# Introduction to integrated environmental modelling to solve real world problems: methods, vision and challenges

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Across the world, stakeholders are asking questions of their governments and decision makers to quantify the risks of environmental threats to their well-being. These questions manifest themselves as ‘deceptively simple questions’, which are easy to articulate but difficult to solve. An example of which is: ‘how much will the eruption of an Icelandic volcano cost the UK economy’. Answering these questions requires predictions of the interaction of multiple environmental processes, this requires the development and maintenance of systems that allow these processes to be simulated, and that is the nascent science of integrated environmental modelling (IEM). Such processes may be long-term (e.g. those that are impacted by climate change) or short-term threats, such as the impact of drought on UK agriculture or the impact of space weather on energy supply systems.

These questions require holistic solutions drawn from different disciplines (Laniak *et al.* 2013). Importantly, the technology has progressed significantly such that models from different disciplines can be linked and integrated assessments of problems can now be made (Kelly *et al.* 2013). Now that it is possible to link models, consideration has to be given to the opportunities, and also the science issues, that are generated by studying interacting processes. These include:

- Understanding interactions within and across disciplines: for example, how best to simulate the interaction between agricultural policy and farming practice (e.g. the EU-funded SEAMLESS project: Van Ittersum *et al.* 2008).
- Reconciling the differing functions used by different disciplines when evaluating similar interacting processes (e.g. sewers and river flooding (Van Assel *et al.* 2010); and sediment transport in rivers (Shrestha *et al.* 2013)).
- Reconciling the different languages that different scientific disciplines use (e.g. soil scientists, ecologists and geologists all have subtly different definitions for what constitutes ‘soil’), thereby reducing the opportunity for error in finding and linking models (e.g. Knapen *et al.* 2013).
- Defining model metadata so that developers can describe, and users can find, evaluate and validly link, the models needed to resolve their problem. Whilst no internationally recognized standard exists, workers such as Harpham & Danovaro (2015) have suggested possible approaches based on existing standards such as ISO 19115.
- Encouraging the development of standardization both in input–output data and the modelling process itself: an example being the use of ontologies and ‘controlled vocabularies’ to identify similarities in the concepts being modelled. Work has been undertaken on metadata standards to assist in the coupling of models (e.g. Peckham *et al.* 2013).
- Understanding the propagation of uncertainty in model chains; projects such as UncertWeb have proposed possible solutions (Bastin *et al.* 2013).
- Providing suitable computational resources to run linked model compositions. Here, high-performance computing (HPC) holds the key, as espoused by the CSDMS project (Peckham *et al.* 2013).
- Quality assurance, and issues of being auditable.

But progress is being made and a number of different initiatives have been undertaken in different science areas: for example, climate, hydrology, environmental regulation, insurance and human health. Climate models can be linked using a number of different frameworks, such as BFG (Barkwith *et al.* 2014), and with models from other disciplines (e.g. Goodall *et al.* 2013). Hydrology has well-developed model linking approaches such as OpenMI and FluidEarth, which provides a toolkit to implement this standard (Harpham & Danovaro 2015). This OpenMI implementation (.NET/in-memory) is complimented by the HPC-based CSDMS (Peckham *et al.* 2013). The United States Environmental Protection Agency (US EPA) has developed their system (FRAMES_3MRA) to enable rapid assessment of the environmental

*From*: Riddick, A. T., Kessler, H. & Giles, J. R. A. (eds) 2017. *Integrated Environmental Modelling to Solve Real World Problems: Methods, Vision and Challenges*. Geological Society, London, Special Publications, **408**, 1–5.

impact of potentially polluting activities (Whelan *et al.* 2014). The insurance industry, which relies on catastrophe models (Royse *et al.* 2014) to assess risk, has spawned its own approach to providing a framework to link models, that of OASIS-LMF (Barkwith *et al.* 2014). Even a discipline area seemingly far removed, such as modelling the human body to safely test new drugs, has its integrated modelling approaches (e.g. Virtual Physiological Human: Hunter *et al.* 2010).

Despite these diverse approaches, several trends exist that provide some confidence that interoperability should be easier in the future. There are a lot of resources and initiatives available, not just dedicated to a single discipline, to ease access: there have been significant recent developments in interoperability – both in data and models; access to HPC is becoming increasingly available (Peckham *et al.* 2013); web services to serve data and model results over the Internet are easy to access (Goodall *et al.* 2013); smart phones have a huge amount of uptake and development behind them (Moore & Hughes 2016); the science of user uptake for both model results and presentation of future risk is maturing (Beven & Lamb 2014); and the number of pilot projects to enable users to run relatively simple models (e.g. EVOp http://www.evo-uk.org) is rapidly increasing. This Special Publication summarizes the progress made in linking data and models, and how it can be used to solve some of the difficult environmental problems discussed above.

This volume first introduces and expands on a number of the key themes described above that underpin the future vision and strategy for IEM, focusing on the experiences of a number of organizations that are promoting these technologies. For example, a common theme in the experience of the British Geological Survey (**Peach *et al.* 2016**) and the Environment Agency in the UK (**Farrell *et al.* 2016**) is the requirement to be able to utilize and link existing models that have often required significant investment in resources to create, and so to establish methods of linking together and adapting existing modelling systems (**Sutherland *et al.* 2014**). A key area of research highlighted by several authors is the building upon a well-developed data and information framework in which appropriate standards of data quality and semantic interoperability are maintained (**Sutherland *et al.* 2014**; **Laxton 2016**). Whilst the resulting model is often more widely reported, the underlying data and information structure sometimes receives less attention in terms of organizational investment but forms the basis upon which successful integrated modelling is built. The need for linking mechanisms that cross discipline, and also national, boundaries has been particularly highlighted by **Moore & Hughes (2016)** and **Peach *et al.* (2016)**.

**Sutherland *et al.* (2014)** review various approaches to hydraulic modelling and discuss the historical development of linked modelling, exploring the implications of fusion and emphasizing that the fusion of models involves not only linking them together, but also providing easier access to information about the models and software tools to facilitate the linking process. These authors also raise another very pertinent issue – the potential blurring between what is considered raw data and what constitutes a model. For example, a monitoring instrument may use an established relationship (in effect, a conceptual model) to derive the value of a parameter (e.g. water level calculated from pressure measurements), and so the water-level data is also modelled to some extent. These authors argue that this blurring of the boundaries is a strong driver for the further development of standards for interoperability between data and models.

Many of the technical requirements (i.e. those relating to data, software and IT infrastructure) to facilitate integrated modelling are already either in place or at an advanced stage of development. These, for example, include protocols for linking models and software, and data standards to promote linked modelling. However, the development of research and user communities to take IEM forwards is also an important requirement, as highlighted by **Sutherland *et al.* (2014)**, who describe the development of the Fluid Earth network to facilitate the development of the Open MI protocol. Both **Gober *et al.* (2014)** and **Glynn (2015)** further emphasized the importance of the community and human dimension in the development of IEM. Through enabling a better understanding of environmental processes and systems, IEM has the potential to assist communities in adapting to increasingly complex environmental stresses: although **Glynn (2015)** indicates that to be understandable and usable by a broader community, IEM will need to involve simplifications (e.g. of the processes involved) and may be subjected to inherent human biases. As a counterpoint to this, **Gober *et al.* (2014)** present examples of how modelling has been used to facilitate the fair allocation of water resources in drought-prone regions of the United States.

Further, Moore & Hughes (2016) point out there is an overall tendency for much of IEM technology to be developed within research organizations, and there is a requirement for an increasing adoption of such technologies for commercial applications, and this process will also require the increasing take-up of IEM by user communities

Sutherland *et al.* (2014) and Moore & Hughes (2016) also describe the development of the Open Model Interface (OpenMI) protocol to link existing models at run-time. Sutherland *et al.* (2014)

further describe the Fluid Earth network, which provides tools for running integrated modelling using OpenMI and also promotes the development of a user community.

The present volume also contains a number of papers that describe the application of IEM to specific environmental problems, including large-scale groundwater modelling for regulatory purposes, smaller-scale groundwater modelling to resolve more local problems and also an increasing opportunity to utilize integrated modelling techniques in catastrophe modelling.

**Farrell *et al.* (2016)** describe the development of the existing National Groundwater Modelling System (NGMS) at the Environment Agency in the UK from a groundwater modelling system to a system that can also perform recharge modelling. This has clearly provided the opportunity for increased efficiency and time-saving in a regulatory environment, and suggests that other types of models (e.g. river flow) may also be integrated with the system in future. This work also further highlights the need for tools and model-linking methods that are easy to use for those who are not software or programming experts. A frequent requirement in groundwater modelling is to be able to constrain the detailed geological structure to better understand groundwater movement. Such a case study is described by **Pasanen & Okkonen (2016)**, where geological modelling using the GSI3D software is used to constrain groundwater modelling using GMS and FEFlow, and in this case the model fusion is facilitated by the integration of data between these different tools.

Being able to apply integrated modelling methodologies to addressing the simulation of natural hazards in catastrophe modelling involves not only linking different environmental models together, but also linking them to financial models representing the extent of financial loss that may occur. **Royse *et al.* (2014)** cite a useful example of such a catastrophe model, which highlights the importance of modelling the whole environmental system and, therefore, the continued development of ‘plug and play’ integrated modelling in which different modelling components can be rapidly interchanged. The example focused on calculating the financial losses resulting from groundwater flooding (Hughes *et al.* 2011).

One of the developments becoming increasingly important in IEM is the consideration and interaction of social aspects in relation to the environment within models. Human interaction with the modelling process is addressed by **Glynn (2015)**. **Gober *et al.* (2014)** emphasize the importance of the integration of human behaviour into environmental decision-making in drought-affected areas of the United States and Canada, and suggests that the value of large-scale climate models can be limited in uncertainties in downscaling these to specific local areas. The use of exploratory modelling, scenario planning and risk assessment is advocated, allowing policy makers to investigate the likely result of policy decisions before committing to them.

The theme of integrating social and behavioural considerations is further developed by **Makropoulos (2014)**, who describes the development of a toolkit to assist in the integration of social concepts into the technical understanding of water resource management. A case study focusing on the city of Athens is described, in which several water resources models are linked together currently by directly integrating the model code via tools such as MATLAB, which provides the basis for enabling social factors to be included.

The need to be able to integrate environmental models into decision support systems to facilitate access to modelled outputs to a range of stakeholders is also discussed by **Rowe *et al.* (2014)** and **Conrads & Roehl (2015)**. **Rowe *et al.* (2014)** suggest that the process of model fusion can have the effect of accelerating model growth as further models are added, even though a simpler model may possibly be more appropriate and provide results that are more usable by decision makers. **Conrads & Roehl (2015)** describes the development of neural-network-based models linked with data mining of related datasets in order to develop the PRISM-2 decision-support system and its use to better understand planning for salinity incursions on the SE coast of the United States.

The papers by **Beven & Lamb (2014)** and **Kingdon *et al.* (2014)** focus on underlying technical developments that are supporting model fusion and which are, to some extent, driven by the need to develop more integrated models of natural systems. **Beven & Lamb (2014)** outline the various sources of uncertainly in IEM, including uncertainties in the input data, the model structure, uncertainties in various parameters used to constrain the model and uncertainties in observations upon which the model is based. **Kingdon *et al.* (2014)** describe informatics techniques that support and utilize IEM, these include the development of environmental sensor networks to monitor changes in environmental systems in real time, the use of semantic interoperability to assist interdisciplinary modelling and the increased availability of cloud computing. Integrated modelling and the development of fused and linked models also have significant implications on understanding the constraints regarding uncertainty. These authors discuss methods for making realistic estimates of uncertainty within linked modelling ensembles.

The issues in estimation of uncertainty are further discussed by **Wildhaber *et al.* (2015*a*)**, who outline a process of downscaling from regional climate models to the river scale, and the impact of the uncertainties involved in linking hydrological and temperature models with a bioenergetics model (**Wildhaber *et al.* 2015*b***) for the pallid sturgeon species of fish. This work provides an excellent case study of the application of uncertainty considerations. A future extension of this work would be the development of a framework for understanding the impact of climate models on large river ecosystems.

The paper by **Laxton (2016)** describes the process of fusion of different geological maps within the OneGeology-Europe project and draws some parallels with the process of model fusion: in particular, the semantic relationships between concepts are important, as are an understanding of the differences in scale.

IEM is too large a problem to be solved by one organization, and requires an increased level of collaboration between organizations and not just within their own country or geographical region. The collection of papers presented in this volume represents a representative cross-section of initiatives in both Europe and the United States. By bringing together these good works, the future for IEM is very promising. Its ability to solve complex environmental problems so that decision makers at all levels can be better informed of the consequences of their actions is becoming a reality, and the deceptively simple questions that are, in reality, very complex can be properly addressed.

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