Modelling in Support of Environmental Regulation: Reflections after the Final Meeting

A GMDSI Monograph

Groundwater Modelling Decision Support Initiative

PUBLISHED BY

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CITATION

For bibliographic purposes this report may be cited as: GMDSI (2022). Modelling in Support of Environmental Regulation: Reflections after the Final Meeting. National Centre for Groundwater Research and Training, Flinders University, South Australia.

ISBN: *awaiting assignment*
DOI: *awaiting assignment*

Acknowledgements

We express our gratitude to all who attended the meeting that is the subject of this report. Particular thanks go to Peter Baker from the Office of Water Science who chaired the meeting. We also thank the meeting panellists, five of whom prepared short presentations that catalysed the ensuing discussion.

We are also grateful to Andriana Stoddart (Office of Water Science) who took prolific notes during the meeting.

Executive Summary

Executives, and others who are pressed for time, are directed to the introduction and conclusion of this document. These contain the contents of the executive summary that does not adorn this page.

Contents

1. Introduction

1.1 Background

On 18th August 2022, GMDSI hosted a web discussion. Its purpose was to garner industry and regulator perspectives on the way in which groundwater modelling is serving the Australian regulatory process. This event followed a suite of other GMDSI-hosted web meetings with state and federal regulatory personnel, and with the IESC. These meetings are reported in GMDSI (2022).

In contrast to previous meetings, attendance at the August 18 meeting was not restricted to regulatory personnel. A general invitation was issued through the NCGRT (National Centre for Groundwater Research and Training) mailing list. It was hoped that the meeting would provide a forum in which groundwater industry personnel could express their opinions on the way in which groundwater modelling is (or is not) serving the regulatory imperative. It also provided a forum for public comment on GMDSI (2022).

1.2 Attendance

Like the previous web meetings, the August 18 meeting was chaired by Peter Baker of Commonwealth Office of Water Science. The meeting began with Peter's introductory remarks. This was followed by five presentations, each of about three minutes duration, by the following personnel:

- Rod Dann: Director, Queensland North Assessments, Commonwealth Department of Climate Change, Energy, the Environment and Water.
- Brian Barnett: Senior Principal Groundwater Modeller and Geothermal Reservoir Engineer at Jacobs. Brian is the lead author of the Australian Groundwater Modelling Guidelines (Barnett et al, 2012).
- Catherine Moore: Principal Scientist Groundwater Modelling at GNS Science, New Zealand. Catherine is a co-author of GMDSI (2022).
- Blair Douglas: Global Practice Lead, Hydrogeology and Water Management, BHP.
- Joel Hall: Principal Environmental Modeller, Western Australia Department of Water and Environmental Regulation.

The panel for the discussion was comprised of all of the above, as well as the following (both of whom contributed to GMDSI, 2022):

- Craig Simmons: Distinguished Professor at Flinders University.
- John Doherty: Director, Watermark Numerical Computing.

The discussion format allowed meeting attendees to ask questions or make points by typing them into a dialogue box. The chair then sought responses from panel members. The meeting format also allowed attendees to make an oral contribution to the discussion on request. However, no attendees availed themselves of this opportunity.

The meeting lasted for about two hours. While 119 people registered for the event, a total of 96 people attended it for at least a short amount of time. (Some of this difference is attributable to multiple registrations from the same people. It is also possible that some of those who registered for the meeting, but did not attend it, expected to hear a recording of the event at a later date. However, the meeting was not recorded in order to remove all impediments to free discussion.) Simultaneous attendance peaked at 73; 61 people attended the event for more than 1 hour. Table 1.1 lists countries from which attendees joined the August 18 meeting.

Country	Number of attendees
Australia	73
USA	11
New Zealand	5
Chile	3
El Salvador	2
Canada	1
United Kingdom	1

Table 1.1. Countries from which attendees joined the August 18 meeting.

1.3 General Impressions

The meeting provided GMDSI personnel with an opportunity to hear from parties from whom they had not heard before. In doing so, it provided a forum in which industry, and those who consult to industry, could express their opinions on the role that groundwater modelling presently plays in the regulatory process, and on the role that they would like it to play.

Impressions from the meeting were mixed.

There was no shortage of goodwill. Both industry and regulatory personnel respect the need for environmental protection that regulation is intended to provide. All parties are willing to work together in order to achieve this goal. At the same time, all parties recognise that the regulatory process has room for improvement. This is not an outcome of regulatory or proponent failure. It is a consequence of the inexactness of environmental science on the one hand, and the emergence of new types of data, and means of processing these data, on the other hand. It is universally accepted that the regulatory process cannot remain static.

Another cause for sanguinity is that both sides of the regulatory fence possess a common understanding of the challenges that beset current regulatory practice. No issues were introduced in the August 18 meeting that had not been introduced in previous meetings with regulators and the IESC. However, it is recognised that the burden of these issues is carried differently by different participants in the regulatory process.

A less sanguine similarity between the August 18 meeting and previous GMDSI-hosted meetings is lack of a clear vision of where to go to from here. Multiple problems require attention. They include a need that is felt by both regulatory and industry personnel for assistance in understanding and learning new modelling and data assimilation technologies. They also include the perceived need to update the current intellectual framework on which the regulatory imperative is based in order to facilitate negotiation between parties that cohabit the complex scientific, political and social landscape that defines the modern regulatory context.

1.4 Purpose of This Document

This document reports on the web meeting of 18th August. Its format follows that of GMDSI (2022). A section is devoted to each of a number of themes that arose during the meeting. Comments from those who attended the meeting are first summarised; words are not attributed to any specific attendee in order to preserve anonymity. GMDSI's perspective on the theme follows this summary. In some cases, this perspective includes suggestions on how problems may be addressed.

Note that views expressed in this document are those of GMDSI. They may not reflect those of meeting panellists.

2. Model Complexity, the Scientific Method and Proponent/Regulator Interaction

2.1 From the Meeting

A number of statements that were made at the August 18 meeting addressed, either directly or obliquely, the issue of model complexity.

A related issue is the role of the "scientific method" in regulatory pursuits. Use of this expression by different speakers suggested different interpretations of its meaning. For some, a more complex model is, by definition, a more scientific model, as it attempts faithful replication of environmental processes that characterise a particular site. For others, implementation of the scientific method requires model-based assimilation of site data for the purpose of uncertainty quantification and reduction, a task that a complex, slow-running model performs with difficulty.

Regulators who attended the August 18 meeting were at pains to point out that they do not view construction of a complex model as a prerequisite for gaining project approval. However no consistent philosophy was presented that explains the relationship between scientifically-based decision-making on the one hand, and the benefits/drawbacks of different aspects of model design (including its structural complexity) on the other hand.

Another factor that regulators take into account when assessing appropriate model complexity is the scale of a proposed development. Proposals for extraction of small amounts of water can generally be accompanied by relatively simple models. The cost of modelling is therefore proportional to the cost of development, and to the environmental risks posed by development. However it is not clear whether a design requirement of a decision-support model should be that its predictions be purposely pessimistic in order to preclude underestimation of environmental risks and, if so, how this aspect of model design should be demonstrated to regulators.

It was apparent from the discussion that the word "model" carries different shades of meaning for different people. Furthermore, differences of opinion on the role of modelling in regulatory decision-making cross the proponent/regulator divide. For some, a "model" is a static, site-specific construct that provides numerical encapsulation of site knowledge. As such, it can be used to make a variety of decision-pertinent predictions. For others, the word "model" should be used as a verb rather than as a noun; it is a continuous activity that is focussed on the uninterrupted harvesting of decision-pertinent information from site data. Acquisition of new data (the need for which can be illuminated by appropriate modelling), and model-based processing of these data, should continue as long as site management is required.

A related question is that of regulator input into model design. Generally, state regulators encourage early discussions with proponents (especially of large-scale projects) in order to achieve consensus on the style and objectives of decision-support modelling. In contrast, federal regulators sometimes express frustration that their engagement with project proponents begins too late for them to contribute to discussions on model design.

2.2 GMDSI Perspective

GMDSI's perspective on decision-support modelling is summarized in its manifesto, and in publications that can be downloaded from its web site. See, in particular, Doherty and Moore

(2021) and Doherty (2022). Both of these documents (especially the former) address the subject of model complexity. They note that often (but not always) the decision-support potential of environmental modelling is best realised using models that are parametrically complex but structurally simple. However, they also note that large, slow-running models are sometimes of high didactic worth, as they can improve decision-maker and stakeholder understanding of the complex interplay of processes that prevail at a particular study site. They may yield insights that inspire new lines of scientific inquiry, thereby supporting the abductive dimension of the scientific method (Baker, 2017). They may also provide a basis for global sensitivity analysis that can enable construction of one or a number of smaller, prediction-specific models; see, for example, Saltelli et al (2004, 2008) and Morris (1991). However, Doherty and Moore (2021) also point out that the greater the level of detail that is represented in a model, the more it becomes necessary to represented this detail stochastically if it is to be used as a basis for site management. Unfortunately, structural complexity and stochasticity are incompatible.

Ideally, the primary role of scientifically-based, decision-support modelling is the harvesting of information from site data in support of exploration of site concepts and reduction of the uncertainties of decision-pertinent predictions of future site behaviour. This role can sometimes challenge the traditional Bayesian separation between prior uncertainty (encapsulated in a stochastic hydrogeological conceptual model) and posterior uncertainty (attained through history-match-constrained parameterisation of that model), for it is not uncommon for history-matching to expose deficiencies in the conceptual model on which a numerical model is based.

The process of continuous, cyclical learning that decision-support modelling should enshrine is schematised in Figure 2.1. This model-enabled learning process should focus on the garnering of information that facilitates decision-making. In doing so, it should attempt to expose mechanisms for site management failure, and to establish whether (or not) failure can be avoided through adoption of appropriate adaptive management protocols. Such “management failure” can be considered to be the hypothesis that model-based application of the scientific method tests when this method is applied in support of decision-making.

It is important to note that an indirect beneficial consequence of the ability of scientifically-based decision-support modelling to quantify and reduce uncertainties of failure-pertinent predictions is its capacity to identify data that can most effectively reduce these uncertainties. This is critical to successful adaptive management.

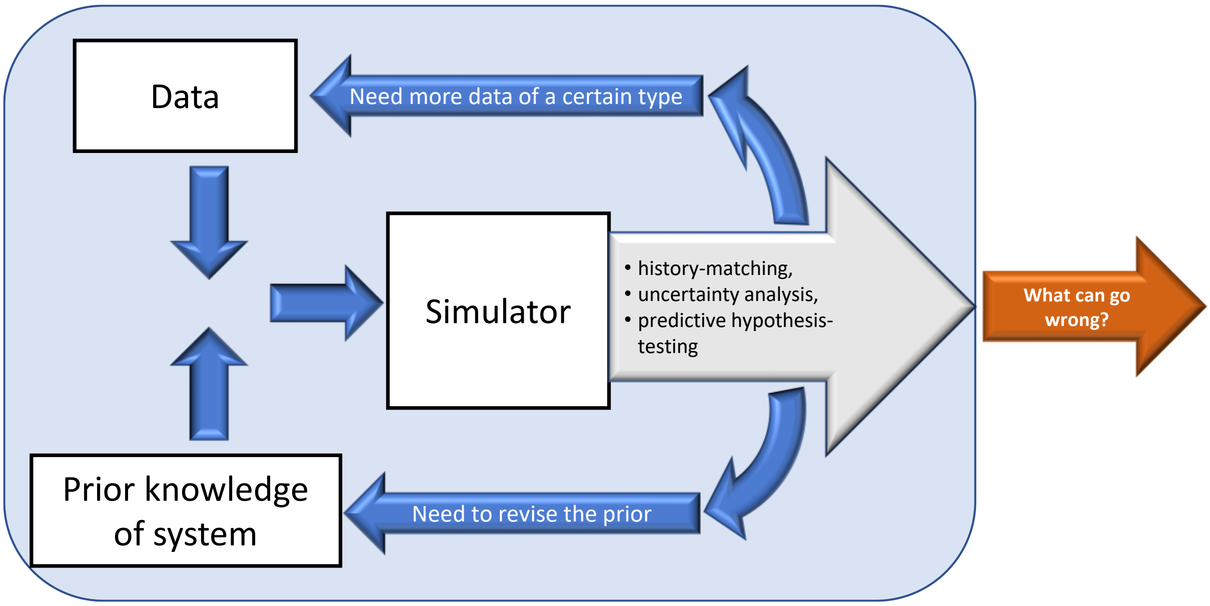

Figure 2.1. Decision-support modelling as a cyclical learning process.

The notion of decision-support modelling as a continuous activity, rooted in the scientific method, has many repercussions for proponent and regulator interaction. Science is an inherently communal activity undertaken by a group of people with appropriate expertise who place the search for truth above allegiance to a particular financial or ideological interest. The design of scientific experiments, and innovative ways to process data yielded by these experiments, benefits from insights and experience of participants from different backgrounds who carry different perspectives. Early discussions between proponents and regulators are an essential component of this process.

3. Uncertainty Analysis

3.1 From the Meeting

It is universally recognized that environmental regulation transpires in a context wherein the outcomes of management actions cannot be predicted with certainty. It was apparent from comments made at the August 18 meeting that proponents and regulators are still coming to terms with the repercussions of uncertainty on the practicalities of modelling, and on how acknowledgement of the pervasiveness of uncertainty should impact regulatory decision-making.

Where a proposed development may pose a threat to valuable environmental assets and/or to the rights of other water users, regulators in many jurisdictions require that proponent modelling be accompanied by analysis of predictive uncertainty. Less rigorous modelling, possibly without uncertainty analysis, is considered acceptable for proposals whose effects on groundwater systems are expected to be small. However, this should not entirely obviate considerations of uncertainty for, presumably, analyses of low-impact effects should still be conservative. Provision of a guarantee that this is the case implies an understanding of the principles of uncertainty analysis as they pertain to a specific site.

It was remarked at the August 18 meeting that it is in a proponent's interest to omit an analysis of predictive uncertainty unless this is specifically requested by a regulator. This avoids drawing an intensity of regulatory attention to an unwanted developmental outcome that is disproportionate to its probability of occurrence.

The practical problems of predictive uncertainty quantification are compounded by a general lack of industry familiarity with details of its theory and implementation. In some modelling contexts, ensemble methods comprise the only viable option; however, the industry as a whole is still learning how to apply these methods to groundwater problems. A meeting attendee commented that it is not uncommon for a small proportion of history-match-constrained parameter realisations that comprise an overall ensemble to induce pessimistic model predictions. This can have a profound effect on ensuing negotiations between proponents and regulators.

The lack of a groundwater modelling graphical user interface that supports development of flexible and comprehensive uncertainty analysis workflows was lamented. This echoes remarks made at previous meetings. Meanwhile, differences of opinion on what constitutes apposite uncertainty analysis are common. A consultant who attended the August 18 meeting reported frustration when what he perceived to be a discerning analysis of predictive uncertainty was rejected by regulators.

It was remarked that deployment of modern uncertainty analysis tools does not, on its own, guarantee the integrity of uncertainty analysis. Decision-support modelling must be accompanied by application of common sense. In some circumstances the latter may yield deeper insights into the possibly of environmental damage than inappropriate and misunderstood use of complex technologies.

3.2 GMDSI Perspective

The implications of some attendee statements are as important as the statements themselves. Most agree that uncertainty analysis is a nice thing to do. But many would ask whether it can be believed. After all, environmental science in general, and groundwater science in particular, are inexact. It follows that numerical simulation of groundwater systems can only be illustrative. This does not erode its ability to sharpen decision-maker intuition. However, it can be argued that a groundwater model does not provide a solid platform on which to build an even more complex numerical edifice that is tasked with quantitative evaluation of predictive uncertainty. Scepticism surrounding the outcomes of uncertainty analysis grows when the tools which enable it are used by those who lack the education and experience to do so.

Appraisal of the uncertainties of predictions made by a groundwater model is itself accompanied by uncertainty. Few would argue that the assertion of a 5% probability of occurrence of environmental damage means anything other than a low probability of its occurrence. It is natural to ask, therefore, that if this is the best that can be done, then is "quantitative" uncertainty analysis worth the trouble?

It seems that while the need to explore the integrity of decision-critical predictions made by a groundwater model is generally accepted, the place that formal uncertainty analysis should occupy in the regulatory framework is shrouded in mist. Industry proficiency is a problem. Ideally, this can be addressed through education and experience. However, clearing of the mist requires firstly that the role of modelling in regulatory support be properly understood; an understanding of the role that uncertainty analysis should play can follow that.

Figure 3.1 provides a pictorial representation of decision-support modelling as it is traditionally conducted for regulatory support. First a study area is defined. This is an area in which development is proposed. Following site characterisation and conceptual model development, a numerical model is constructed. The latter simulates processes within the study area that are pertinent to management of that area's groundwater. In doing so, it provides decision-makers and stakeholders with a (moving) pictorial representation of the system. The model is calibrated against measurements of historical system behaviour; according to the traditional view, this ensures that its predictions of future system behaviour are not too wayward. Until recently, these steps alone were sufficient for model-based decision support. At the centre of this support is the "calibrated model".

Theory and experience have demonstrated that, depending on the calibration dataset, history-matching can reduce the uncertainties of some predictions but not of others. A model's ability to predict future system behaviour under conditions that are very different from those which prevailed in the past may be limited. Hence, as is illustrated in Figure 3.1, uncertainty analysis is now accepted as an important component of the regulatory decision-support workflow. This "blurs" the picture of future system behaviour that a calibrated model provides. Acknowledgement of this picture's fuzziness is fundamental to the decision-making process.

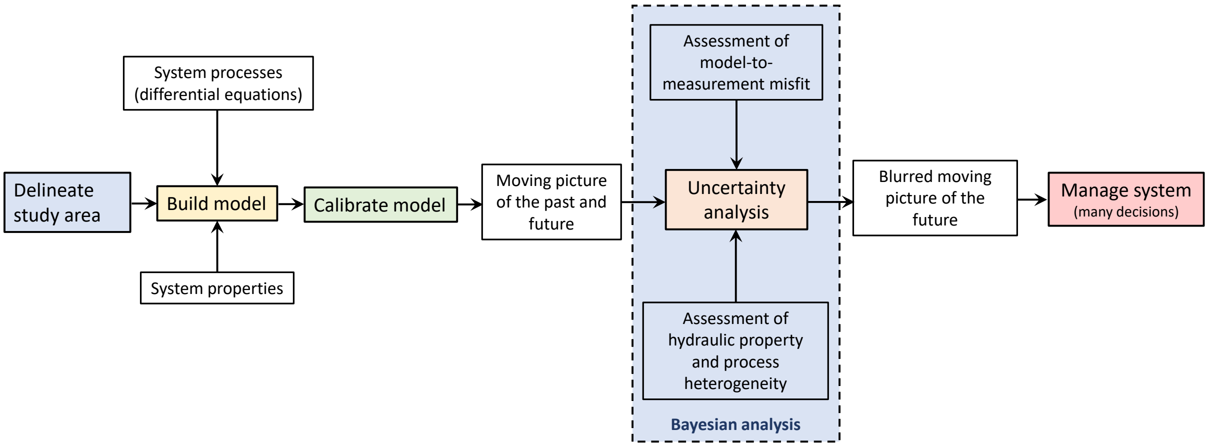

Figure 3.1. Traditional view of model-based decision-support.

While the workflow that is illustrated in Figure 3.1 is an improvement over previous workflows that omitted uncertainty analysis, it does little to clear the prevailing intellectual mist. The reason for this lies in the ordering of its steps. This ordering requires that uncertainty analysis be seen as an afterthought to conceptual and numerical model development. Furthermore, because uncertainty analysis was not required in the past, it is not unnatural to consider it as an optional extra, given the expertise that is required to understand it, and the numerical difficulties that are sometimes encountered when implementing it. Additionally, because history-matching takes place in isolation from conceptual and numerical model development, and is often based on a structurally complex (and therefore rigid) model, site data is endowed with a muted voice. The process is therefore open to confirmation bias; it is not compatible with a scientific state of mind that is marked by perpetual scepticism and a relentless desire to acquire new knowledge.

An alternative schematised workflow is depicted in Figure 3.2. This workflow is based on the premise that model-based support for the decision-making process increases in proportion to its ability to illuminate the risk of management failure. Risk is discussed in the next section of this document. In this section, we note that assessment of risk requires assessment of the likelihood of occurrence of one or more unwanted impacts. While it may not be possible (or even required) that a figure such as "5%" be associated with their occurrence, decision-makers and stakeholders must be provided with a strong basis for intuitive assessment of their likelihood.

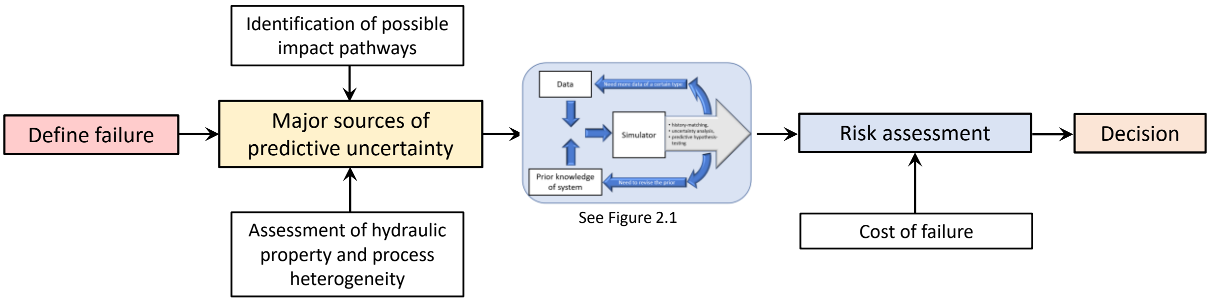

Figure 3.2. Alternative view of the decision-support modelling process.

An important difference between Figures 3.2 and 3.1 is the place that is occupied by numerical simulation. "The model" that is central to the workflow of Figure 3.2 occupies part of a data-processing loop (see also Figure 2.1); activities that also comprise this loop may require the services of software packages such as PEST and PEST++. Implementation of this workflow may also require the deployment of more than one model, each tuned to the making of a specific risk-pertinent prediction. Alternatively, the workflow of Figure 3.2 may not require use of a simulator at all. Numerical simulation is superfluous if other data assimilation and processing methodologies can provide risk-pertinent forecasts whose uncertainties can be tested. The workflow of Figure 3.2 exists for processing of risk-informative data. Simulation is required to the extent that it serves this purpose.

The uncertainty-focussed workflow of Figure 3.2 can accommodate simple models as well as complex models. However, to avoid invalidation of risk assessment, a simple model must be deployed in such a way as to guarantee over-estimation, rather than under-estimation, of predictive uncertainty. In some circumstances this may inflate the assessment of risk. However, where a low-cost, purposefully conservative model can demonstrate that risks are small, the risk analysis process is well served.

Implications of adoption of the workflow of Figure 3.2 over that of Figure 3.1 go well beyond those of workflow implementation details. The mindset behind the workflow of Figure 3.2 is equally important. Consider, for example, the issue with ensemble methods that was raised earlier in this section. As stated, it is not uncommon for a small proportion of parameter realisations that comprise a history-matched ensemble to induce uncomfortable model predictions. However, because of the way in which ensemble methods work, it is also not uncommon for these same realisations to yield model outputs which do not replicate some critical aspects of historical system behaviour very well. If this is the case, then these realisations should be identified and removed from the ensemble. Alternatively, if they do enable a model to provide good replication of an historical measurement dataset, then they have identified one or a number of impact pathways that can instigate management failure. In doing this, they may suggest strategies for acquisition of further data that may resolve the failure issue. In either case, parameter realisations that result in pessimistic model predictions are worthy of considerable attention.

There are circumstances where ensemble methods may not comprise the most appropriate numerical tool for exploration of management failure. Reasons for this include the following.

- Use of ensemble methods is often based on simplistic representations of spatial heterogeneity. They may therefore suppress stochastic expressions of connected hydraulic conductivity that comprise realistic impact pathways.
- On most occasions of their use, the number of realisations that comprise an ensemble is limited to only a few hundred. The temptation to use a limited number of realisations is high where models are complex and run slowly. This number may limit exploration of some important failure mechanisms.

Modelling that is undertaken with risk analysis as its primary objective may therefore sometimes benefit from deployment of methodologies such as direct predictive hypothesis testing that are tuned to the exploration of specific failure mechanisms. This methodology places few constraints on history-match-emergent patterns of hydraulic property heterogeneity that can induce management failure. It is up to decision-makers to decide whether a particular failure-inducing disposition of heterogeneity is realistic.

Regardless of their specifics, workflows that are inspired by Figure 3.2 are likely to have greater decision-support alacrity than those that are inspired by Figure 3.1. At the same time, the intellectual framework that motivates the workflow of Figure 3.2 is likely to prove more effective in clearing the conceptual mist that presently shrouds discussions of regulatory model usage than that which motivates the workflow of Figure 3.1.

Appendix A provides an abbreviated list of uncertainty analysis technologies that can be used in conjunction with groundwater modelling to explore the range of possible management outcomes.

4. Risk and Society

4.1 From the Meeting

Closely related to the matter of uncertainty is that of risk.

Regulatory personnel who attended the August 18 meeting acknowledged that environmental risks associated with the proposals that cross their desks are rarely zero. However, they do not see a complete absence of risk as a necessary pre-condition for project approval, as this would be both unrealistic and unfair. What is important to them is that risks be identified, and that they be shown to be manageable.

While definition of risk is context-specific, it is generally accepted that risk increases with the likelihood of occurrence of an unwanted developmental outcome, and with the cost of that outcome. Presumably, model-based processing of environmental data can illuminate the former ingredient of risk, at least to some extent. Quantification of the other ingredient of risk can also be difficult. The cost to society of environmental damage can rarely be measured in dollars. Furthermore, it is not a regulator's job to determine this cost (even if their decision-making must take it into account), for appraisal and protection of society's values is the role of government. Evaluation of the cost of damage is complicated by the fact that development-incurred environmental impairment is often continuous rather than categorical; that is, it is a matter of degree rather than being absolute.

In spite of the problems that beset evaluation of risk, and in spite of expectations that proposal adjudication be based on risk, regulators are given little guidance on risk-based decision-making. Some comments that were made at the August 18 meeting reveal that this leaves both regulators and project proponents in an uncomfortable position. Regulators remarked that the possible adverse consequences of a proposed development are never far from their minds. However, they face difficulties in balancing these consequences against proponent-supplied assurances that they are unlikely to eventuate, or that the possibility of their occurrence can be diminished through adaptive management. Problems in joint exploration of risk are compounded by the fact that (as was mentioned in a previous section) proponents are sometimes loath to draw a regulator's attention to adverse consequences of a proposed development lest the ensuing discussion elevates the perception of their likelihood.

4.2 GMDSI Perspective

Regulator and proponent frustrations in dealing with the matter of risk are easy to understand. Indeed, given the difficulties associated with environmental risk evaluation, these frustrations may be a defining characteristic of the regulatory process. However, this should not obstruct the search for an intellectual framework that can facilitate accommodation of risk in a way that is satisfactory to industry, regulators and society at large.

Improving a situation requires that the situation first be understood. An understanding of the regulatory process requires an understanding not just of environmental systems on which its attention is focussed, and of simulation and data assimilation technologies that can be used to investigate these systems. It also requires an understanding of the societal context in which environmental regulation must operate, and of the manner in which society acquires its values, for it is these values that underpin the perceived cost of environmental damage, and hence the evaluation of developmental risks.

Society learns what it values when it anticipates what it may lose. It is science, orchestrated by the regulatory process, that can inform it of this. Hence while the regulatory process must express society's values, society is simultaneously informed by the issues that it raises, and by the knowledge that it reveals. Hence the regulatory process does not exist in isolation from the political and cultural processes that it serves. At the same time, the scientific activities which it oversees allow a society to discover its own values, and judge its appetite for risk.

Like natural systems, society is heterogeneous. Risks that are acceptable to some, are unacceptable to others. These and other conflicts are resolved through the political institutions that society establishes for this purpose. As threats to environmental well-being mount, environmental regulation becomes an increasing source of social tension, and an increasing focus of political attention.

Figure 4.1 attempts to depict the context in which regulatory decision-support modelling must operate, with particular emphasis on the fluidity of this context. It depicts two cycles. The inner cycle has already been discussed; see Figure 2.1. Ideally, it is defined by an approach to regulatory-support modelling that is based on the scientific method and is energised by the scientific spirit. This sustains a continuous cycle of data acquisition and processing that is enabled by modern-day simulation and partnered software. This inner cycle is devoted to exploration of mechanisms of possible management failure, and to identification of data acquisition strategies that can reduce the uncertainties of failure-pertinent predictions.

An inquiry into unwanted consequences of a proposed development may reveal possibilities that society finds uncomfortable. In the debates that follow, individuals and groups become better acquainted with their own values as they contemplate the balance between industrial activity on the one hand and environmental protection on the other hand. As science uncovers the workings of a natural system, it simultaneously teaches society about itself as it exposes issues that demand cultural and political resolution.

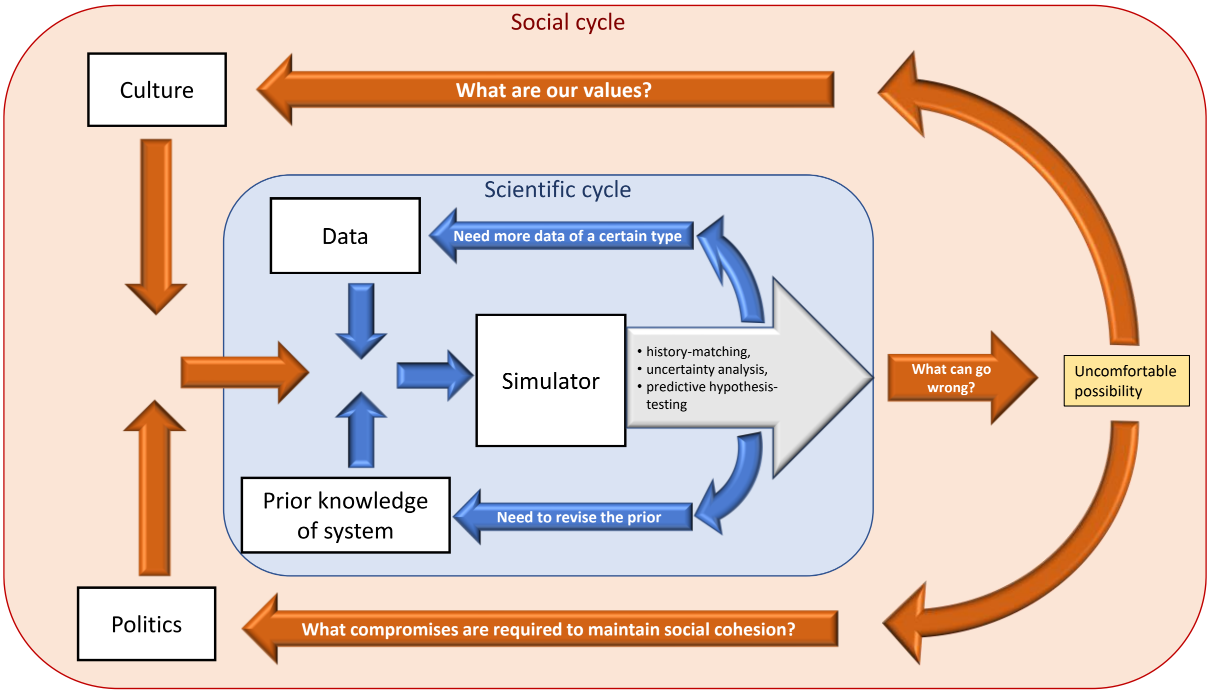

Figure 4.1. The regulatory context.

Science, and the scientific mindset, is central to the inner cycle of Figure 4.1, and hence to the outer cycle. As scientists, regulators and project proponents are therefore charged with a duty to act as societal role models. This duty is discharged through an unwavering commitment to acquiring new skills, through eschewing the temptations of confirmation bias, and through dedication to the dispassionate pursuit of truth with studied indifference to what this pursuit may reveal. The cohesion of society, the outer cycle of Figure 4.1, depends on this.

The above considerations suggest that scientifically-based, risk-informed, regulatory decision-making may require that regulatory and proponent personnel engage with the broader scientific community on the one hand, and with the general community on the other hand, to a greater extent than they presently do. While this may run the risk of slowing the decision-making process, it may also render this process more satisfactory from both a scientific and societal perspective.

Some suggestions of how such engagement may be achieved follow. These are also discussed in GMDSI (2022).

Proponent modellers and regulatory personnel require access to advice from experienced scientific personnel who are familiar with the type of model-based data-processing that is schematised in Figures 4.1 and 2.1. (The need for proponent and regulator education has been a recurrent theme of GMDSI-sponsored meetings.) Personnel who can provide such advice are employed by both industry and government. Involvement by a scientific third party in a regulatory process may catalyse the development of a small but energised "scientific community" that applies the scientific method to a specific environmental issue. This is likely to provide a more fruitful context for disinterested scientific inquiry than that which relies on proponent modelling on the one hand, and regulatory assessment of proponent modelling on the other hand. It is also likely to induce greater public confidence in the regulatory process.

At the same time, the regulatory imperative would be well served by a set of government-endorsed guidelines that emphasise the centrality of the scientific method and the scientific mindset to the performance of all players. This is further discussed in Section 7 of this document.

The inner and outer circles of Figure 4.1 meet where the risks posed by development are exposed. This is the point at which attempts should be made to prevent public discourse from becoming polarised along traditional societal fault lines by activists on both sides of an environmental debate that draw little inspiration from the scientific method. Transparency of the regulatory process, and a perception by society of an unwavering commitment to continuous, disinterested inquiry by qualified scientific personnel, would do much to inspire societal confidence in the inner circle of Figure 4.1.

At the same time, those who have the power to do so, should impress upon society that risk is omnipresent, that some risks are not worth taking but that others can be managed. Trade-offs are the cost of progress. These may be required at an individual site; alternatively, development at one site may be traded off against that at another. Ultimately it is politicians who must make these decisions. The language that they use to inform the public of how they make these decisions should honour the firm scientific base on which these decisions should rest, at the same time as it recognises the ubiquity of uncertainty that forms the context of scientific inquiry.

5. Cumulative Impact Assessment

5.1 From the Meeting

As in most previous meetings, the issue of cumulative impact assessment was raised at the meeting of 18th August. One attendee sought current ideas on best practice. Other attendees noted the importance of shared data, and obstacles to data-sharing posed by commercial confidentiality. It was also noted that it is unfair to ask an individual proponent to provide estimates of cumulative proponent impact.

5.2 GMDSI Perspective

Best practice for cumulative impact assessment is context-specific. Experiences of the Queensland Office of Groundwater Impact Assessment (OGIA) are worthy of study by other jurisdictions. These experiences demonstrate that access to data, and a good relationship with both industry and the public, are essential. These relationships are fostered by an aura of technical competence supported by a culture of disinterested pursuit of scientific truth.

The notion of "cumulative impact" suggests a study area that is larger than that required for assessment of any individual impact. We note that this does not imply that regulatory oversight should require construction of a single, large, complex model that represents the details of all existing and proposed mining and extraction activities within that area. A tiered modelling approach, involving simulation at multiple scales, may provide better prognoses of impact.

The primary contributor to local impact is generally local stress, the effects of which may be augmented by neighbouring stresses. Local, highly parameterised models may enable assimilation of local data, and stochastic exploration of local impact. Meanwhile, the boundary conditions of these models (and the uncertainties associated therewith) may be informed by a regional model that represents, in simplified form, other extractive activities. This regional model can assimilate data pertaining to regional stresses.

Documentation and sharing of experiences will suggest the most appropriate approach to cumulative impact assessment modelling at any particular location.

6. Feedback and Review

6.1 From the Meeting

An attendee of the August 18 meeting remarked that insufficient attention is paid to reviewing, and learning from, regulatory experiences to date, and from ways in which modelling did (or did not) serve the regulatory process. Of particular interest to the attendee is whether proponent model predictions of environmental impact have turned out to be reliable.

As has already been discussed, other attendees highlighted the need for close interaction between regulators and proponents. It was remarked that documentation of these interactions, and reflections on them, may provide a basis for improvements in the way in which the regulatory imperative is served in the future.

6.2 GMDSI Perspective

There is little doubt that well-documented reviews of the regulatory process, and of the role of modelling in that process, would benefit the environmental community.

In industries such as the airline industry where safety is paramount, workplace culture and protocols are under constant review. If mistakes are made, they are investigated. The purpose of these investigations is not reprisal (especially if mistakes were made while following accepted procedures). Rather, it is to ensure that mistakes are not repeated.

Environmental science does not lend itself to definition of workplace protocols that, if meticulously followed at every site, ensure quality outcomes. As has already been discussed, model-based processing of environmental data requires collegiate and innovative implementation of the scientific method by those who are committed to this method. Nevertheless, while every site is different, much can be learned from experiences at other sites. This is especially the case if these experiences are reviewed by personnel who are familiar with the latest decision-support modelling technology. Such a review may highlight how the decision-making process could have been improved with new technology, or by adoption of a mindset that is more amenable to innovative use of that technology.

Items to which a review of this type may draw attention include the following:

- Whether risks that accompanied a proposed development were defined early in the proposal process;
- Whether and how regulators responded to inadequacies in proponent modelling;
- Whether regulators insisted on a style of modelling that was not well tuned to exploration of risk, and/or whether they rejected reasonable arguments put forward by proponents that an alternative modelling philosophy may better serve collegiate scientific inquiry;
- Whether both parties would have benefitted from assistance provided by a disinterested third party;
- Whether enough attention was paid to the specifics of how adaptive management would reduce risks to environmental assets, should approval be granted;
- Whether the outcomes of the regulatory process were conveyed to stakeholder groups, and the community at large, in ways that induce confidence in that process;
- Whether guidelines provided to proponent modellers and regulators aided or abetted negotiations between these groups.

7. Guidelines and Guidance

7.1 From the Meeting

As has been stated, the need for practical guidance in understanding and implementing new technologies was mentioned a number of times at the August 18 meeting. This need is intensified by the perplexing array of options that are available for implementing uncertainty analysis, not all of which are supported by popular groundwater modelling graphical user interfaces. Other options, such as PEST-support utility programs, or the PyEMU library, present modellers with steep learning curves.

Other remarks suggested that guidance is needed at a deeper level than simply in selection and use of modelling tools of trade. A philosophical reference point is needed for resolving differences of opinion on issues such as appropriate model complexity, the manner in which history-matching and uncertainty analysis are conducted, and how to tread the path that leads from analysis of risk to the making of decisions.

It has been apparent in all GMDSI-hosted meetings that industry and government are united in seeking a regulatory framework that is fair to proponents, while affording protection to environmental and cultural assets that society values. At the same time, there appears to be a general feeling that the regulatory process has room for improvement. This feeling will never disappear, for technologies and values are constantly changing. Nevertheless, views that were aired at most meetings reveal a commonality of opinion that recent changes in both of these have been large enough to warrant some modifications to the current regulatory framework and to the culture that sustains it. However there seems to be little idea of how these changes will happen.

7.2 GMDSI Perspective

The need for progress in the way that environmental science is conducted, and is then used to support negotiations that balance economic activity against environmental protection, is ever-present. The emergence of new data acquisition and processing technologies, and a heightened community awareness that improvements to living standards are empty if the environmental cost of these improvements is too high, have raised its exigence.

A philosophical framework is required that can serve as a point of reference for technology-based assessment of environmental risks posed by extractive industries, and for negotiations that emerge from assessment of these risks. This point of reference can only be the scientific method, implemented through a disinterested pursuit of truth through rigorous analysis of environmental data. Together, these can enable inquiries into risks that development poses, and exploration of strategies through which these risks can be managed or ameliorated. At the same time, perception by society of a regulatory framework that promotes and sustains a culture of scientific inquiry will do much to elevate the trust that it places in that framework.

It is apparent from discussions that emerged in GMDSI-hosted meetings that both regulators and proponents would like to move in this direction. It is also apparent that a clear exposé of the philosophical framework that should guide this movement is missing. Such an exposé should attempt to explain the scientific method in ways that the general community can understand. It should suggest ways in which this method can best support the regulatory imperative, given currently available technology and software. It should also note how commitment to the scientific method can foster a community of scientific inquiry that serves society’s values while maintaining its cohesion (see Figure 4.1). Lastly, it should suggest ways in which the scientific community can interact with the wider community, to the mutual benefit of both.

Appendix B of this report presents a possible outline for such an over-arching reference document.

As was discussed in GMDSI (2022), this regulation-focussed reference document should not be confused with educational resources that should be developed and updated on a regular basis. The purpose of this educational material should be to assist regulators and proponents in understanding and implementing current technologies. The latter will change as technology changes; hence these resources should be viewed as didactic aids rather than as reference points for regulatory culture.

8. Conclusions

This document comprises a brief report on statements made, and opinions aired, during a web meeting that occurred on 18th August, 2022. This meeting was the last of a series of GMDSI-sponsored discussions that focussed primarily on the role that numerical simulation plays in the regulatory process, but also examined related topics such as the nature of regulator-proponent interaction, and links between risk analysis and decision-making. Previous meetings are reported in GMDSI (2022). In contrast to previous meetings, the August 18 meeting was open. Hence attendees included personnel from both industry and government.

Issues that were raised at the August 18 meeting had much in common with those that were raised during previous meetings. Those that received most attention are reflected in the section-headers of this document.

If there was any difference in emphasis between the August 18 meeting and those which preceded it, it was in its exploration of the links between analysis of uncertainty and evaluation of risk on the one hand, and the making of decisions on the other hand. The role of the scientific method in design of a modelling strategy that supports these activities was also discussed. The focus on these topics is partly attributable to the attention that they received in GMDSI (2022), and to the fact that attendees were invited to comment on this document. It also reflects the presence at the August 18 meeting of project proponents and their consultants. These are heavily invested in a regulatory process that must apply an inexact science to balance the benefits of economic activity against the need to protect the environment.

Most attendees at most meetings acknowledged that execution of the regulatory imperative must move with the times. Furthermore, there appeared to be a general acceptance that the time is ripe for some changes. This acceptance follows recent advances in simulation and data assimilation technology. It recognises that these advances can provide a stable platform for transparent, scientifically-based, collaborative decision-making that can earn the respect not just of government and industry, but of society at large.

It is GMDSI's opinion that progress of this type requires development and documentation of a philosophical/intellectual framework that can serve as a reference for model usage in the regulatory context. This should comprise the contents of a discussion document that, in time, may serve as a government-sanctioned regulatory guidelines document. Suggestions for some of the contents of this document appear in Appendix B.

9. References

Barnett, B., Townley, L.R., Post, V., Evans, R.E., Hunt, R.J., Peeters, L., Richardson, S., Werner, A.D., Knapton, A. and Boronkay, A. (2012). Australian Groundwater Modelling Guidelines, Waterlines Report, National Water Commission, Canberra.

Doherty, J. (2022). The Decision-Support Modelling Workflow. A GMDSI Monograph. National Centre for Groundwater Research and Training, Flinders University, South Australia.

Doherty, J. and Moore C. (2021). Decision Support Modelling Viewed through the Lens of Model Complexity. A GMDSI Monograph. National Centre for Groundwater Research and Training, Flinders University, South Australia.

GMDSI (2022). Discussions with Regulators and GMDSI Reflections. National Centre for Groundwater Research and Training, Flinders University, South Australia.

Morris, M.D. (1991). Factorial sampling plans for preliminary computational experiments. Technometrics, 33 (2), 161–174.

Saltelli, A., Tarantola, S., Campolongo, F., and Ratto, M. (2004). Sensitivity Analysis in Practice - A Guide to Assessing Scientific Models. John Wiley & Sons Ltd., 219p.

Saltelli, A., Ratto, M., Andres, T., Campolongo, F., Cariboni, J., Gatelli, D. Saisana, M., and Tarantola, S. (2008). Global Sensitivity Analysis - The Primer. John Wiley & Sons Ltd., 292p.

Appendix A. Modelling and Decision-Making

This short appendix briefly explores the relationship between environmental modelling and decision-making. Of necessity, this exploration is general, for decision-making culture varies greatly between institutions. Modelling should adapt to this culture.

It is universally accepted that a groundwater model cannot provide "the right answer" as far as the environmental future is concerned. However, if properly designed and deployed, it can be used to define the range in which the right answer lies, without overstating this range. It can therefore provide invaluable inputs to a decision-making process that is based on assessment of risk.

Risk can be loosely defined as the cost of something going wrong times the probability of something going wrong. The more costly are the consequences of an unwanted decision outcome, the more important it is that decision-makers associate realistic probabilities with this outcome. It is equally important that these probabilities not be over-stated, as this may incur the unnecessary preclusion of an otherwise beneficial management plan.

It follows that the effort that is devoted to model-based exploration of predictive possibilities, and to containment of these possibilities through assimilation of pertinent data, should increase with the cost of unwanted management outcomes.

The technology through which environmental modelling can explore the uncertainties of decision-critical predictions while limiting these uncertainties to realistic values, is undergoing continual improvement. A simplified hierarchy of methods is presented in Figure A.1. These are listed in order of increasing cost, and in order of increasing reliability of their outcomes.

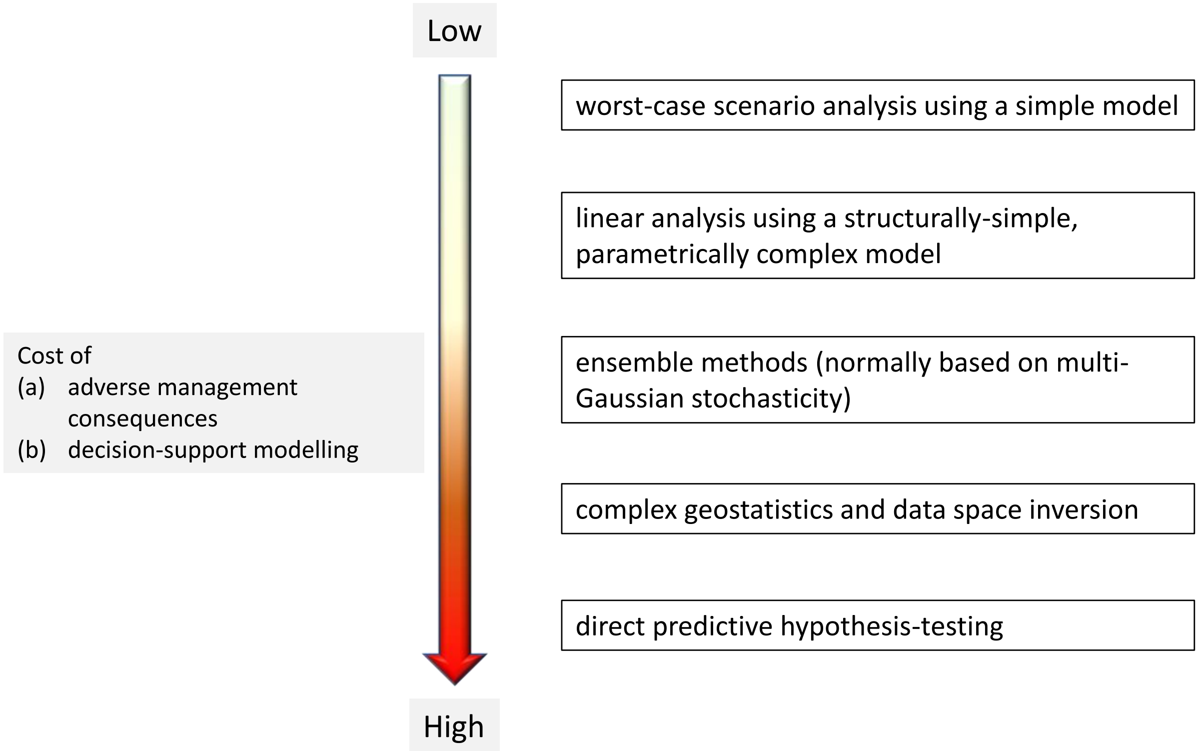

Figure A.1. Methods of model-based uncertainty analysis, ordered according to cost of implementation.

Many nuances apply to Figure A.1. There are many modelling circumstances where attention should be paid to the imperfect nature of environmental simulation. This may require development of a stochastic error model whose outputs are superimposed on those of a numerical model. Variables that govern the operation of this stochastic error model may or may not be informed by model-to-measurement misfits revealed through history matching.

Other circumstances may require the development of multiple numerical models based on multiple hydrogeological conceptual models. The cost of implementing this decision-support modelling strategy rises with the level of hydrogeological and numerical model complexity. Furthermore, care must be taken to ensure that the design and parameterisation of alternative numerical models does not preclude exposure of the most pessimistic management outcomes that are compatible with each conceptual model.

Appendix B. Regulation and the Scientific Method

It is suggested in this report that the groundwater industry would benefit from production of a document that describes modern perceptions of the scientific method, and proposes ways in which this method can enable execution of the regulatory imperative in ways to which government, industry and stakeholder groups can commit. This appendix suggests, in note form, the possible contents of a document which government may consider for adoption as part of its continuing efforts to modernise the regulatory framework.

Part 1: Setting the Context

Chapter 1: Introduction

- The need for the present document.
- Why the scientific method:
    - a universally-accepted common ground that exists outside of sectional interests;
    - agnostic in the values that it serves;
    - encourages development of a community approach to decision-making that is enabled by a central core of experts who are engaged in a disinterested search for truth.
- Difference between this document and other guideline documents:
    - attempts to provide an intellectual framework to underpin application of the scientific method in the regulatory context;
    - provides a reference point for environmental decision-making, particularly as this applies to definition and appraisal of risk;
    - provides only limited discussion on the principles and practice of any particular scientific tool (such as numerical simulation); these comprise the contents of complementary educational texts.

Chapter 2: Overview of the Scientific Method

- *Induction* and Bayesian methods;
- *Deduction* and hypothesis-testing;
- *Abduction* and the creation of fertile ground for “lightbulb moments”;
- Relationship between the scientific method and decision-making; unwanted outcomes as scientific hypotheses;
- The inexact nature of environmental science, the importance of abduction and the value of information;
- Scientific virtue;
- Science as a community-building activity.

Chapter 3: Some Examples of Groundwater Model Usage in the Regulatory Framework

- Impacts of water extraction;
- Impacts of agricultural contamination;
- Aquifer contamination by industrial chemicals;
- Commonalities:
    - uncertainties in system stresses;
    - uncertainties in system processes (physical and chemical);
    - uncertainties in the hydraulic properties of the media through which groundwater and contaminants move;
    - heterogeneities and discontinuities in subsurface structure;
    - availability of data through which some of these uncertainties can be reduced;

    - the need to make costly decisions in the face of remaining uncertainty.

Chapter 4: Quick Overview of Groundwater Modelling

This short chapter is not meant to be a textbook. It is required for context-setting only.

- The partial differential equations that govern groundwater and contaminant movement, and what they mean;
- Simple solutions (analytical);
- Complex solutions (numerical);
- Hydraulic properties and upscaling;
- Why a model's parameters comprise distorted representations of true system hydraulic properties;
- The conceptual model on which a groundwater model rests;
- Competing conceptual models;
- The siren of model complexity and whether it lives up to its promises;

Chapter 5: History Matching and Uncertainty Analysis

This short chapter is not meant to be a textbook. It is required for context-setting only.

- Inverse problems, ill-posedness and nonuniqueness;
- Calibration, regularisation and the cost of uniqueness;
- Spatial correlation and some other geostatistical concepts;
- Bayesian history-matching;
- Other types of uncertainty analysis.

Part 2: Scientifically-Based Environmental Regulation

Chapter 6: Decisions, Hypotheses and Numerical Simulation

- The hypothesis that is implied in making a decision:
    - hypotheses that characterise the regulatory imperative;
    - identification of modes of management failure;
    - the need to define hypotheses before modelling begins;
    - hypothesis rejection criteria - demonstrable incompatibility with how a system operates, the hydraulic properties of the system, and/or the historical behaviour of the system.
- Modelling, uncertainty analysis and hypothesis-testing:
    - model outputs: never right, quantifiably wrong (in theory);
    - decision-support modelling as harvesting of information;
    - challenging the prior;
    - uncertainties in uncertainty quantification;
    - repercussions for risk assessment;
    - hypotheses that characterise adaptive management.
- Questioning common assumptions:
    - modelling metrics: definitions of failure and utility;
    - what model complexity can and cannot achieve;
    - parameter compensatory behaviour - is this always a bad thing?
    - the need for strategic abstraction in model design;
    - benefits of structural simplicity and parametric complexity.
- Decomposing the problem:
    - the importance of experimental design;
    - identifying sources of information;
    - harvesting information from data;
    - flow of information from data to predictions;

    - can one model serve all purposes?
- Modelling failure and regulatory failure:
    - underestimation of risk;
    - the onus of proof;
    - regulatory supervision of scientifically-based hypothesis-testing.

Chapter 7: The Relationship Between Regulators and Proponents

- Early discussions:
    - identification of risks;
    - formulation of hypotheses – for approval and adaptive management;
    - strategies for handling conceptual model uncertainty;
    - conceptualisation of prior probabilities;
    - agreement on experimental design (for model-based data assimilation);
    - public expectations of modelling and how these will be handled.
- On-going discussions:
    - provisional model results;
    - revision of the conceptual model;
    - early indications of data inadequacy;
    - changes to modelling strategy if excessive run times and numerical instability compromise data assimilation and uncertainty assessment;
    - negotiating alterations to modelling strategy.
- Approval:
    - outcomes of hypotheses-testing;
    - assessment of risk and negotiations associated therewith;
    - deciding whether risks can be managed – either now or contingent on acquisition of further data;
    - definition and testing of hypotheses on which adaptive management may rest;
    - plans for continued data acquisition and processing.
- Compliance:
    - system re-conceptualisation as it experiences new stresses;
    - re-assessment of risks following model-based processing of monitoring data.

Chapter 9: Relationship between Regulators and the Public

- Communicating science:
    - the scientific method;
    - the scientific community and its importance to scientific inquiry;
    - the role of simulation and data assimilation;
    - the pervasiveness of uncertainty;
    - itemisation of hypotheses, and criteria for their rejection.
- Living with risk:
    - the link between uncertainty and risk;
    - communicating risk;
    - distinguishing between manageable risk and unmanageable risk;
    - the need for transparency;
    - regular updating of risk assessment as development proceeds.
- Modelling and the general public:
    - didactic modelling;
    - modelling as hypothesis-testing, and why this is different from didactic modelling;
    - discussion of modelling results and what they mean;
    - the logical path from model outputs to decisions;
    - adaptive management - continuous model-based risk re-assessment.

Chapter 10: Regulator Responsibilities

- Regulator job statement:
  - supervising implementation of the scientific method;
  - definition of regulatory failure;
  - the importance of science communication.
- Informed subjectivity – its importance and pitfalls;
- Dispute resolution;
- Knowing when to seek help;
- Continuing education;
- Resources.

Appendix: Checklists

Implementation of the scientific method, especially as it is applied to an inexact science, cannot be formulaic. Nevertheless, the need for regulators to "tick boxes" is recognised. This protects them from criticism, at the same time as it provides a basic level of quality assurance.

Checklists that pertain to implementation of the scientific method in the regulatory context are provided. They are grouped into sections, some of which are itemized below:

- Problem definition and decomposition;
- Design of a modelling strategy;
- History-matching (if undertaken);
- Assessment of uncertainties;
- Management of risks;
- Communication of risk;
- Responsibilities to proponents and the general public.

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