Start, development and status of the regulator-led national groundwater resources modelling programme in England and Wales

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Abstract: Over the last 10 years there has been a unique regulator-led programme involving extensive development of regional groundwater models across England and Wales for water resources purposes by the Environment Agency for England and Wales. Eight regionally managed programmes are underpinned by a framework, which has allowed a coordinated national approach. The main uses of the models are for catchment abstraction management and licensing. Models have also assisted in monitoring network design, investigating groundwater quality and implementing groundwater source protection zones. A five-yearly review of the programmes recognized the importance of benefit realization and stakeholder involvement as well as technical good practice. The programme already delivered provides a solid foundation for supporting the management decisions required in areas such as climate change mitigation and integrated catchment management using appropriate tools at a time of rapid organization change and financial uncertainty.

Over the last 10 years there has been extensive development of regional groundwater models across England and Wales for water resources purposes. This work has significantly improved understanding of, for example, the Chalk aquifer, and is therefore of use to hydrogeologists who would not normally use groundwater models (Soley *et al.* 2012). Several features mark this programme out as distinctive, perhaps unique in its approach:

(1) the national programme has been led by the powerful national environmental regulator, the Environment Agency for England and Wales;
(2) there has been collaboration between the regulator and water companies so that any arguments are not about which model to use;
(3) a national modelling framework has been developed including Modelling Guidance Notes produced and revised over the years by a group of about 20–30 practitioners from the regulator, universities and consultants (Hulme *et al.* 2002);
(4) the Environment Agency has invested in modelling training in collaboration with universities, as part of provision for a modular Masters degree in Environmental Engineering;
(5) a central server system (the National Groundwater Modelling System) has been developed, with the aspiration to make model results more readily available in the UK where data are not accessible, unlike other countries such as the USA, where access to data is widely available.

It is worth considering briefly whether the UK groundwater modelling programme is different in an international context, and if so, why this should be the case. Examples of models focusing on

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practical water management, as opposed to academic models, which purely investigate understanding, were already evident in the mid-1990s, for example in the work of the Kansas State Geological Survey (Sophocleous *et al.* 1995). The US Geological Survey completed regional models of the USA as part of their Regional Aquifer System Analysis (RASA) programme (1978–1996). Sun *et al.* (1997) provide a bibliography of the reports and models generated under this programme. Some individual states within the USA have completed extensive groundwater modelling programmes, notably the Texas Groundwater Availability Modeling (GAM) programme (Sophocleous 2010), mandated by the State Legislature, which required that groundwater-conservation districts must use GAM data to develop groundwater management plans. Nine major aquifers were modelled, requiring 17 different models to provide full coverage of publicly available models. Stakeholder engagement was a strong feature of the GAM programme. With a total investment of US$9.9 million (equivalent to £6.2 million at 2010 exchange rates), this is a comparable level of effort to the UK programme, which has invested approximately £20 million in 40 models since 2000. In Europe, a country-wide analytical element groundwater model was developed in The Netherlands (de Lange 2006), which has some features in common with the country-wide modelling being attempted in the UK. More recently, Snepvangers *et al.* (2008) report the development of a groundwater model encompassing the entire north of the Netherlands at a resolution of $25 \times 25\ m^2$ as an integral part of a Methodology for Interactive Planning for Water Management (MIPWA), intended to resolve conflicts among 17 water management parties, including several provinces, water companies, water boards and some municipalities. A national groundwater-surface water model of Denmark has also been established and integrated to support water management (Refsgaard *et al.* 2010).

The programme in the UK is different because it is led by the environmental regulator for England and Wales, the Environment Agency, which has a statutory duty to manage the sustainable development of groundwater (as well as surface water) resources. For such a small island, the geology and hydrogeology of the UK is very diverse. The most productive (principal) aquifers coincide generally with areas of high population and demand. They also support river flows and wetlands. The need to manage (groundwater) abstraction pressure led to the introduction of an abstraction licensing system in the 1960s. However, in the last two decades, greater focus has been placed on understanding and balancing the needs of abstractors with those of the water environment (Rushton & Skinner 2012). This has now been reinforced by European legislation (the Water Framework Directive) that requires assessment and reporting of the state of (groundwater) resources.

It follows that one of the Environment Agency's roles is to quantify the available water resources in those principal aquifers under the greatest abstraction pressure, and to regulate abstraction to ensure that the impacts of abstraction on springs, rivers and wetlands are limited to an acceptable extent. The Environment Agency uses a risk-based approach, balancing the threat to the environment with the benefits from the proposed activity or development. Often the available data do not provide the full picture, yet a decision still has to be made, making a judgement of the risks involved (Environment Agency 2008*a*). Conceptual and numerical models are therefore often an essential part of the risk-based approach. These are based on scientific principles and use available data and a professional assessment of the local circumstances. Conceptual and numerical regional groundwater models have been developed by all eight Regions of the Environment Agency (Fig. 1) to meet regulatory responsibilities, including investigating hydrogeological impacts upon rivers and wetlands of conservation value.

This paper is divided into three main sections. The first section reflects on the start of the current 10-year national groundwater modelling programme from the UK Government's environmental regulator's perspective (following the foundations laid by Rushton & Skinner 2012). It also summarizes the main legal and regulatory drivers that shaped the requirement for the programme, and explains how conceptual and numerical models form an integral part of the regulatory decision-making framework.

The second section discusses the implementation of the programme, achieved by learning and sharing good practice within a project management framework. It summarizes the lessons learned from reviewing the programme, such as the successes in justifying hard decisions and explaining these to non-specialists, and the importance of benefits realization, good communication and stakeholder participation.

The final section looks forwards to the future and asks what could be done better to ensure that models are fit for purpose, deal with uncertainty and provide useable outputs. It poses the key challenges that lie ahead, of focusing on achievement of measurable environmental changes, tackling climate change and river basin management in a context of ongoing budgetary pressures and organizational change. It concludes that the modelling programme has provided a strong foundation for addressing future challenges, but that the key to the process is not just the models themselves, or even the modellers,

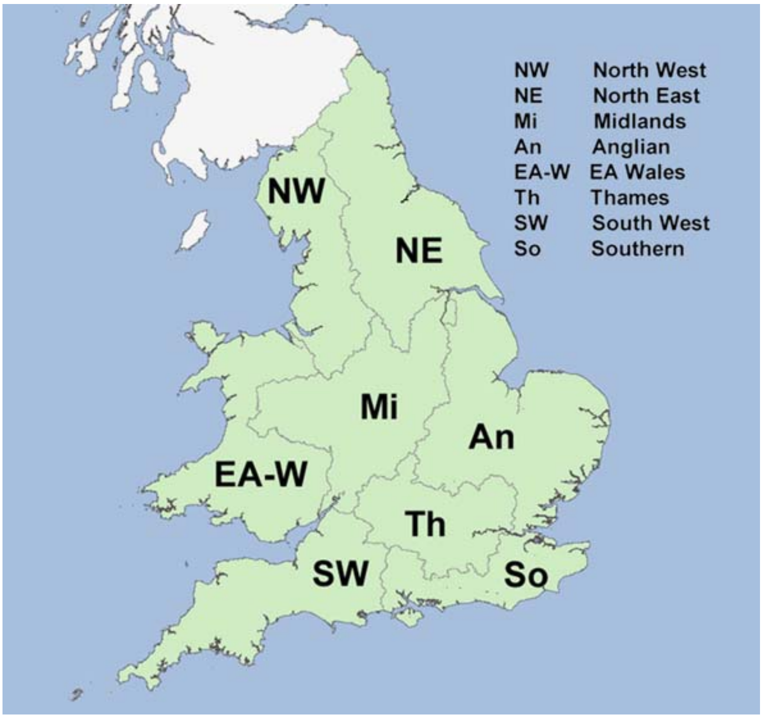

Fig. 1. Regions of the Environment Agency in England and Wales.

or even groundwater, but also about sharing understanding, and using the right tools to make the right water resources management decisions in a timely way.

Reflections: the origin of the modelling programme

An historical overview of the need for a national groundwater modelling programme is provided by Rushton & Skinner (2012). Following the 1963 Water Resources Act, a Water Resources Board was established in England and Wales to oversee the development of water resources nationally (Downing 2004). This was superceded by the creation of multifunctional public Water Authorities in 1973 following the Water Act (Brassington 2004). In 1988, the UK Government privatized the water industry, resulting in private sector water companies, along with a new National Rivers Authority as the industry regulator responsible for management of water resources. The National Rivers Authority was divided into eight Regions, which were retained on creation of the Environment Agency in 1996, following the passing of the Environment Act in 1995 by the UK Government.

On the formation of the Environment Agency in 1996 as a single UK environmental regulator responsible for land, air and water, it was recognized that there was a situation with 'improved models and increased modelling capacity spread between regulators, water industry and consultants but with modelling projects issue-driven and often uncoordinated in a basin context' (Skinner 2008). This situation led at best to wasteful duplication of modelling effort by the regulator and water companies, and at worst to expensive licence appeals and public inquiries with opposing parties challenging the technical credibility of each other's models.

There was also a lack of integration whereby 'Quality and resource issues were often investigated in isolation and there was a worrying lack of regard for problems of scale, with local issues, say the granting of an abstraction licence for a single borehole or the delineation of a [groundwater source] protection zone, being assessed using different data and algorithms from those for a regional assessment in the same basin' (Skinner 2008).

The Environment Agency's national programme of groundwater modelling has its origins in the desire to develop conceptual and, where appropriate, numerical models of all the principal aquifers in England and Wales. To address this, the Environment Agency initiated a national technical framework for groundwater modelling, reported by Hulme *et al.* (2002), to provide a set of standards and practices to minimize these problems. Skinner (2008) reported that, because of the existence of national standards and common practice, the work done by the Environment Agency, water companies and other private industry is more likely to be complementary in the same or adjacent areas and increases the level of factual consensus on which planning decisions can be taken.

A survey of previous groundwater models (only regional time-variant groundwater flow models financed in full or partly by the Environment Agency or its predecessor organizations) was undertaken during 1998–1999. These were reported in the Interim Report of R&D Project W6-034 (referred to in Brown & Hulme 2001). It provides a useful overview of the historical use of groundwater models in the regulatory process of the Environment Agency. During the 1970s and 1980s most regional groundwater models were developed by research institutions, notably the University of Birmingham; however, in the 1990s there was a trend towards private consultancy firms acquiring modelling expertise and building regional groundwater resource models for the Environment Agency. The historical overview was summarized by van Wonderen & Wilson (2006), who note the main influences exerted on the evolution of models. These include technological aspects, such as developments in IT technology (hardware and software) and, often related to IT developments, the approaches to data collation and interpretation. They also relate to the improvement of data (especially surface data such as digital terrain models) and information availability, in terms of both improved time series and spatial distribution and detail (e.g. 3D geological modelling of bedrock aquifers and overlying drift deposits, Kessler *et al.* 2004; Lelliott *et al.* 2006). The continued improvement in data and information allows for improved understanding of the complex geological, hydrological and hydrogeological aspects of the deeper aquifers and their relationship with shallower aquifers, surface waters and wetlands (considered as a whole as a 'groundwater system').

Why are (groundwater) models needed?

Hydrogeological setting and abstraction pressures. The principal aquifers of the UK are found in the densely populated lowlands of England where abstraction pressures are greatest. The most important are the Chalk, the Permo Triassic Sandstones, the Jurassic Limestones and the Lower Greensand. They occur within the section of the geological sequence referred to as the Younger Cover, which ranges in age from the Permian to the Quaternary. Aquifers do occur in Devonian and Carboniferous strata of the underlying Older Cover, but they are much harder and more compact rocks and are regarded as of secondary importance in terms of water supply (Price 1996; Downing 1998).

Legal and regulatory drivers. The Water Framework Directive (WFD) is currently the most important water legislation within the European Union (EU), setting environmental targets for the water environment for the intermediate and long term. This Directive requires EU Member States to achieve 'good ecological status' for surface water, and 'good status' for groundwater by 2015 (Council of European Communities 2000, transposed into UK law by DEFRA 2003). The WFD allows for time extensions to 2027, or less stringent objectives after taking into account the technical feasibility and whether solutions are 'disproportionately costly'.

The WFD also requires that there is no deterioration that will result in a change to a lower status. River Basin Management Plans will be produced for the whole of the UK, and will show how actions will be taken locally, through a series of six-yearly River Basin Planning cycles. Good status is defined in terms of the ecological health of water bodies, as well as water quality, 'chemical status', and quantity, 'quantitative status'. The Environment Agency is a 'competent authority' for implementation of the Directive in England and Wales, and has defined 356 WFD groundwater bodies – a groundwater body is defined with specific meaning in the Directive as a unit which either yields $>10\ m^3/day$ of water or supplies drinking water to at least 50 people. In effect the definition encompasses all aquifers as it includes all strata that can transmit water of any significance. It should be noted that a groundwater body generally corresponds to a specific surface water or groundwater catchment/watershed, but not always. Four tests are made to determine whether a groundwater body is at good quantitative status (Tomlin & Ward 2009):

(1) the overall water balance;
(2) the extent of interactions with dependent surface water bodies;
(3) damage to dependent terrestrial ecosystems (wetlands);
(4) the risk of saline intrusion.

The demarcation between good status and poor status is explained below in the 'Future challenges' section about the EU Water Framework Directive. Method statements for each of these tests are available on the Environment Agency's website at http://www.environment-agency.gov.uk/static/documents/

Research/GW_Quantitative_Classification_140110.pdf. The approach to groundwater quantitative classification is summarized in a paper by the UK Technical Advisory Group on the implementation of the WFD (UKTAG 2007).

Groundwater conceptual and numerical models play an important role in assessing the water balance and surface water–groundwater interactions in support of these tests. They are also one of the tools used within the Environment Agency's Resource Assessment and Management framework which underpins the Catchment Abstraction Management Strategies (CAMS; Environment Agency 2010) prepared by the Environment Agency for each catchment in England and Wales to indicate the available water resources.

The Environment Agency also has a programme of Restoring Sustainable Abstraction (RSA), intended to address concerns of ecological impacts upon rivers and wetlands that may be due to historic over-abstraction of water (see Shepley 2010 for example). Much of the work within the programme is undertaken by the private water companies through agreed five-year capital investment cycles regulated by the UK water industry regulator, OFWAT. Another important component of the programme is compliance with the EU Birds and Habitats Directives (Council of European Communities 1994). These Directives require competent authorities, including the Environment Agency, to ensure the protection of internationally important conservation sites (the 'Natura 2000' network) by demonstrating that their permits (such as water abstraction licences and discharge consents) are having 'no significant effect' on the integrity of these sites. Since many of the investigations within the RSA programme potentially involve resource recovery (groundwater resources are nominally valued at typically in the range £2–7 million per million litres/thousand cubic metres per day, according to research for the Department for the Environment, Food and Rural Affairs; DEFRA 2007*a*), a robust conceptual model and defensible tool such as numerical groundwater modelling is often required to achieve confidence in decisions that affect, for example, groundwater sources for public water supply.

Conceptual models and decision frameworks. The process whereby hydrogeologists interpret the available information to produce a justifiable set of simplifying assumptions to describe a groundwater system is called conceptual model development (Brassington & Younger 2010). Groundwater resource investigations are undertaken to help gain this conceptual understanding of the groundwater system, in order to assess and manage groundwater resources and the impacts of natural and anthropogenic factors upon resource availability and resource behaviour. Brassington & Younger (2010) provide a framework for conceptual model development to assist with the planning of groundwater investigations and to act as an audit trail for independent scrutiny. The process of conceptual model development is also described in the Environment Agency's groundwater modelling guidance notes (Environment Agency 2002*a*, 2008*b*) and groundwater protection policy (Environment Agency 2008*a*). A similar process is outlined for contaminant transport studies (Environment Agency 2001*b*). The importance of the conceptual model has been illustrated by Rushton & Skinner (2012). The conceptual understanding must be relevant to the issue under investigation, which may be more than just the groundwater flow system. Skinner (2008) argues that models need to be able to portray the role of groundwater in the context of its land and water interaction in the catchment and be capable of being scaled to a level of detail necessary for the issue in question. Groundwater flow modelling also plays an important role as the foundation for groundwater quality modelling and aquifer protection, as described in the Environment Agency's Groundwater Protection Policy (Environment Agency 2008*a*).

The groundwater resource conceptual and numerical models provide a decision-support framework for issuing and review of permits such as water abstraction licences, and enable the Environment Agency to justify regulatory decisions. The models are important assets that enable forecasting and planning for the future to ensure security of water supply and protection from adverse conditions such as extreme hydrological events (e.g. droughts, groundwater flooding, climate change).

Model use can be seen in the context of strategic or 'operational' water resources management, and 'tactical' use (Grout & Whiteman 2000). Tactical uses (see Table 1) could be seen in part as developing preparedness for adverse conditions (e.g. extreme events such as low flow periods). This requires a holistic and basin-scale approach to understanding the role of groundwater systems and the influences exerted upon them (either natural or anthropogenic). The operational use relates to regulatory duties such as complying with European Directives and national legislation (see Table 2).

An example of the use of groundwater models for Catchment Abstraction Management Strategies is given by Whiteman *et al.* (2012). An example of a tiered, risk-based approach to wetland impact assessment is given by Whiteman *et al.* (2004). The importance of the conceptual model along with location of receptors such as rivers and wetlands in identifying groundwater monitoring networks is discussed by Tomlin & Ward (2009).

Table 1. *Tactical uses of groundwater models*

Use	Purpose
Review water resources management plans	Evaluation of the limits of sustainable water resources development
Local impact assessment	Use of the model to assess impacts of different groundwater management options on users, springs, river flows and wetlands
Forecast water supply yield for prevailing groundwater conditions	Establish current resource state and determine the optimum groundwater use for the immediate future. This would include the forecasting of potential aquifer yield during a drought
Forecast need for mitigation measures	Linked to the previous use. Relates to the use of models in assessing mitigation needs such as river support and cutback/cessation of abstraction
Forecast operational yield of aquifer storage and recovery schemes	To assess the net gain in the short and long term
Climate change	Assessing the impact of climate change on groundwater resource systems
Land use change	Impact on groundwater resource system
Design of optimum hydrological monitoring network	Evaluation of the 'value' of monitoring facilities
Groundwater contamination	Use of groundwater flow model and associated datasets in contaminant transport studies (e.g. minewater and contaminated land remediation)
Groundwater quality forecasts	Use of the model datasets in forecasting nitrate and other chemical pollutant concentrations in groundwater
Planning applications	Use of the model and datasets to support hydrogeological impact assessments for new developments (e.g. mining)

Implementation of the programme

Scale of the programme

The national modelling framework outlined by Brown & Hulme (2001) and reported by Hulme *et al.* (2002) provides a technical and management approach to individual projects as part of planned regional modelling strategies. Each of the seven regions of the Environment Agency in England and also the Environment Agency Wales (Fig. 1) developed a regional modelling strategy, with an appropriate scope of modelling planned to meet regulatory needs. These programmes reflect the recommendations made in the national framework (Hulme *et al.* 2002), with an emphasis on investment in well-documented and adequately tested conceptual models. Where appropriate (mainly

Table 2. *Strategic operational uses of distributed groundwater models*

Business area	Legal and regulatory drivers	
Strategic Water Resources Planning	EU Water Framework Directive Catchment water abstraction management strategies (CAMS) Addressing historic over-abstraction (restoring sustainable abstraction, RSA)	EU Habitats Directive Review of Consents) Periodic Review (including National Environment Programme)
Operational Management	Abstraction licensing Water availability forecasts	
Monitoring	Asset management of monitoring network Monitoring network design	
Groundwater quality	Framework for groundwater quality investigations Groundwater protection zones Nitrate directive Contaminated land	

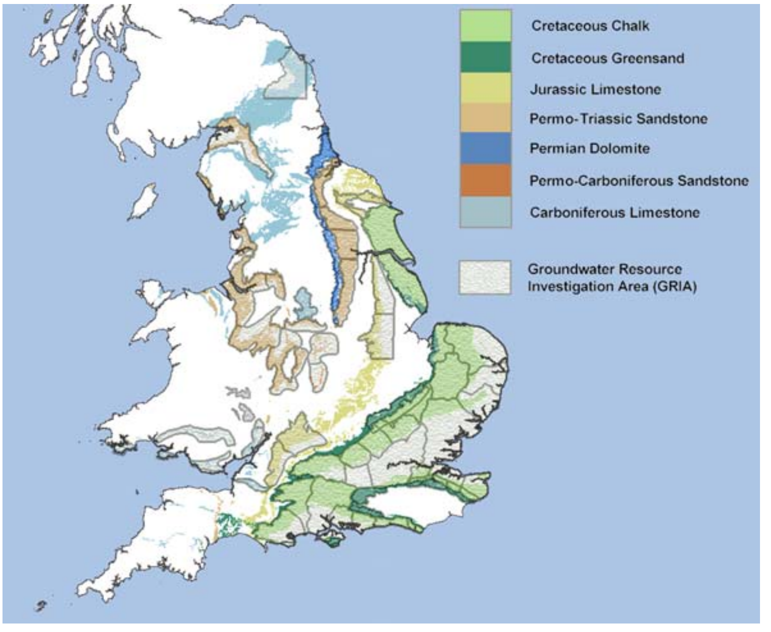

Fig. 2. Principal aquifers and groundwater resource investigation areas in England and Wales.

where abstraction pressures are greatest), regional numerical models have been developed.

Forty-four regional groundwater resource investigations have been undertaken by the Environment Agency over the last 10 years, with a typical investment of around £3m per year over the period 2000–2005. The locations of the groundwater investigation areas in relation to the principal aquifers in England and Wales (note that these do not necessarily correspond to the extent of aquifer outcrop or the numerical model boundaries) are shown in Figure 2 and the number of investigations are listed by region in Table 3. Progress to 2009 with the Environment Agency's programme is shown in Figure 3 in which investigations:

(1) completed are shown in green;
(2) in progress are shown in pale green;
(3) yet to be undertaken are shown in yellow;
(4) not planned are shown in white (non-aquifer or low-yielding aquifers).

Of the investigations already completed, 16 were full numerical models. In some cases the investigation did not proceed to the numerical modelling stage, for example the Wirral/West Cheshire model,

Table 3. *Numbers of regional groundwater resource models developed by the Environment Agency and used in the regulatory programme in England and Wales by region*

Region	Total number of models developed		
	Conceptual model only	Numerical models including models developed prior to 2000 which have been used since	Numerical models developed 2000–2009
Anglian		10	8
Midlands		10	9
North East		6	5
North West	1	3	3
Southern		4	4
South West		3	3
Thames		7	7
Wales	3	1	1
Total	4	44	40

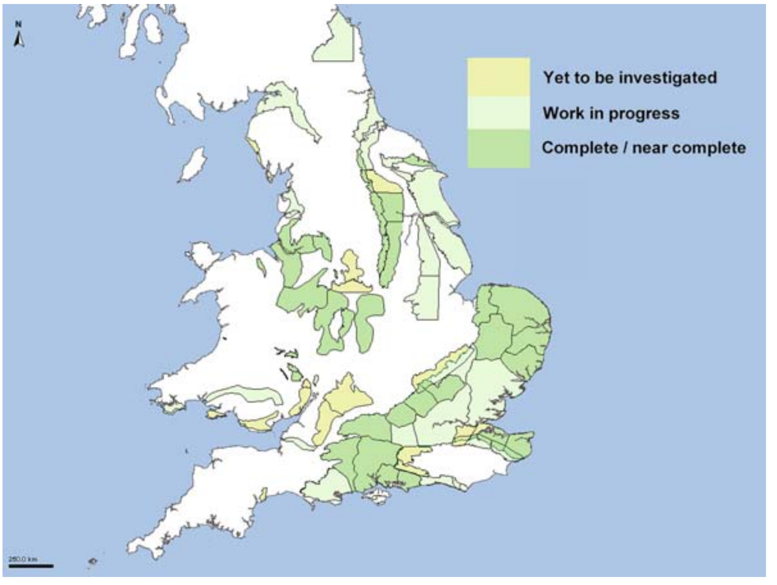

Fig. 3. Progress with the Environment Agency's groundwater resource investigations in England and Wales to 2009.

due to the considerable uncertainty and lack of data available to build an aquifer-wide numerical model. In this case, the focus was changed to carrying out in-house local-scale models of key locations, focussing on the key issues, for example saline intrusion along the Mersey and the effect of public supply abstraction locally on surface waters. In many areas, development of a quantified conceptual understanding has been sufficient, with regional numerical models developed only where the pressure on groundwater resources or other drivers requires it. Some areas of principal aquifer remain unmodelled, simply because there are no strong regulatory drivers for modelling (see also Fig. 4 which refers to the cyclic process of model development).

The regional modelling programmes are being prioritized according to regulatory needs, and the timetable harmonized with the published timetables for Catchment Abstraction Management Strategies, the EU Habitats Directive Review of Consents and the EU Water Framework Directive.

For example, the modelling strategy for the Midlands Region (Shepley 2003) included a review and update of the West Midlands–Worfe aquifer conceptual understanding and numerical model due in 2006. This update was completed as planned (Fielding *et al.* 2007; Shepley 2009). The West Midlands–Worfe groundwater model was initially constructed in the late 1990s, as reported by Rushton & Skinner (2012), and continues to be used to assess groundwater resources as part of Catchment Abstraction Management Strategies (Shepley & Soley 2012). Although the model was constructed with a relatively coarse grid (500 m), the small size of the model with short run-times has really been an asset, even though now the grid could be much finer.

Grout *et al.* (2004), reporting on the findings of the Anglian Region strategy for groundwater investigations and modelling, discuss several areas of the Environment Agency's business that can benefit from the groundwater models and their supporting conceptual understanding and validated datasets. In addition to developing the regional groundwater models, there was a need to react to more immediate regulatory needs, such as the Habitats Directive Review of Consents. The groundwater resource assessment and modelling programme was valuable in helping to meet tight deadlines for the Habitats Directive Review of Consents. Appropriate Assessments of high-priority sites within the Anglian Region (see Whiteman *et al.* 2004) benefited significantly from the data collation and modelling work. The models were also used to support Catchment Abstraction Management Strategies, by providing abstraction and discharge data, GIS maps of the conceptual hydrogeology, recharge estimates, naturalized river flows, and licensed and recent actual scenario river flows. Sustainability appraisals were informed by using the models to investigate alternative resource recovery options, providing in-depth support to licensing decisions and assessing the potential impacts of climate and land-use changes upon groundwater resource availability.

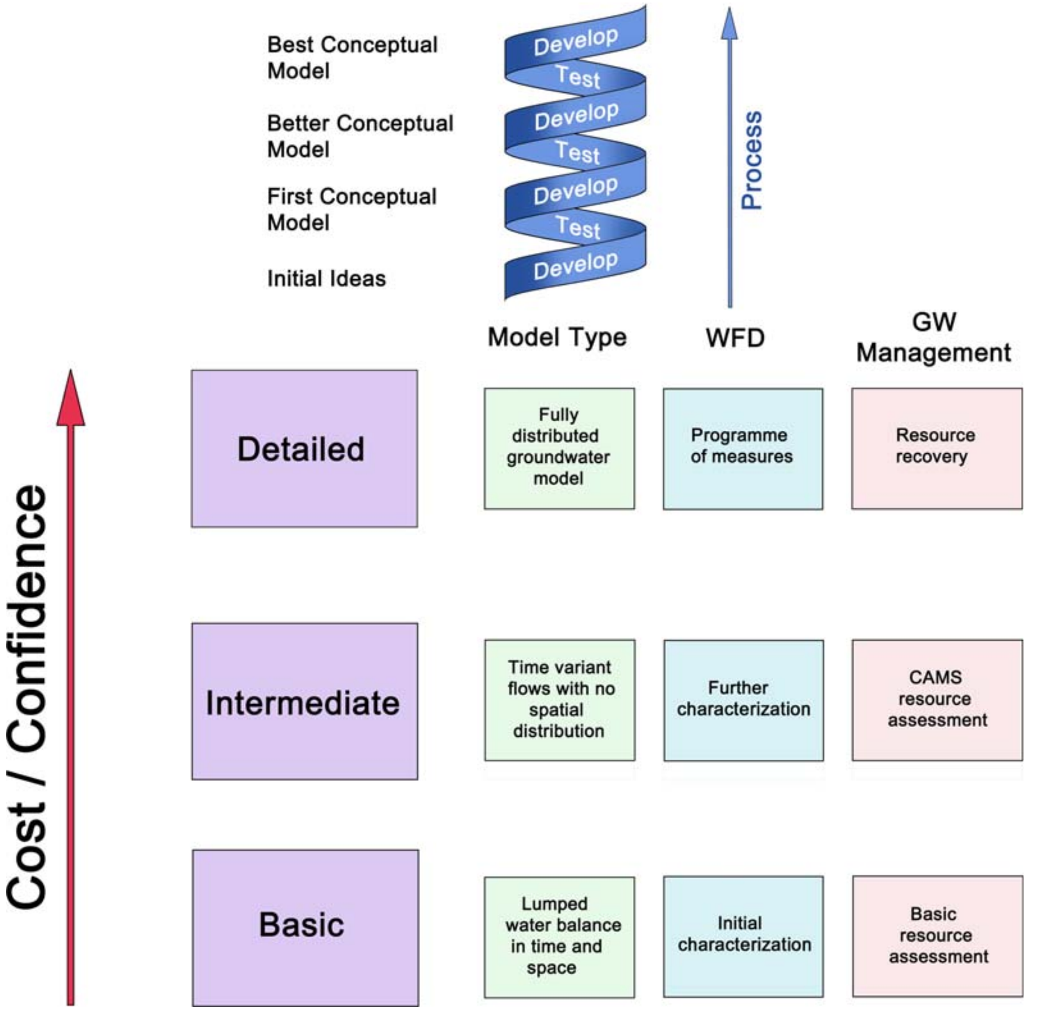

Fig. 4. The cyclic process of conceptual model development (from Environment Agency 2002*a*). WFD, EU Water Framework Directive; CAMS, Catchment Abstraction Management Strategies.

How was good practice learned and shared?

The Environment Agency has promoted good technical practice by establishing a set of groundwater resources modelling guidance notes and template project brief (Brown & Hulme 2001; Hulme *et al.* 2002; Rushton & Skinner 2012), and by supporting the UK Groundwater Modellers' Forum, which promotes best practice. The audience for the guidance is primarily Environment Agency staff and their consultants. As the national modelling programme developed over the last 10 years, the guidance notes have continued to be updated to reflect new technical methods and other non-technical components of good practice (Farrell & Whiteman 2008*b*; Environment Agency 2008*b*).

Environment Agency modelling studies take a phased approach, inspired by Professor Ken Rushton (Environment Agency 2008*a*; Rushton & Skinner 2012), in which it is usual to develop and test quantitatively a conceptual model, with long-term or seasonal water balances, before detailed numerical modelling. The upper part of Figure 4 illustrates the cyclic approach to development and testing of the conceptual model. The lower part demonstrates that you can use a simple model, such as an analytical or spreadsheet tool, for some regulatory decisions (such as a basic groundwater resource assessment). However, a more complex model is sometimes required for other tasks, such as CAMS. When a more complex model is used, this will lead to the refinement of the conceptual model (as in the upper diagram). It is important from a regulator's perspective to take a risk-based approach and stop the cycle of improvement of the conceptual model as soon as practically possible. The conceptual model is only updated when there is a good regulatory reason for doing so, for example if new data become available that must be incorporated to determine an abstraction licence, or if checking of model findings proves that the current conceptual understanding is inadequate. In this way, scarce resources are targeted effectively.

From the outset of the modelling programme, the benefits of adopting a collaborative approach were recognized. The guidance promoted the formation of a technical steering group and appointment of an external technical reviewer to each project. This has proved crucial to the successful delivery of the modelling projects. Modelling project teams have been formed to share knowledge and experience of different specialists within the Environment Agency (hydrologists, ecologists as well as hydrogeologists) working alongside consultants, and key stakeholders including water company hydrogeologists and environmental bodies. This has promoted consensus on technical approaches and issues amongst peers.

An important component of good practice, which has emerged over the last 10 years of the modelling programme in the UK, has been the close working relationship with the British Geological Survey in understanding the geology of the study areas, which underpins the hydrogeological (conceptual) model. This has been enhanced and promoted by the British Geological Survey's development of 3D digital geological models (Farrell *et al.* 2009).

Reviewing the programme

Roughly five years after the original strategic review (Brown & Hulme 2001) in 2005/2006, the Environment Agency completed a subsequent review (van Wonderen & Wilson 2006). The most important recommendations from this review are listed below.

Data and knowledge management. Modelling studies provide useful processed and quality checked data. There is an opportunity for improved management and access to these data sources. With good data systems in place, considerable time and money can be saved.

Expectation management and benefits realization. Greater awareness of groundwater models is needed amongst end users and non-technical managers and decision-makers so that the possibilities that models can offer and their limitations and uncertainties are understood better. There is a degree of misunderstanding about what a model is and what it can do – models are seen as numerical tools that can provide accurate answers, rather than modelling being seen as a process allowing users to make informed, sometimes qualitative, decisions (see example from Oreskes 2003 in Hughes *et al.* 2012).

There is a clear need for dissemination of the role and capability of conceptual and/or numerical models as the best tool available for understanding many aspects of groundwater behaviour. For this reason a series of method statements was prepared by van Wonderen & Wilson (2006) to clarify the role of groundwater modelling in undertaking the Environment Agency's regulatory activities such as the RSA programme or implementation of EU Directives such as the Water Framework Directive.

Communication and stakeholder participation. Communication and participation are essential to the benefit realization of regional groundwater modelling studies. This goes wider than the Project Technical Steering Group mentioned in the section on project management. The end user requirements should be clearly understood at the outset of the project and these should drive the scope and detailed approach to delivery. These end users and other key stakeholders should be involved at all stages of model conception, development and implementation. This emphasis has already led to closer involvement of Environment Agency staff in the development of models and has created a much stronger feeling of ownership amongst Environment Agency staff (e.g. in the Lincolnshire Limestone and Lincolnshire Chalk modelling studies; van Wonderen, pers. comm. 2010). A useful approach to communicating the usage of groundwater modelling results with stakeholders is presented by Hughes *et al.* (2012).

What is the current position?

A model should always have a specific purpose and should be designed to address that purpose. The first step in modelling is therefore to articulate the modelling objective(s), then to design the model to meet the objective(s). See, for example, the modeling protocol discussed by Anderson & Woessner (1992). Skinner & Rushton (2012) pose a series of questions for those managing modelling projects into the future. Experience from the programme during the last 10 years suggests that there are two further questions to ask at the start of a modelling study (from the perspective of a publicly funded environmental regulator):

(1) What is the most cost-effective programme of work required to make risk-based decisions with the timescales required for regulatory delivery?
(2) What is the value to the Environment Agency's regulatory role/UK economy of achieving the project's objectives?

In the UK, although Skinner made the argument for national coverage of regional groundwater models, he also recognized the need for 'a continuing need to keep a balance between the capability of the numerical tools available and the conceptual understanding and the limitations of data availability' (Skinner 2008). In addition to these constraints, from a regulatory perspective, it is important to always stay focussed on the question to be answered, as defined in the objectives of the study, to ensure the 'fitness for purpose' of modelling studies. This means that modelling is kept as simple as possible to defensibly answer the regulatory questions – where the risks are greater, a more sophisticated (expensive) modelling approach may be justified.

Van Wonderen & Wilson (2006) state that 'Distributed numerical models are not always required. It is not unusual that decisions on groundwater resources issues can be based on the conceptual model and possibly with the use of analytical or lumped parameter modelling tools'. The concept of parsimony (a model should be no more complex than necessary to predict the observations of sufficient accuracy to be useful) in hydrological modelling (Wheater *et al.* 1993) is also applicable to groundwater modelling studies.

In a comparative review of international modelling guidelines, Middlemis (2004) points out that the approach in England and Wales has emphasized the construction of regional-scale numerical models, although many other modelling approaches exist. The UK experience has shown that the most lasting legacy of a regional groundwater resources study is the documented and disseminated conceptual understanding and the calibrated datasets, for example distributions of aquifer properties in space and recharge in time and space, rather than merely the numerical model and its results. At the scoping study stage, it is important to assess the relevance of the regional groundwater flow systems to the local issue, and the degree of uncertainty in the (groundwater) system before embarking on a costly and time-consuming regional groundwater model. Examples where simple modelling tools have been used are listed below.

Wetlands. Local impact assessments of protected wetland sites undertaken as part of the Environment Agency's RSA programme have integrated hydrogeology and ecology into a combined eco-hydrological conceptual model (Whiteman *et al.* 2009).

River flows. The Environment Agency has used simple analytical tools for many years as screening tools for the assessment of potential impacts of groundwater pumping upon river flows (see Soley *et al.* 2012). Hulme *et al.* (2012) developed an intermediate tool for the same purpose, and show how it is possible to build a relatively simple numerical model, an 'impact model' within a short period of time (days or weeks), in which a hydrogeologist licensing a new groundwater abstraction source can incorporate the essential hydrogeological conditions. An 'impact model' was prepared by Hulme *et al.* (2012) and used as a part of an assessment of the ecological impact of two groundwater abstraction licences on the River Leith in NW England for the EU Habitats Directive.

Saline intrusion. Streetly & Buss (2004) undertook a study of the Manchester and East Cheshire Permo-Triassic sandstone aquifer, in which detailed numerical models were developed only for local areas where abstraction pressures were greatest. Elsewhere in the same aquifer unit (Trafford Park), where there was considerable uncertainty over boundary conditions, they developed a relatively simple model to test sensitivity in the transient water balance. They then used simple analytical approaches to assess the risk from saline upconing as part of a tiered risk assessment approach to new abstraction proposals.

Successes

As stated by Rushton & Skinner (2012), one of the main objectives of developing the Regional and national modelling programme in England and Wales was to share a common conceptual understanding with key stakeholders of our groundwater systems to support 'optimal resource development', thereby justifying hard decisions and avoiding expensive public inquiries such as the Axford inquiry (Bateman *et al.* 2000). Since the inception of the current programme, the Environment Agency has avoided direct dispute with licence applicants over the technical details of models by sharing a common understanding of the groundwater flow system with the key external stakeholders. Equally, there is a need to continue the investment in a shared understanding and participatory approach in future resource recovery resulting from the EU Water Framework Directive and the RSA programmes in their implementation phase. Reviewing the impact of existing abstractions has led to a more sustainable level of abstraction licensing. Model-specific benefits achieved by each region have been recorded and classified as either cash-releasing, productivity, cost avoidance, risk mitigation, service improvement, income generation or environmental improvement. Although it is difficult to quantify many of the benefits, it is clear that some relate to potential cost savings in the order of millions of UK pounds, such as use of the East Shropshire model as part of implementation of the Shropshire Groundwater Scheme Phase 5 and associated reduction of the risk of groundwater contamination by the river augmentation boreholes.

It is important to present the results from groundwater modelling studies so that they are understandable not just to modellers but also managers and stakeholders who need to use the model results to make decisions (Rushton & Skinner 2012). The outputs of the conceptual models, such as catchment or receptor-focused, or seasonal water balances, hydrogeological cross-sections and maps from the programme have been presented in a variety of ways to enable this engagement (e.g. see Whiteman *et al.* 2012).

One benefit of the national groundwater modelling programme has been the establishment of an active groundwater modelling community in the UK, not just within the Environment Agency but also including consultants, academics, regulators and regulated industry. This community is exemplified by the UK Groundwater Modellers Forum (http://www.groundwateruk.org/html/modelling/home.htm), which exists to promote technical discussion on the acceptance of best practice for a range of issues amongst the community and to stimulate research.

What could be done better?

In a groundwater resources study, the degree of and approach to investigation and modelling needs to focus on the questions to be answered, the available time and budget to provide those answers, the required level of confidence in the answer (risk), the relative importance of the groundwater 'component' of the issue, and availability of data. The Environment Agency's modelling guidance promotes a phased, cyclic approach (Fig. 4) and always recognizes the need for keeping modelling no more complex than justified by the risks – experience has highlighted the relative merits of simple approaches. The Environment Agency has a number of different tools that can be used for assessing both groundwater resources and contaminant hydrogeology. These range from simple risk screening methods and GIS-based tools, through simple analytical models to more complex numerical models (Farrell & Whiteman 2008*a*) (Table 4). Farrell & Whiteman (2008*a*) note the particular need for 'intermediate' tools which are more realistic than simple analytical methods, and also more rapid to develop than regional numerical models. For example, a rapid model for estimating the reduction in river flows due to groundwater abstraction has been applied successfully in the River Leith catchment (North West England) by Hulme *et al.* (2012).

The importance of recognizing and dealing with uncertainty in modelling (Beven 1993; Oreskes 2003) is widely recognized amongst hydrogeologists (see e.g. Hunt & Welter 2010). Sources of error or uncertainty in a groundwater model include the field data, conceptual model, model input data, mathematical representation of the physical processes, and predictive uncertainty (Anderson & Woessner 1992; Hulme *et al.* 2002 Section 6.6). Oreskes (2003) states that 'models can never fully specify the systems that they describe, and therefore their predictions are always subject to uncertainties that we cannot fully specify'.

Shepley & Voyce (2010) discuss the use of groundwater resource models in regulatory decision-making. They note a spectrum of the use of models

Table 4. *Tiered guidance and modelling tools for groundwater resources and contaminant modelling components of integrated catchment management (after Farrell & Whiteman 2008a)*

Complexity/cost	Water resources	Groundwater contamination
Simple	Conceptual modelling Guidance (Environment Agency 2002*a*)	Conceptual modelling (Environment Agency 2001*b*)
↓	Simple risk screening tools, for example Water Resources GIS risk engine	Groundwater vulnerability maps
	Simple/analytical (deterministic) models for example IGARF (Environment Agency 2001*a*)	Analytical (deterministic) models for example Remedial Targets Method (Carey *et al.* 2006)
	Analytical (probabilistic) code (rarely used)	Analytical (probabilistic) code for example ConSim (Environment Agency 2003)
Complex	Numerical models for example MODFLOW (McDonald & Harbaugh 1988)	Numerical models (rarely used) for example MODFLOW + MT3D (Zheng 1990)

for decision-making. At one end of the spectrum multiple conceptual and numerical models are used (as advocated by Poeter 2007) in cases where the consequences of the decision are non-reversible or very difficult or expensive to reverse (e.g. nuclear waste disposal). Alternatively, when the results of a decision are reversible or mitigation is possible and where there is potential agreement between interested parties (such as management of groundwater abstraction), Shepley & Voyce (2010) argue that a single numerical model with a thorough conceptual understanding could be used to inform a decision, provided that appropriate monitoring is put in place so that the predicted results can be checked. Where the predictions do not match observations then appropriate measures can be taken, the conceptual model re-evaluated and improved, which can in turn lead to improvement of the numerical model. Reality is nearly always different from predictions; however, the difference between prediction and reality may not be important in the context of the management decision (Konikow & Bredehoeft 1992). Although uncertainty is not quantified, using this approach improves confidence in the conceptual and numerical model (Shepley & Voyce 2010).

Use of the Environment Agency's groundwater models for management of abstraction is likely to fall into the end of the spectrum where the results of the management decision are reversible. The Environment Agency's guidance for groundwater resources modelling (Hulme *et al.* 2002) is consistent with this approach.

Anderson & Woessner (1992) provide a brief introduction to the use of inverse codes to assist/guide a calibration. Application of uncertainty analysis to groundwater models is also described by Hill & Tiedeman (2007). The EU HarmoniCA project also provides guidance on uncertainty analysis (Refsgaard *et al.* 2006). Some attempts have been made in the UK to apply systematic uncertainty estimation techniques to groundwater models, such as the application of UCODE (Environment Agency 2002*b*).

It is important to remember that groundwater investigations involve dealing with uncertainty all the time, especially with a numerical groundwater model. Black & Black (2012) present examples of how the inverse modelling code PEST (Moore & Doherty 2006) has been applied to significantly improve model parameter estimation (calibration) and to provide robust sensitivity data. Rushton (2003, p. 386) points out, however, that the greatest challenge in model refinement is to identify critical features which were not included in the original conceptual models.

Since there will always be uncertainty in the model, experience shows that each modelling study from the Environment Agency programme reaches a stage where the project team and technical reviewer agree that the model is 'fit-for-purpose' to answer the questions posed in the objectives of the study.

Modelling studies need to reach real solutions for strategic decisions – a good example is given by Whiteman *et al.* (2004), who used a tiered, risk-based approach, involving groundwater models ranging from simple analytical methods to regional groundwater resource models for wetland impact assessment.

Skinner (2008) recognized the requirement for the models to meet the needs of communication and assist in presenting the evaluation of options to the interested stakeholder in a meaningful way. The Environment Agency's National Groundwater Modelling System (NGMS) is a map-based system for viewing the results of groundwater models (Whiteman *et al.* 2012). NGMS will allow access to modelling results by a much wider audience than historically. NGMS also promises to make the process of keeping models operational much more efficient and achievable using standard national datasets.

With hindsight, it is clear that it is not possible to maintain (in operational use) the many models held locally with differing pre- and post-processing utilities ('stand-alone' models) developed over the last four decades. Within the Environment Agency, models should be useful and usable by hydrogeologists in general, not just groundwater modellers. It is essential that hydrogeologists who use a model receive some training in modelling, to recognize the assumptions, limitations and uncertainty that is a part of modelling. The Environment Agency has developed modelling training with universities in the UK as part of a modular Masters training programme in Environmental Engineering that underpins a technical development framework for groundwater professionals recognized by the Geological Society of London.

The groundwater modelling programme was conceived and has been driven by hydrogeologists and groundwater modellers. Feedback from outside our community suggests that modellers (as well as other geoscientists) can be perceived to focus in great detail on technical issues, perhaps of academic or hydrogeological interest, and also the modelling process, rather than the consequences of the management decsion. This issue was recognized by Rogers (1978), cited in Konikow & Bredehoeft (1992), who suggested that more effort should be spent on understanding the hydrogeological system rather than model validation since 'in focusing on model validation, the analyst is likely to learn more about the model than the system being modelled, or about useful policy implications'.

The 'so-what? test'

At each stage of a project the 'so-what' test should always be applied – asking the questions:

(1) How useful was the conceptual model/numerical model for your decision-making?
(2) Could the decision be made with less information?
(3) Would the consequences have been different?

The process of groundwater resource assessment provides a decision-making framework for building, testing and sharing understanding. However, the numerical groundwater models themselves are *only* a (valuable) tool for risk-based decision making, for example in hydrogeological impact assessment (Boak & Johnson 2007). An example of the 'so-what' test in practice is given by Shepley & Voyce (2010), who question the need for a more detailed local conceptual recharge model in the East Shropshire groundwater model. In this case, the key test is whether the more detailed model would make any difference to operational decisions of the Shropshire Groundwater Scheme, such as commissioning a new group of river augmentation boreholes. Shepley & Voyce (2010) conclude that, in a moderate diffusivity aquifer such as the Permo-Triassic Sandstone in Shropshire, very detailed recharge models are unlikely to provide critical information for decision-making on water management.

It must be acknowledged that groundwater modelling in a regulatory context is a process to help decision-making, but not an end in itself. Hydrogeologists and groundwater modellers are sought for advice on below-ground environmental issues and interaction with the surface environment. Whereas practising hydrogeologists will continue to use numerical models, they must be careful not to become over-reliant on the use of numerical models, but to exercise confident professional judgement. Their experience and confidence needs to be built up by regular comparison of what the model predicts with what actually happens, such as observed streamflows and groundwater levels. This process can lead to continual refinement of the numerical model, as described in more detail by Rushton (2003, p. 378).

In practice this means, for example, use of the modelling tools by Environment Agency hydrogeologists to help them do their job, not merely involvement in constructing the calibrated historic numerical model.

Future challenges

As discussed above, the only reason for the successful establishment of a, possibly unique, national programme of regional scale numerical groundwater modelling in England and Wales was the realization by the UK Government's environmental regulator that modelling would meet its regulatory needs. In order to see what the future regulatory need for groundwater modelling will be, it is important to examine the future direction of the Environment Agency as an environmental regulator that makes decisions based upon observed or modelled data, outlined in its new Corporate Strategy 2010–2015 (Environment Agency 2009). The Strategy is focused on results which are beneficial to the environment ('outcomes') with success measures defined against five key areas, including:

(1) 'reduce climate change and its consequences';
(2) 'protect and improve water, land and air';
(3) 'work with people and communities to create better places'.

Examples of success measures include:

(1) surface, ground and coastal waters and wetlands have achieved or are improving toward 'good status' or 'good potential' under the Water Framework Directive;
(2) over-abstraction within water bodies is reduced and fewer abstractions cause environmental damage.

The Corporate Strategy provides a powerful mandate for groundwater conceptual and numerical models, with their ability to provide a decision-support framework for making risk-based decisions affecting groundwater resources in a timely manner. Some of the key challenges facing groundwater modelling into the future are outlined in this section.

Climate change poses questions of resource availability, maintenance of baseflow to receptors such as rivers and wetlands, security of supply, and even groundwater flooding during intense storm events. Groundwater models can be used to assess the potential impacts of climate change upon groundwater resources and borehole yields (Yusoff *et al.* 2002; Herrera-Pantoja & Hiscock 2008). Groundwater also has a role to play in adaptation strategies, in which greater use could be made of groundwater storage to mitigate against the impacts of climate change (Shepley *et al.* 2009; Shepley 2010). In a sense, the situation has come full circle to the conjunctive use schemes of the 1970s (see Skinner 2008) to a point where groundwater could increasingly be an important part of an integrated catchment use of water resources.

The Water Framework Directive (Council of European Communities 2000) provides a regime that enables the approach to dealing with uncertainty outlined above. The Directive requires member states to designate water bodies as 'good' or 'poor' status with long-term targets to maintain or improve status (see section on legal drivers

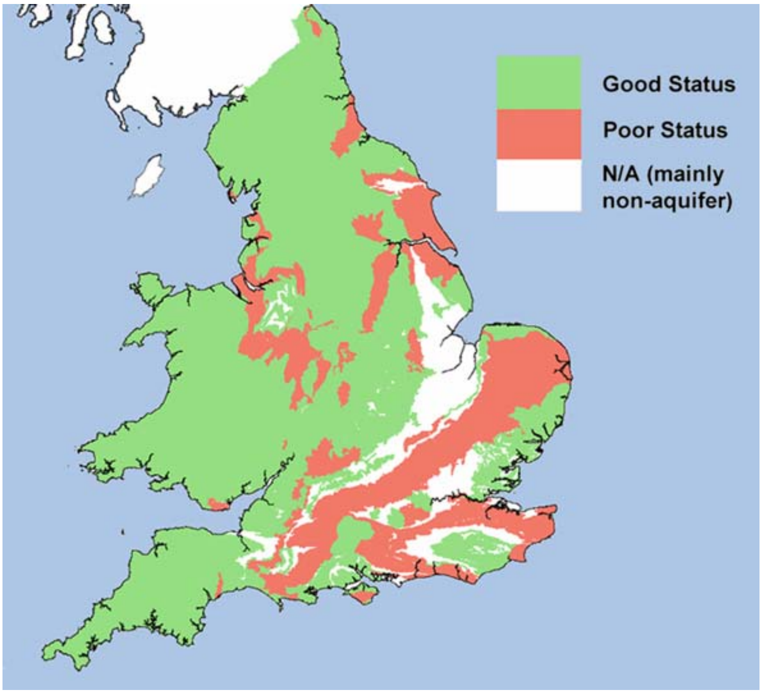

Fig. 5. Combined results of the four WFD groundwater body quantitative tests for the first river basin cycle in England and Wales.

above). There is a legal requirement for monitoring and review based on a six-yearly cycle. There is therefore an implicit requirement to review conceptual and numerical models within this legal management framework (Council of European Communities 2009).

Figure 5 illustrates the combined outcome of the four groundwater quantitative status tests from the first cycle of river basin planning. Where groundwater bodies have failed one of the four quantitative status tests (see section on legal drivers above), this means:

(1) a water balance indicating over-abstraction; or
(2) depletion of dependent surface-water bodies by losses to groundwater; or
(3) ecological damage to a dependent terrestrial ecosystem (wetland) as a result of lack of groundwater or poor quality groundwater; or
(4) saline intrusion of a groundwater body due to historic over-abstraction in coastal aquifers (or those with deep connate saline groundwaters).

In those cases where groundwater body status is poor, the WFD requires solutions (known in WFD as 'Programmes of Measures') to restore groundwater and surface water bodies to good quantitative, chemical and ecological status. Integrated catchment conceptual models are needed to achieve this, including groundwater quantity and quality elements, surface waters, hydromorphology and ecology.

In many cases, however, confidence in the groundwater status being either good or poor is low due to inadequate conceptual understanding of groundwater flow components or river-aquifer interactions. The WFD therefore provides an important driver for a programme of groundwater investigations into the future – the national modelling programme that the Environment Agency has already delivered gives us a foundation to improve the risk assessments made in the first cycle and come up with appropriate measures.

The global economic recession means that there will be budgetary pressures on all public sector bodies for the foreseeable future, requiring strict prioritization of scarce resources and delivery of value for money. In turn, these changes, along with the technical and legislative challenges outlined above, are driving frequent and profound organizational changes. The drive towards integrated catchment management and the ecosystems approach required by the UK Government (DEFRA 2007*b*, 2008) means that the future of the groundwater modelling programme will need to be increasingly targeted and fit-for-purpose, focussing on delivering changes to the benefit of the environment. Some of the likely beneficial changes in groundwater modelling include making access to models and their results easier for a range of users and decision-makers (Whiteman *et al.* 2012) and the use of 3D digital geological models (Culshaw 2005), fence diagrams and other products by the British Geological Survey, for use in a variety of applications.

Conclusions

The UK has seen a productive period in regional groundwater resource modelling over the last 10 years, and much progress has been made from a technical, regulatory and benefits realization point of view. Perhaps the main lesson from this process, looking forward to the future, has been that it is not just about the models themselves, or even the modellers, or even groundwater, but also about sharing understanding, and using the right tools to make the decisions in a timely way which benefit the environment.

It seems unlikely that the Environment Agency can repeat the extensive modelling programme of the last 10 years given current and future predicted resources. However, it has provided us with a sound foundation to help deliver the aims set out in the Environment Agency's new corporate strategy. Over the next 10 years there is likely to be greater emphasis on integrating groundwater modelling into wider catchment understanding and management and adopting more risk-based approaches. With the development of more user-friendly modelling platforms, the Environment Agency should be in a stronger position to capitalize on the investments of the past by making groundwater modelling tools and outputs more accessible to non-specialists, promote greater uptake in regulatory decision-making, and enhance stakeholder engagement.

The authors would like to acknowledge the generous support and guidance of many colleagues in the UK groundwater community over many years, and in particular the UK Groundwater Modellers' Forum for promoting the development of this volume.

Disclaimer

The views expressed in this paper are those of the authors, and do not necessarily represent those of the Environment Agency for England and Wales.

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