrinsic assumptions, assessing current modelling approaches (see contributions by Barbetta et al., 2008; Brocca et al., 2008; Croke et al., 2008; Fink et al., 2008; Gerold and Leemhuis, 2008; Kourgialas et al., 2008; Moramarco et al., 2008; Pause et al., 2008; Perumal et al., 2008; Spath et al., 2008), and allowing multi-scale model evaluation (Newham et al., 2008; Pause et al., 2008).

In the context of NRM, it is important to consider equally: 1) sampling – how often and where to appropriately monitor to represent scale-dependent processes (Harmel et al., 2006; Strobl and Robillard, 2008), 2) scaling information – what knowledge can be transformed from one scale to another (Kjeldsen et al., 2006), and 3) communication – how to best convey information arise from (new) data collection to decision makers (Dalgaard et al., 2003). Similar considerations have also been taken up by initiatives such as the IAHS PUB ‘Prediction in Ungauged Basins’.

The influence of sampling strategy options on modelled nutrient loads was demonstrated for spatial scales (Dalgaard and Kjeldsen, 2008; Sherman and Read, 2008) and temporal scales (Ullrich et al., 2008). Dalgaard and Kjeldsen (2008) demonstrated the information “loss” or “gain” by different up- and down-scaling methods to regionalise nitrogen balances. Specifically, they demonstrated how farm-level information from a Danish landscape was up-scaled to the landscape level using different pathways and then compared results for different European landscapes. They concluded that bottom-up methods for up-scaling are needed to adequately convey information from research to decision makers. Using Great Barrier Reef Lagoon soil nutrient data, Sherman and Read (2008) investigated how different spatial sampling strategies influenced model outputs. Spatial scales ranged from individual farms to sub catchments with areas >1000 km². Bias in the subsoil nutrient data suggested that total phosphorus loads may be underestimated whereas subsoil nitrogen loads are likely to be overestimated. Ullrich et al. (2008) compared various temporal frequency sampling strategies and four different load estimation methods with modelled results. Nitrate-N load estimation results differed considerably depending on sampling strategy, load estimation method, and period of interest. The highest sampling frequency (daily) results were substantially better than for example bi-weekly sampling (see also Ullrich and Volk, 2010) and produced different model parameters in the calibration and evaluation process. Dong et al. (2005) and Bárdossy and Das (2008) came to similar conclusions for rainfall sampling and rainfall observation networks for hydrologic modelling.

4. Modelling

Hydrologic and biogeochemical models are valuable NRM decision making tools, especially since the impacts of land use and management on water quality and contaminant flux must be accurately assessed for a range of scales. Models are applied to support assessment for landscape dependent differentiation of
water and contaminant balances in large river basins (or large geopolitical regions), to quantify transport in and through medium-sized basins and sub-basins (or small geopolitical regions such as cities and counties), and to provide detailed estimates for planning and remediation in smaller catchments and assessment units such as river sections, communities, fields and small farms (Wu and Hobbs, 2002; Drewry et al., 2006; Boardman, 2006; Sullivan and Meigh, 2007; Liu et al., 2008; Volk et al., 2008, 2010). Because one model alone cannot satisfy all of these requirements, the suitability of different models and data must be evaluated to define the “scale-appropriate” methods (Rogers, 1978; Moussa and Bocquillon, 1996; Booij, 2003; Xu et al., 2007).

However, even with ‘scale-appropriate’ modelling, the inherent uncertainties in NRM simulation, especially in spatially-explicit simulation, should be considered by model practitioners and model developers. Simulation uncertainty is affected by the: 1) data availability and model skill that represent a chosen spatial and temporal scale (see contributions by Bernini et al., 2008, Pechlivanidis et al., 2008, van Griensven et al., 2008), 2) issue of equifinality as affected by the number of calibration parameters (Beven, 1993), 3) scale and application appropriateness of model algorithms (Kjeldsen et al., 2006), and 4) fundamentally our conceptual understanding of environmental systems, the assumptions and algorithms used to represent those systems (Dalgaard et al., 2003).

Lively discussion of these issues is pushing model development in new directions: a changing paradigm of using hydrologic and biogeochemical models as learning tools to test hypotheses on catchment function and the development of new model types and approaches. However, in reality it is ‘still’ debated when parameter reduction and consequently more simplistic modelling versus more sophisticated and management-oriented models, which include more parameters, is most a appropriate in guiding NRM decision making (Sivapalan et al., 2003; Crout et al., 2009; Argent et al., 2009). Sensitivity analysis, such as Monte Carlo approaches, evolutionary optimising techniques, or Bayesian methods, can assist in understanding parameter behaviour (Dunn et al., 2003; Refsgaard et al., 2007; Blasone et al., 2008), but these recently developed techniques are not commonly applied in NRM. Also decision-support systems like Bayesian networks (Dorner et al., 2007) or data-driven approaches, e.g. artificial intelligence methods, have become popular in real-time forecasting. For instance in the contribution by Liersch and Volk (2008), a comprehensive rainfall-runoff database tool for rapid flood risk assessment to support flood management was demonstrated. This database tool is readily applied by unskilled users because model outputs from the conceptual IHACRES model are integrated and can be applied to diverse catchments due to the parsimonious data requirements.

In practise we found that all model methods and types can potentially support NRM decision making; however, diagnosing model-specific limitations and their suitability for ‘scale-appropriate’ application should be pursued. As Beven (2009) stated, this is a long-term process that is accomplished by further improving knowledge and observations of environmental systems. We encourage the NRM community to pursue this goal by communicating the value and limitations of new monitoring techniques and new multi-criteria model evaluation approaches (Newham et al., 2008; Pause et al., 2008; Birkel et al., 2010).

5. Conclusions

Water availability and water quality have become the paramount NRM issues in many parts of the world. Triggered by these large-scale issues, a variety of regional and federal monitoring networks have been established to assess water resource and improve resource management. However, these programs often do not provide sufficient information to establish adequate understanding of catchment hydrologic and biogeochemical functions or to adequately evaluate and enhance hydrologic and biogeochemical models. A number of recent publications have emphasised the need for finer temporal and spatial resolution measurements to effectively manage water and water quality problems at larger scales, e.g. sufficiently detect sources and determine delivery mechanisms to attain catchment nutrient reduction goals (Kirchner, 2006; Dunn et al., 2008; Soulsby et al., 2008). However, financial resources are scarce and even existing monitoring networks are often threatened (Shklimanov et al., 2006), which further demonstrates the need for effective and efficient monitoring strategies.

The results summarized in this paper emphasize the need to address catchment scale and to carefully consider temporal scale and monitoring methodology in strategic monitoring design. Similarly, it is imperative that field researchers, modellers, and NRM decision makers closely communicate and interact to increase the value of data collected in monitoring programs and to improve the ability of models to guide decision making.

To overcome current limitations of modelling to support natural resources management, we strongly recommend enhanced communication and cooperation between modellers, field researchers, and decision makers to improve data collection and NRM modelling. This vision is not new but seeks to truly bring together all participants in NRM with the aims of:

1) Enhancing our understanding of limitations and uncertainties of current monitoring and modelling strategies in conjoint learning communities.
2) Increased scale-dependent linkages of monitoring and modelling techniques.
3) Improving representation of hydrologic and biogeochemical phenomena in model development and application.

The value of the monitoring programs and modelling to NRM decision making can be improved, for example by capturing data at spatial and temporal scales that are more appropriate for the specific NRM issues, and by estimating and reporting the uncertainty of collected data. Early collaboration on what information is required and the design of monitoring strategies associated can then form the basis of a learning community that is sensitive to diverse interests (infrastructure, social, economic, environmental, normative, legal) so that more acceptable NRM strategies result. Also the understanding gained from improved coupling of existing and new monitoring technologies and mutual recognition or their limitations will enhance the ability of models to accurately represent real-world processes thus reducing the uncertainty of simulation results as well as reducing misunderstandings in interpretation modelling results. Information gained from monitoring is aimed at guiding decisions in NRM by providing scale-appropriate, spatially-oriented information, which may include information relevant for, i.e. land use change, land management, and economic considerations. Conversely, improving communications within all facets of the community will facilitate scale-appropriate model development, flexible model structures, and multi-criteria and multi-scale model evaluation which is highly regarded as useful.

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