Discussions with Regulators and GMDSI Reflections

A GMDSI Monograph

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Groundwater Modelling
Decision Support Initiative

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Acknowledgements

The series of meetings that are reported herein would not have been possible without the enthusiastic participation of nearly 80 Commonwealth, state and territory regulators, water planners and members of the IESC.

We are deeply grateful to all of them for having given us their time, and for having provided us with valuable insights into the many problems that they face in carrying out complex and important tasks on society’s behalf.

We also thank Peter Baker and Christina Fawns, both from the Office of Water Science. Peter chaired all of the meetings, while Christina provided invaluable organisational and secretarial support.

Executive Summary

This report documents discussions between GMDSI personnel on the one hand, and regulators from all Australian states, the Commonwealth government and the Northern Territory on the other hand. Discussions were also held with the Independent Scientific Expert Committee on Coal Seam Gas and Large Coal Mining Development (IESC). These meetings took place during late 2021 and early 2022; engagement was by video conferencing.

The meetings provided a forum for regulatory and related personnel to voice some of the problems that they face in reviewing environmental impact reports submitted by proponents of projects which range in size from very small to very large. Of particular interest to GMDSI personnel were regulator experiences in assessing the integrity of groundwater modelling work that is undertaken to support applications for project approval, and maintenance of compliance with project approval conditions. The utility of current guideline documents in assisting regulators to assess proponent modelling work was also of interest to GMDSI.

This document reports the outcomes of these discussions under fourteen themes. Most of the themes were raised at most of the meetings. Viewpoints on some of these themes differed between different personnel, and between different jurisdictions. Near-unanimous agreement prevailed for other themes. A section of this document is devoted to each of them. In each of these sections, we first relate experiences and points of view that were expressed at the meetings. We then provide our own reflections on these subjects. The report concludes with a summary of these reflections. These include suggestions for development of a formal guidance document which enunciates a coherent intellectual framework, based on the scientific method, for appraisal of proponent applications and compliance. The reader is directed to the concluding section of this document if time does not permit the reading of the fifteen sections that precede it.

We note that a small number of meeting attendees were water planners rather than environmental regulators. Many of the issues which they raised coincide with those raised by regulatory personnel; hopefully they are dealt with adequately in this report. However, a few issues that are specific to water planning may receive less-than-adequate attention herein as the focus of this report is on groundwater model usage in environmental regulation.

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1. Introduction

1.1 Background

Between November 2021 and March 2022, GMDSI hosted a series of web meetings with state, territory and Commonwealth regulatory personnel; water planning and other personnel attended some of these meeting. A meeting was also held with the IESC. All of these meetings were chaired by Peter Baker of the Office of Water Science; Peter is also a member of the GMDSI steering committee. Representing GMDSI at these meetings were Catherine Moore, Craig Simmons and John Doherty, all of whom contributed to the writing of this document. Christina Fawns (from Office of Water Science) assisted with organisational and secretarial tasks.

Meeting dates are listed in Table 1.1. Also shown are the number of non-GMDSI personnel who attended each meeting. GMDSI deeply appreciates their attendance.

Jurisdiction	Date	Non-GMDSI attendees
Queensland	16/11/2021	18
Commonwealth	25/11/2021	10
South Australia	14/12/2021	8
IESC	15/12/2021	6
Western Australia	18/2/2022	8
Northern Territory	22/2/2022	7
New South Wales	24/2/2022	8
Tasmania	4/3/2022	7
Victoria	11/3/2022	5

Table 1.1. Meeting dates and attendance numbers.

1.2 Purpose of the Meetings

The purpose of these meetings was to allow GMDSI personnel to learn about the role that groundwater modelling plays in regulatory oversight and decision-making by listening to the experiences of those who are engaged in these activities on a day-to-day basis. Items of particular interest included the following:

- the nature and quality of groundwater modelling work that is commissioned by project proponents;
- the quality and decision-relevance of modelling work reporting;
- the relationship between groundwater modelling and biological/ecological risk assessment;
- the extent to which uncertainty analysis accompanies model-based prognoses of environmental impact;
- the adequacy of the modelling peer review process;
- assistance provided by the Australian Groundwater Modelling Guidelines and other government and IESC guidance documents;
- the need for improved regulator assistance through upgraded guidelines, educational material, and/or expert advice;

- how interactions between development proponents and regulatory personnel affect model design and deployment;
- the role of groundwater modelling in adaptive management, and regulatory oversight of the adaptive management process;
- the interplay between local and cumulative impact assessment;
- community expectations of groundwater modelling.

Unsurprisingly, perspectives on these and other issues vary between jurisdictions. This is partly an outcome of the different issues that modelling must address in different parts of the country. It also reflects regulator expertise, and the relationships between regulatory personnel and those who build groundwater models. In some jurisdictions, models are built solely by project proponents; these models are then assessed by regulatory personnel. In other jurisdictions, a regulatory body may commission consultants to build one or a number of models which regulatory personnel then run as a basis for approval assessment. In still other cases, groundwater models are built by a government department with whom a regulatory agency has a close relationship.

1.3 Purpose of this Document

This document reports on discussions that took place during this series of meetings.

We recognise that a report such as this cannot reflect all comments made by all attendees of all meetings. It therefore runs the risk of omitting some important points of view. We apologise for any such omissions. We also apologise if some concerns that were expressed at some meetings are misrepresented herein. Meeting discussions were not recorded in order to remove obstacles to candid conversation. Discussions were often passionate and free-flowing. For this we are grateful.

The structure of this report reflects issues that were raised repeatedly throughout our meetings, and that therefore appear to be common to most jurisdictions. It is hoped that identification of these issues, and presentation of viewpoints pertaining to these issues, can assist in addressing them. A separate section of this document is devoted to each issue. We recognise that many issues overlap. Nevertheless we hope that our attempts to categorise them can facilitate their discussion. In some cases, the discussion of one issue provides a framework for discussion of another issue which is addressed later in the document. It is best, therefore, that sections of this document be read in order.

Each section of this document is divided into two subsections. The first subsection echoes points raised by regulatory personnel. The second subsection contains GMDSI comments and reflections on these points.

1.4 GMDSI Risks

GMDSI comments are technical in nature. This reflects the expertise of the authors.

Notwithstanding our attendance at the series of meetings that are the focus of this report, the authors admit that their knowledge of day-to-day problems that beset regulators remains limited. We have learned much from these meetings. However the meetings were short; our education is therefore incomplete.

We ask that our comments be seen for what we have intended them to be. That is, they are perspectives provided by scientists on a field of endeavour that spans many scientific disciplines, and that has governmental, bureaucratic and social dimensions of which we are only vaguely aware. In commenting on issues from a scientific perspective, we are commenting from the only perspective that we have. We readily acknowledge that this is not the only perspective that exists. We further acknowledge that amelioration of some of the difficulties that regulators face requires more than enunciation of scientific principles.

It is our belief that clear definition and adoption of scientific principles as they apply to groundwater modelling should render the jobs of neither regulators nor proponents any more difficult than they already are. Nor should it lengthen the regulatory process, or render it more complex. In contrast, shared acceptance of a scientific basis for decision-support modelling should facilitate productive proponent-regulator negotiation on important matters such as model complexity. It can do this by making it clear that assessment of decision-support groundwater modelling should not be based on how complex a model is, or how “realistic” are its attempts to simulate subsurface processes. Rather, it should be based on whether modelling has correctly exposed the risks that accompany a proposed development, and on whether modelling-based claims that these risks can be managed are credible. With the goal of decision-support modelling clearly defined, modelling itself, as well as discussions that are associated with modelling, can often be simpler, less stressful, and more productive than they are today.

We ask our readers to forgive us if they perceive that our reflections are inadequate, or fail to address some important issues. We do not have all the answers. We are grateful to have had the opportunity to listen to those whose jobs are important and demanding. Reflections expressed herein continue the conversation that began with the meetings.

1.5 GMDSI Responsibilities

We have endeavoured to keep this document brief. This limits the discussion of any particular issue, and the number of issues that are discussed. We apologise if we have failed to address an issue that is seen by some as important.

In text that follows, we refrain from associating any point of view with any group of attendees in order to protect that group from misrepresentation. Hence comments and points of view are presented without identifying those who made the comments, or who hold the points of view.

We realise that in writing a report such as this, and by presenting a GMDSI viewpoint on each issue, we have effectively given ourselves the “last word” on each issue. We do not want attendees to view this as disempowering. Hence GMDSI invites comment. Comments can be made on the GMDSI web page which hosts this document; these will be public, and hence available for all to see.

2. The Relationship between Modelling and Data

2.1 From the Web Meetings

There are many circumstances in which approval for a proposed development can be adjudicated without reference to a groundwater model. This applies particularly to proposals to extract small amounts of groundwater at locations that are far removed from ecologically sensitive receptors. It may also apply to proposals pertaining to locations where data are lacking, so that the basis for construction of a groundwater model is seen as tenuous.

It was not uncommon for meeting attendees to remark that they sometimes find it difficult to differentiate those occasions where a model is required from those where it is not. The question "when is there sufficient data to build a model" was repeated at a number of meetings. Repetition of this question suggests a need for guidance.

While data insufficiency may justify model avoidance, some attendees remarked that project proponents may sometimes draw the opposite conclusion, for there are occasions when a proponent provides a model as a replacement for data. There are also occasions when a proponent endows a model with predictive powers that are not aligned with a regulator's intuitive appraisal of the information content of available data. On these occasions, it may be difficult for a regulator to articulate a deep-seated concern that the integrity of predictions made by the model are not as good as claimed by the proponent.

2.2 GMDSI Perspective

"Model" has a broad definition; any calculation undertaken on any platform (including the back of an envelope) can be regarded as a model. Granting of an approval requires at least some calculation. This calculation may not be complex. It may pertain to the areal extent of a cone of depression, or to the upper limit of long-term-averaged streamflow depletion. In the absence of data, assumptions must be made. These assumptions must be such as to over-estimate, rather than under-estimate risks posed to environmental assets by a proposed development.

Data may be scarce. But data are never entirely absent. Parameters that are employed in simplistic calculations generally embody some degree of site knowledge, even if this knowledge is only sufficient to guarantee that hydraulic properties that appear in these calculations are pessimistic from an impact perspective. By erring on the side of pessimism, the precautionary principle is followed. The risk of environmental damage is thereby minimised.

In reality, therefore, the question of data insufficiency pertains not to whether a model should be built; it pertains to the level of model complexity that is warranted. While this subject is addressed in the following section, we make some initial remarks on this topic in the present section.

Data contains information. Information reduces uncertainty. If no site-specific data have been collected, a hydrogeologist must rely on experience, or on the literature, to select hydraulic properties that guarantee predictive conservatism, and hence minimise environmental risk.

It is important to note, however, that lack of site data does not preclude construction of a complex numerical model. However, as for a simple model, the hydraulic properties with which a complex model is endowed should guarantee predictive conservatism. However it makes little sense to build a complex numerical model, only to parameterise it with worst-case hydraulic properties. It is far less expensive when erring on the side of caution, to endow a simple model with worst-case hydraulic properties, while ensuring at the same time that "worst case” accommodates any predictive error that model simplicity may incur. If the potential for predictive error that is incurred by model simplicity is significantly smaller than that which is incurred by the need for predictive conservatism, then the returns on building a complex model are not worth the cost of its construction.

Suppose, however, that there is just a little data available – say a few drillholes that support construction of a basic geological model, and a pumping test or two. Obviously, both the spatial disposition of geological units and the hydraulic properties of these units, are likely to be uncertain because of data scarcity. If a numerical model is built, and if it is not equipped with worst case hydraulic properties, then both the disposition of geological units, and the hydraulic properties that are ascribed to these units, should be represented stochastically. That is, a large number of models should be built, each expressing a different realisation of subsurface features and properties that are only vaguely known. Decision-critical predictions should then be made with all of these models so that their uncertainties can be evaluated. Furthermore, these predictions should be made enough times, based on enough stochastic realisations, to ensure that their uncertainties are not underestimated.

If:

- predictive uncertainty, calculated in this way, provides a less pessimistic appraisal of worst case conditions than that provided by a simple model which is equipped with worst-case parameters; and
- this more refined appraisal or predictive uncertainty allows granting of an approval that would otherwise be denied;

then construction of the complex model is worth the effort.

This example illustrates an important point. Model complexity, on its own, does not reduce the uncertainties of decision-critical predictions of future system behaviour. In common with predictions that are made in other ways, the uncertainties of predictions made by complex models are functions solely of data availability. A complex model can quantify the repercussions of data insufficiency better than a simple model because it can grant superior stochastic representation to aspects of a system that are only poorly known; the repercussions of data insufficiency can therefore be expressed as predictive uncertainty.

Implied in the question “how much data is needed to build a model” is the premise that once a certain data threshold is crossed, it is possible to build a numerical model that can make one or a number of decision-critical predictions with a reasonable level of accuracy (i.e. with a low level of uncertainty). The assertion of predictive accuracy rests on the notion that predictions made by a complex numerical model cannot be too much in error. This assertion is unfounded. So too is the notion that construction of a model can replace acquisition of data.

3. Appropriate Model Complexity

3.1 From the Web Meetings

This issue has many dimensions. In one form or another, it was raised during all meetings.

At most meetings it was opined by more than one attendee that the decision-support utility of a model increases with its complexity. The stated reason for this is that a complex model possesses greater predictive accuracy than a simple model.

Public notoriety of a project can influence modelling strategy acceptability. Meeting attendees remarked that where environmental risks and/or the possibility of adverse publicity are high, then only a complex model is acceptable. This may mollify criticisms from stakeholders or academics that something important has been omitted from the model, and that this omission impugns the model’s claim to simulation and predictive integrity (which are seen as the same thing). Support for arguments such as these can be found in the model confidence classification scheme that forms the centrepiece of the Australian Groundwater Modelling Guidelines (AGWMG - Barnett et al, 2012).

Some meeting attendees lamented the fact that many of the models that cross their desks are not complex enough. Perceived inadequacies include the following:

- insufficiently detailed representation of local stratigraphy;
- omission of the spatial and temporal details of recharge processes;
- failure to simulate flows in rivers and creeks;
- failure to simulate water quality where its deterioration may impact ecosystem health.

Despite the general acceptance that complex models are better models, some attendees noted that the predictive credentials of some of the complex models that they assess, or use for their own regulatory decision-making, are impugned by the inability of these models to replicate the temporal and spatial details of past system water levels and flows. This is in spite of the fact that measurements of these quantities are included in their calibration datasets. Furthermore, rarely are predictions made by a complex model accompanied by analyses of their uncertainties. While this situation is slowly changing, some attendees raised doubts about the integrity of uncertainty limits that are awarded to predictions made by very complex models; doubts arise from the difficulty of calculating these limits.

Other attendees asserted that while complex models are sometimes difficult to history-match, and while their predictions are sometimes difficult to subject to uncertainty analysis, they are nevertheless the decision-support tool of choice in contexts where hydrogeological knowledge is good. They claimed that the simulation integrity of any model suffers less from its inability to replicate the nuances of past system behaviour than from lack of respect for known or assumed hydrogeology. This is especially the case if a groundwater system will be subjected to stresses in the future which are significantly different from those which prevailed in the past.

Some attendees suggested that the issue of model complexity is multi-facetted. They suggested that there may be occasions where regulatory decision-making is best served by a number of models rather than by a single model. Each model should be dedicated to a specific predictive task; its performance should be optimised for that task.

All attendees recognised that the cost of complex model construction is high, and that it is unfair to insist that all project proponents construct a complex model. This is especially the case where the environmental footprint of a proposed development is low. In cases such as this, a simple analytical model may be sufficient for demonstration of environmental security.

For most attendees, the issue of appropriate model complexity is fraught with difficulties. Many expressed the need for guidance beyond that which is offered by the AGWMG model classification scheme.

3.2 GMDSI Perspective

The issue of appropriate model complexity is extensively discussed by Doherty and Moore (2021). This manuscript can be downloaded from the GMDSI web site. We provide a brief summary of its conclusions herein.

Assessment of the benefits and drawbacks of any decision-support modelling strategy requires prior definition of the metrics against which they should be assessed.

Fundamental to delineation of decision-support modelling metrics is acceptance of the notion that any prediction that is made by any groundwater model is accompanied by uncertainty. The magnitude of this uncertainty is set by availability of data, or lack thereof. Simulation, combined with data assimilation (implemented through use of a model in concert with software packages such as PEST/PEST++) can reduce the uncertainties of decision-critical predictions of system behaviour, but only to the extent that the information content of available data allows it.

Freeze et al (1990) assert that it is incumbent on the decision-support modelling process to calculate the uncertainties of model predictions on which decisions depend so that the risks associated with contemplated courses of management action can be assessed. Model-quantified uncertainties are themselves uncertain. Nevertheless, a decision-maker has the right to expect that “the right answer” is bracketed by model-calculated uncertainty limits, for this will forestall unpleasant surprises once a decision is made and groundwater management is altered. Alternatively, if a simple model explores only the pessimistic end of a predictive probability distribution, it is incumbent on the modelling process to guarantee that the model-calculated worst case is worse than that which will occur in reality once system management is altered.

According to Doherty and Simmons (2013), decision-support modelling fails when a model-calculated uncertainty interval is too narrow; environmental risks are therefore understated. On the other hand, usefulness of the decision-support modelling process is eroded if this process does not reduce uncertainty limits of a decision-critical prediction to the extent that available data allows, if this reduced uncertainty can alter a decision.

It follows that if a model is simple, it must be designed to overstate uncertainty, possibly by exploring overly pessimistic worst-case scenarios. Any surplus uncertainty must be sufficient to accommodate predictive bias that may be accrued through model simplicity, or through use of heuristic rather than model-calculated uncertainty limits.

Conceptually, a complex model does not need to include the possibility of simplicity-induced predictive bias in the predictive uncertainty intervals which it calculates. At the same time, because it can offer stochastic representation to system property and geometry details, it possesses a superior ability to quantify uncertainty. It follows that a complex model (in theory) possesses the ability to calculate reliable predictive uncertainty intervals; they do not therefore need to be the outcomes of a purposefully pessimistic guess. Meanwhile, through the imposition of history-matching constraints on the values of its parameters, the uncertainties of predictions made by a complex model can be reduced through data assimilation. A complex model can therefore quantify the repercussions of data insufficiency at the same time as it reaps the benefits of data availability. The narrower predictive uncertainty intervals that emerge from use of a complex model may permit decision choices that would otherwise be precluded by use of a simple model that guarantees predictive conservatism. As a by-product of its ability to support uncertainty analysis, a complex model can also suggest data acquisition strategies that can most effectively reduce the uncertainties of some of its key predictions.

However, the situation is more nuanced than this.

Firstly, there are some practical issues that cannot be avoided. Structurally complex models often take a long time to run, and are often numerically unstable. This makes quantification and reduction of uncertainty difficult. Decision-support modelling based on a complex model may not therefore be capable of satisfying the decision-support modelling metrics that are outlined above.

There are also some conceptual matters that require attention. Doherty and Moore (2021) distinguish structural complexity from parametric complexity. They argue that in many (but not all) cases, a structurally simple, but parametrically complex model can satisfy the decision-support modelling metrics that are outlined above. A decision-support modelling strategy that is based on this type of model can efficiently harvest information from measurements of system behaviour and transmit this information to predictions that matter. If properly designed, it can also quantify posterior predictive uncertainty with integrity. The ability to harvest information from the historical behaviour of a system reduces the chances of unwanted surprises arising in future management of that same system.

Doherty and Moore (2021) also argue that the decision-support imperatives outlined above may be best served if design of a decision-support model is tuned to the making of one or a small number of predictions. White et al (2014) show that strategic model construction and innovative history-matching based on an appropriately weighted, multi-component objective function, can reduce the propensity for model-incurred and calibration-induced predictive bias.

It is apparent, therefore, that the issue of appropriate model complexity requires consideration of more than just the complexity of an environmental system. It requires consideration of data availability and the capacity (or lack of capacity) of these data to inform decision-salient predictions. It requires recognition of the fact that the task of the decision-support modelling process is to harvest information from the former and transmit it to the latter, while still allowing the latter to "wiggle" to the extent that they are not constrained by this information. It also requires recognition of the practical difficulties that a complex model faces in achieving these goals. Included in these difficulties is the inconvenient fact that attempts to create a "realistic" digital representation of complex subsurface conditions probably requires the hardwiring into a model's structure of system details of which a modeller is unsure. This makes stochastic representation of these details impossible. The risk of understating predictive uncertainty, or of biasing important model predictions, then rises.

In summary:

- The spectrum of model complexity is a continuum that extends from back-of-the-envelope calculations to complex numerical simulation.
- At no point on this spectrum is a model capable of providing more accurate predictions just because it is complex. Predictive accuracy is a function of information availability.
- A suitable response to the question, "how complex should a model be?" is as follows. If the making of a decision requires less predictive uncertainty than has currently been assigned to management-salient predictions, and if site data holds more information than has been harvested by models that have currently been built, then a more complex model may be required. However this model must be capable of harvesting

that information, and of quantifying post-data-assimilation uncertainty without understating it.

Finally, the authors recognise that, as well as being technically nuanced, the issue of model complexity is socially nuanced. Decision stakeholders who are not familiar with groundwater modelling often interpret the word “model” literally. Instead of viewing the decision-support modelling process as an information-harvesting activity that can reduce the uncertainties of decision-salient predictions, they may see a groundwater model as a digital entity that can replicate the details of unseen subsurface processes. For stakeholders such as these, simulation can play an important didactic role, for it can provide a powerful, animated illustration of how groundwater moves in complex geological environments. However the decision-support imperative and the didactic imperative are two different things. A model must be built for one reason or the other; rarely can it serve both purposes.

We defer consideration of community expectations of groundwater modelling to a later section.

4. Conceptualisation

4.1 From the Web Meetings

The issue of hydrogeological conceptualisation is related to that of model complexity.

A common remark, particularly from meeting attendees with hydrogeological backgrounds, is that proponent models do not always respect hydrogeological concepts to the extent that they should. Instead, they provide a simplified representation of local geology that diminishes the impact that some geological entities may have on decision-critical model predictions.

Some attendees stated that one annoying consequence of depicting geological details in a simplified manner (for example, by replacing multiple stratigraphic layers by a single model layer) is that subsurface hydraulic properties must then be upscaled prior to representation in a model. The ability of field or laboratory measurements of lithological properties to inform model parameters is therefore diminished.

Similar statements were made about other aspects of model construction such as representation of recharge processes, and simulation of the interaction between ground and surface waters. Government hydrogeological staff are often much more familiar with the details of local conditions and processes than are consultants who build models for project proponents. Sometimes they may wish to see these details represented in any model on which project approval and/or compliance rests, even if some of these details may be of secondary importance to decision-critical predictions which the model is required to make.

Some attendees confessed to becoming particularly irritated if a proponent uses software such as PEST/PEST++ to history-match a numerical model that they see as conceptually flawed. They maintained that attainment of a good fit between model outputs and a calibration dataset for the wrong reasons can exacerbate predictive bias incurred through simplistic representation of hydrogeological detail.

It was stated by some meeting attendees that rectification of this problem requires that proponents and regulators agree on a hydrogeological conceptual model prior to construction of a numerical model. It also requires that they agree on an approach to numerical model development that respects this conceptual model at an agreed-upon level of spatial and temporal detail. It follows that regulators should have considerable involvement in the design and deployment of a model that will be used for approval and compliance purposes. This circumvents the possibility of regulator knowledge and experience being ignored.

4.2 GMDSI Perspective

There can be no doubt that:

- the integrity of a numerical model rests on the integrity of the conceptual model on which it is based;
- early discussions between proponents and regulators should comprise an essential component of the regulatory process. (This is discussed in a later section.)

Some remarks from the previous section of this document are salient to the present discussion. These pertain to the need for stochastic representation of that which is incompletely known. This applies particularly to representation of fine scale geological detail if, indeed, geology is represented at this level of detail in a groundwater model. Hardwiring of incorrect geological details in just a single realisation of these details may bias model predictions to the same extent as simplification of these details. At the same time it can degrade exploration of predictive uncertainty. Errors in representation of geological detail can also preclude attainment of a good fit between model outputs and measurements of historical system behaviour. This behaviour may expose the presence of prediction-pertinent subsurface conditions of which a hydrogeologist may have been previously unaware.

In contrast, strategic upscaling of local geology may enable parameters to do the “stochastic work” of uncertainty quantification and reduction. This comes at a cost, however. A looser relationship between parameters and geologically recognisable subsurface entities diminishes the extent to which field measurement of the latter’s properties can inform these parameters. This may inhibit flow of information from expert knowledge, through parameters, and ultimately to model predictions. On the other hand, history-matching can be more productive where a simplified model structure is populated with abstract parameters. This may enhance flow of information from measurements of system state through parameters to model predictions.

Obviously, decision-support model design requires a trade-off. Solution of the optimisation problem that is implied in this trade-off can only be site-specific. It requires that a modeller identify sources of information that are pertinent to decision-critical model predictions. The decision-support modelling process should then be designed to:

- harvest this information;
- express uncertainties that result from a deficit of information.

There is no “right” way to build a decision-support groundwater model. Compromises are always required. However, the decision-support modelling metrics of failure and utility that are discussed in the previous section of this document are universal. We can express the first of these metrics using a word that is borrowed from Bredehoeft (2005). “Surprises” must be avoided at all costs once approval is granted and development proceeds. History-matching that accompanies the decision-support modelling process must be attuned to early warnings of surprises; it should create fertile ground for “abductive learning” that may expose the need for conceptual model refinement (Baker, 2017).

5. Uncertainty

5.1 From the Web Meetings

All meeting attendees recognised that predictions made by groundwater models are uncertain. They also acknowledged the importance of quantifying the uncertainties of predictions on which regulatory approval and compliance decision-making are based.

However, knowledge of this subject among attendees varies greatly. As a cohort, regulators can find it hard to assess proponent attempts to quantify model predictive uncertainty. Where regulatory agencies undertake modelling themselves, they do not generally quantify predictive uncertainty; however they intend to do so in the future.

Implied in statements made by some meeting attendees is that model complexity, on its own, has the capacity to reduce the uncertainties of many management-salient predictions. This has been discussed in previous sections. Some attendees expressed a desire for the groundwater model classification scheme that is central to the Australian Groundwater Modelling Guidelines to provide a more detailed basis for linking a model's design to the credibility of its predictions. We note that while this request is understandable (especially where a complex model is mistrusted), it ignores the imperative for a model to be capable of quantifying the uncertainties of its own predictions.

Acknowledgement of the existence and importance of uncertainty leaves regulators in an uncomfortable position. Some attendees seemed to be more aware of the practical and conceptual implications of model predictive uncertainty than others.

Practical implications include the following.

- Where a simple model is used to predict the consequences of a proposed development, assignment of an uncertainty interval to its predictions is generally heuristic. Often this is done through worst case scenario analysis. In cases such as these, a regulator must be satisfied that "worst case" is, in fact, worst case. The onus of proof that this is the case is on the project proponent; the onus of seeking proof is on the regulator.
- Where a more complex model is employed to predict the consequences of development, uncertainty analysis becomes more sophisticated. Often it is implemented by generating a suite of calibration-constrained, stochastic parameter fields. A management-salient prediction is then made many times, each with a different one of these fields. The probability distribution of the prediction can then be assembled from its frequency distribution. Implementation of this process requires that:
    - the methodology and assumptions on which predictive uncertainty analysis rests be clearly outlined in a proponent's report;
    - the outcomes of this analyses be understood by regulatory personnel; and that
    - regulatory personnel are satisfied that predictive uncertainty is not understated.

As is discussed in a later section, these implications require that regulators possess technical skills that were not required by previous generations of regulators.

An important conceptual repercussion of the omnipresence of uncertainty, is that uncertainty analysis will often reveal that the risks to environmental assets posed by a proposed development are nonzero. Regulatory approval must therefore be based on acceptance of a certain level of risk, or on an assurance that risk can be reduced or eliminated through adaptive management. It is then incumbent on a proponent to prove to regulators that adaptive management can indeed achieve the level of risk-reduction that they require.

Many meeting attendees expressed the need for guidance in assessing risks posed to environmental assets, and in making decisions in contexts where risks are demonstrably nonzero.

5.2 GMDSI Perspective

Uncertainty is the “unifying principal” on which groundwater decision-making, and hence design of a decision-support modelling strategy, is based. As discussed in documents such as Freeze et al (1990), Doherty and Simmons (2013) and Doherty and Moore (2019), the quest for quantification and reduction of the uncertainties of decision-salient predictions influences the manner in which a model is built, parameterized, history-matched and deployed. In ways that have already been described, it provides a basis for selection of an appropriate level of model complexity.

The uncertainty that is ascribed to a particular model prediction is a function of data availability, and the capacity of the decision-support modelling process to harvest prediction-pertinent information from these data. Conceptually, while complex models cannot be guaranteed to make accurate predictions, they do possess the ability to associate uncertainties with their predictions. This is because they are designed to explicitly represent many of the individual components of a complex groundwater system. Because the relationships between model parameters and aspects of environmental reality that these parameters represent is more direct for a complex model than it is for a simple model, parameters pertaining to these components can be informed by expert knowledge and the outcomes of site characterisation studies. However rarely is information from these sources sufficient to endow model parameters with values that are known to be correct. Therefore their values must be expressed stochastically.

Another benefit of model complexity is that a complex model may be capable of harvesting more information from field measurements of system state through history-matching than can be harvested by a simple model. However this will occur only if:

- the parameterization complexity of the model matches its structural complexity;
- the model is fast-running and numerically stable;
- details of the subsurface that are imperfectly known are adjustable rather than fixed.

In practice, these three conditions are often violated by a complex model. A middle ground between inappropriate simplicity on the one hand, and cumbersome complexity on the other hand must therefore be sought. This is discussed in previous sections of this document, and in papers that are referenced above. The point that we make here is that model complexity should not be pursued as an end in itself. Simulation (whether based on a simple or complex model) provides a means to a greater end, this being quantification and reduction of the uncertainties of predictions that matter to a decision.

From the above it follows that, in order to assess a proponent’s modelling work, a regulator must understand sources of information, and how an appropriately designed modelling process can harvest information from these sources in order to reduce the uncertainties of decision-salient predictions. A regulator should also possess the knowledge to know when this has not occurred, and hence when a proponent’s claims to uncertainty reduction are not based on fact.

If regulators do not possess this knowledge, then they should at least know the uncomfortable questions that they should pose to a proponent when a model (either simple or complex) is presented to them. These questions should seek assurances that predictive uncertainty intervals are overstated rather than understated; hence regulators (and society) can be sure that no unpleasant surprises await them after project commencement. It is incumbent on a proponent to satisfy a regulator that this is the case; it is incumbent on a regulator to seek these assurances from a proponent.

If a regulator does not possess the knowledge to pursue these assurances through an appropriate line of questioning, and to assess the scientific merits of answers that a proponent provides, then they should possess sufficient knowledge to know when it is necessary to request assistance from someone who does. Should this occur, assistance should be made available.

Where the outcomes of model-based uncertainty analysis demonstrate that a proposed project is not risk-free, these same outcomes may provide the basis for design of an adaptive management scheme that reduces environmental risk. In particular, if model-based uncertainty analysis demonstrates that risks posed to certain environmental assets are nonzero, presumably it can also illustrate why this is the case. For example, it may expose the existence of possible impact pathways; in doing so, it may suggest ways through which propagation of drawdown and/or contamination along these pathways can be detected before environmental damage is incurred. It follows that if adaptive management is proposed as a means of ameliorating project risk, then regulators should ask proponents whether and how this will work based on their modelling to date. This matter is further discussed in the next section.

Requests by regulatory personnel for guidance in making and justifying their decisions to a sceptical public in the face of pervasive uncertainty are valid. Identification of an acceptable level of risk is an important ingredient of decision-making in the face of uncertainty. It should be acknowledged as an important component of the regulatory process.

6. Approval, Compliance and Adaptive Management

6.1 From the Web Meetings

At many meetings, attendees complained that regulatory resources that are devoted to the approval process eclipse those that are devoted to oversight of compliance. This is despite the fact that approval for large projects is often granted under an extensive set of conditions, extending over many years; compliance with these conditions requires monitoring.

It was further noted that compliance monitoring, particular when a project proceeds under a regime of adaptive management, may require higher levels of time and expertise than many regulatory personnel currently possess.

6.2 GMDSI Perspective

Planning for adaptive management requires:

- that failure of groundwater system management be defined and agreed upon by proponents and regulators;
- that a monitoring network, together with a system of thresholds, be established that provides early enough warning of incipient management failure for failure to be forestalled;
- identification of management actions that will be taken in response to the crossing of monitoring thresholds.

For example, “failure” at a particular site may be denoted as the occurrence of a specific drawdown under a particular groundwater-dependent ecosystem. Alternatively, it may be denoted as a specified number of successive days in which streamflow in a particular river is less than a certain threshold. Mechanisms for failure may include the existence of structural or alluvial features with high and connected hydraulic conductivity. At some sites, failure may follow less-than-expected wet season recharge.

If a project is to proceed under an adaptive management strategy, then it is incumbent on project proponents to convince regulatory personnel that implementation of this strategy reduces risks to environmental assets to an acceptably low level, taking all possible failure mechanisms into account. Modelling is generally required in order to explore the assertion that adaptive management can work at a particular site. It is also generally required to support adaptive management once development has commenced. Modelling for adaptive management may require a greater level of sophistication than modelling for project approval. Hydraulic property fields that are employed in adaptive management modelling must be:

- realistic from a hydrogeological point of view;
- pessimistic from a management point of view;
- allow model outputs to replicate present and past measured system behaviour;
- be regularly updated so that a model can replicate emerging system behaviour once project operations commence.

At the same time, adaptive management simulation must be “self-managed”. That is, the simulation process itself must monitor system states and fluxes as it calculates them, and then initiate pertinent management reactions once monitoring thresholds are crossed.

7. Baseline Data

7.1 From the Web Meetings

At most meetings, at least one attendee lamented the insufficiency of baseline data before initiation of many projects. Reasons for baseline data shortage include the following.

- A lengthy period of time is required for acquisition of data that characterise the natural behaviour of an environmental system over a number or climatic cycles. This time may far exceed that over which planning for a project has taken place.
- Acquisition of data is expensive. Proponents are often unwilling to invest in data acquisition until project approval has been granted.

The negative consequences of baseline data inadequacy are obvious. Without knowledge of system behaviour under a range of historical environmental conditions, it is difficult to separate future project impact from natural climate-induced system variability. This is especially the case in dry times when a groundwater system suffers most stress, and when arguments about the deleterious outcomes of development are generally most heated.

7.2 GMDSI Perspective

The issue of baseline data insufficiency has repercussions for modelling as well as for monitoring.

Baseline data records the response of an environmental system to natural variability of climate, and perhaps to persistent anthropogenic stresses. With a comprehensive baseline dataset, system behaviour at monitoring points is therefore somewhat predictable, provided conditions in the future are not too different from those that prevailed in the past. Predictions of future system behaviour can be made using a purpose-built model. Perhaps one such model can be developed for each monitoring point; see, for example, Peterson, and Fulton (2019) and Obergfell et al (2019). Once development proceeds, it should be possible to separate the baseline signal from the development signal at these monitoring points.

If baseline time series are short, models pertaining to monitoring points can still be built and history-matched. Signal separation can still be attempted once development proceeds. However uncertainties in attribution of a signal to different sources becomes higher under these circumstances, especially if baseline monitoring does not span periods of unusually wet and/or dry conditions.

The ability to separate development signals from background signals at monitoring points brings other benefits as well.

Some types of development have the potential to exert profound impacts on a groundwater system. This occurs when stresses to which a system will be subjected in the future will be very different from those that it has experienced in the past. Pre-development predictions of groundwater impact may therefore rely solely on assessments of hydraulic properties arising from site characterisation and expert knowledge. However, once development begins, its embryonic effects on the groundwater system can be measured. This may allow back-calculation of system hydraulic properties at the scale at which impact occurs. Impact predictions can then be revised. Separation of the impact signal from other signals is critical to this process.

Adaptive management also benefits from a rich baseline dataset. If time series of groundwater levels have not been gathered over a sufficiently large period of time at monitoring locations that are critical to adaptive management, then (as remarked above) separation of climatic signals from development signals becomes uncertain. The precautionary principle dictates that software which implements signal separation should then presume the worst as far as the development signal is concerned. This may trigger a premature adaptive management response. It follows that gathering of a comprehensive baseline dataset generally serves a proponent’s interest, as well as the public interest.

However, because of:

- the large timeframe over which baseline data should be acquired if they are to be effective (this timeframe often exceeds that over which there has been any intention to interfere with a natural groundwater system); and
- issues of land access and expense that may be associated with acquisition of baseline data;

early acquisition of baseline data at locations where development may one day occur is a matter that deserves serious consideration by appropriate authorities.

8. Cause and Effect

8.1 From the Web Meetings

Generally, regulatory assessment of a proposed development depends at least partially on the effect that it will have on groundwater-dependent ecosystems, including riverine ecosystems whose health depends on maintenance of flow and water quality during dry conditions.

The relationships between altered groundwater conditions at a point of ecological impact, and biotic/ecosystem health at that impact point are often difficult to quantify. This is particularly the case for ecosystems that are sustained by groundwater outflow. Nevertheless, protection of groundwater-dependent ecosystems requires knowledge of these relationships.

At many meetings, regulatory personnel expressed frustration that the linkage between conditions that are calculable by a groundwater model and the health of biota that require protection is unclear. Rarely do proponent reports translate predicted groundwater impact into biotic risk. This reflects inadequate knowledge about relationships between the two, and the high degree of uncertainty that accompanies these relationships, to the extent that they are known. Regulators are thus left in the invidious position of having to assess biotic risks themselves, or of having to rely on drawdown or water quality thresholds whose salience to biotic health are questionable.

The situation can be summarised as follows.

- Uncertainties that accompany groundwater model predictions are often very high.
- Proponent-calculated uncertainties pertaining to these predictions are not always credible.
- Relationships between groundwater model predictions and biotic health criteria often lack clear definition, and are also highly uncertain.

Regulator frustrations are easy to understand.

8.2 GMDSI Perspective

It is difficult to do anything other than to share regulator dismay on this issue.

It was suggested at one of our meetings that a partial solution to this problem may be the addition of biological health packages to groundwater models. This, it was stated, would allow seamless calculation of biotic risk by a calibrated groundwater model. However, we note that groundwater systems are affected much less by biotic conditions than biotic systems are affected by groundwater conditions; hence these calculations are more appropriately made by groundwater model postprocessors. These postprocessors can then be updated independently of groundwater simulation software.

Frustrations felt by regulators suggest a need for those with ecological/biological expertise to develop indices for biotic health that are based on numbers that can be readily calculated by a groundwater model. These indices can then be identified early in the proposal process as key modelling outcomes on which regulatory decision-making will be at least partly based.

Ideally, model outputs from which indicators of biotic health are evaluated should be calculable without incurring long model run times nor inducing numerical instability. They can therefore be subjected to optimisation under uncertainty using members of the PEST++ suite. They may then form a basis for design of an adaptive management strategy that minimises environmental risk, and that can be regularly updated as more data are acquired.

If would also benefit decision-making and adaptive management if biological health calculations are based on model outputs whose uncertainties are comparatively low. Biological health indicators that are calculated in this way may require inclusion of “safety-margins” to accommodate this situation. The size of these margins in comparison to the uncertainties of alternative biological health indicators that may be based on more uncertain model outputs implies an optimisation problem whose solution may be site specific.

Obviously, the development of model-compatible, but regulator-useable, biological health indicators is a matter for much-needed inter-disciplinary research.

9. Early Communication

9.1 From the Web Meetings

Most attendees at most meetings agreed that the regulatory process is best served if discussions between project proponents and regulators begin early in the proposal process. Early meetings between regulators and proponents may allow agreement to be reached on at least the following issues:

- the hydrogeological conceptual model;
- identification of environmental assets to which a proposed development may pose a risk;
- identification of key model outputs on which regulatory decisions will be based;
- field data in which decision-pertinent information may reside;
- design of a modelling strategy that can harvest this information;
- the means through which uncertainties arising from information insufficiency will be quantified.

Many state regulators informed us that discussions between them and project proponents generally begin early in the proposal process. This applies particularly to proponents of large projects whose budgets permit high-end modelling. It applies to a lesser extent to proponents of smaller projects. Nevertheless, early communication with all of these groups is generally encouraged. It benefits proponents because they can familiarize themselves with regulator expectations. At the same time, it gives regulators the opportunity to inform proponents of their expectations. (It is to be hoped, however, that both sides of these discussions are receptive to good ideas.)

In contrast to state regulators, Commonwealth regulators are more likely to complain that their interaction with project proponents commences too late in the approval process for them to have anything other than a reactive role.

Some attendees noted that interaction between regulatory and proponent institutions requires caution, as it may compromise the perception of regulator independence. They also noted that the ability of regulators to contribute to technical discussions requires a workable knowledgeable of site conditions on the one hand, and decision-support modelling on the other hand; regulators may therefore require assistance from pertinent experts when engaging in these discussions. This matter is addressed in the following section of this document.

9.2 GMDSI Perspective

Science is an innately collegiate activity that benefits from an exchange of ideas and a blending of experiences. It is underpinned by a philosophy that places scepticism at its centre and adopts logic as its language. Much has been written on the philosophy of science. Perhaps the best know exposé of the scientific method is the falsification viewpoint espoused by Karl Popper (Popper, 1963) in which the scientific method is described as one of proposing and testing hypotheses. A hypothesis can be rejected, but never entirely accepted, as an explanation for natural phenomena.

Identification of an environmental asset that may suffer damage as a consequence of a proposed development implies a hypothesis that damage will actually occur. The scientific method can then be directed to testing this hypothesis. Rejection of the hypothesis follows demonstrable incompatibility between it and one or more of the following:

- physical and chemical processes that are known to operate within an environmental system;
- hydraulic (and other) properties of the system;
- observed behaviour of the system.

Model-based processing of site data enables testing of environmental damage hypotheses. Under some circumstances it may enable rejection of a particular hypothesis, perhaps at a certain level of confidence. If it does not allow its unequivocal rejection, model-based processing of environmental data may demonstrate that the hypothesis can be rejected if certain adaptative management protocols are put in place.

Each site that comes under regulatory purview thus provides the context for a scientific experiment in which one or a number of environmental damage hypotheses are tested against available or yet-to-be-acquired data. The inexactness of groundwater science, and the complexities of natural systems, necessitates considerable innovation in formulation of hypothesis-testing strategies. Innovation is more likely to emerge from multi-party discussions than from dialogue between those who have a vested interest in the outcome of a scientific experiment.

In short, communication between proponent and regulatory personnel is necessary to implementation of the scientific method at a particular site. It is thus necessary to scientifically based government regulation.

We restrict further comment to the following two points.

1. As already stated, some attendees admit that, in order to maximise their contributions to the design of strategies that implement innovative, model-based processing of site data, they may require (and sometimes employ) specialist assistance.
2. Regulator-proponent communication should be based on the premise that both parties can benefit from this communication. Proponents have the opportunity to learn from regulator knowledge of local issues and local hydrogeology. At the same time, while regulators have a responsibility to “lay down the law”, it should not be forgotten that the laws of science and mathematics are not for any individual or party to lay down.

10.Regulator Expertise

10.1 From the Web Meetings

Modelling expertise varies greatly between individual regulators, and between state/territory/Commonwealth regulatory agencies. At most meetings, some attendees informed us that their training does not allow them to undertake modelling work themselves, nor understand the details of modelling work that is undertaken by others. However they are able to undertake, and fully understand, simpler calculations that accompany proposals whose environmental impact is likely to be small. They also understand the principles on which groundwater simulation rests.

Some regulatory personnel have many years of hydrogeological experience. This stands them in good stead when reviewing hydrogeological concepts on which proponent modelling is based. However this is not always matched by modelling experience. Furthermore, regulatory expertise in data assimilation and uncertainty analysis (both of which are key ingredients of decision-support modelling) is highly variable. (We note that the groundwater industry in general is depleted in personnel with knowledge and experience in data assimilation and uncertainty analysis.)

Despite this, regulators are often asked to appraise modelling work undertaken in support of large development projects, some of which may need to rely on adaptive management in order to proceed.

In at least one jurisdiction, regulatory personnel base decisions on their running of complex groundwater/surface water models that were built for them by consultants. They feel uncomfortable with the inability of these models to replicate some important aspects of past system behaviour. They do not understand the consequences of this for model predictions of future system behaviour. In other jurisdictions, government personnel build their own models. However, they feel that their efforts in decision-support model development and deployment would be well served by a better understanding of highly parameterised inversion and uncertainty analysis.

Most regulatory personnel can seek help from a third party if they need it. However it was not readily apparent that help is sought as a matter of course. Nor can it be guaranteed that those from whom help is available have the skills required to assess high-end modelling work and concomitant predictive uncertainty analysis.

Many attendees expressed a desire for educational material which explains the concepts of decision-support modelling, history-matching and uncertainty analysis “in simple terms”. While this may not furnish them with the skills required to undertake such work themselves, it will at least allow them to engage in conversations with proponent modellers, to ask the right questions, and to know when the answers to these questions are unsatisfactory.

10.2 GMDSI Perspective

Regulators are asked to adjudicate on matters that span many disciplines. Groundwater modelling (and associated activities such as data assimilation and uncertainty analysis) is just one of those disciplines.

Under ideal conditions, a regulator could gain some assurance that conclusions pertaining to environmental safety drawn from a proponent’s modelling work are credible because of the peer review process that generally accompanies such work. However, as will be discussed in another section, this is generally not the case. With very few exceptions, a proponent's model is always declared as "fit for purpose" by the proponent's handpicked peer reviewer. Despite this, a regulator's instincts often inform them that a proponent's assessment of environmental risk is inadequate; however they lack the confidence, or the knowledge, to say more than this.

As discussed in the previous section, most regulators feel that discussions with project proponents should begin early in the proposal process. This allows risks to be identified, and modelling goals to be established, before modelling begins. However, engagement in these discussions generally requires an even higher level of regulator expertise than that which is required for review of a proponent's modelling work.

Unfortunately, lack of regulator expertise cannot be rectified with guideline documents such as those provided by Barnett et al (2013) and Middlemis and Peeters (2018). These may allow a regulator to insist that certain modelling and uncertainty analysis protocols be adopted, while lacking a deep understanding of what these protocols mean. However they do not allow a regulator to judge whether these protocols have been correctly followed. Nor do they allow a regulator to be an active participant in discussions that ensure that model-based processing of site data meets the unique challenges that groundwater management poses at a particular site.

The role of guidelines is discussed in the following section of this document. At this point we note that provision of guidelines is accompanied by certain (but unavoidable) dangers. Guidelines cannot replace textbooks or other educational resources. Neither a regulator, a modeller, nor a stakeholder can consider that they are "educated" in the field of decision-support groundwater modelling just because they are familiar with the contents of a small number of guideline documents. These documents cannot, therefore, be seen as an "easy fix" for lack of expertise.

A greater danger is the notion that knowledge of an entire field of learning can be replaced by a checklist that, if followed, guarantees satisfactory execution of that expertise. We understand the difficulties of providing regulatory oversight of a highly technical and continuously advancing field of knowledge in which site-specific innovation is the key to success. However, in the end, nothing replaces expertise.

Our discussions with state regulators lead us to the conclusion that there is no shortage of local hydrogeological knowledge. However hydrogeological expertise does not necessarily equate to modelling expertise, especially if hydrogeological expertise insists that a model is not credible unless it furnishes a "geologically realistic" picture of the subsurface. As explained in a previous section, this may encumber a model's ability to replicate historical system behaviour at the same time as it makes uncertainty analysis extremely difficult. Well-intentioned regulator guidance may therefore inadvertently limit the ability of the modelling process to uncover hydrogeological surprises which may impact predictive uncertainty.

Limitations in regulator expertise do not comprise a problem that should necessarily be fully overcome. After all, regulators cannot be all things to all project proponents. Obviously, those regulators who lament their lack of modelling expertise should seek further education (if they are motivated to do so). However educational resources are difficult to find – especially for those who seek to understand the many nuances of modern-day, decision-support groundwater modelling but do not intend to undertake it themselves. This creates a strong case for federal and state governments, or bodies such as GMDSI, to develop the necessary training material. Other stakeholder groups would also benefit from the provision of such educational material.

Meanwhile, regulatory personnel should have the opportunity to seek advice and/or assistance if they need it. Help may be required:

- at an early stage of the approval process where risks are identified, and where modelling strategies are developed;
- intermittently during the approval process if data assimilation and uncertainty analysis expose issues which require a review of modelling strategy;
- at the project approval stage;
- in planning and oversight of adaptive management.

As well as modelling expertise, federal regulatory personnel note that they would sometimes benefit from the advice of someone with local knowledge of an area when their involvement in regulatory supervision is precipitated by the “water trigger”.

It is acknowledged that good modelling advice is hard to obtain. Furthermore, it cannot be expected that academia or CSIRO is the best place to seek such advice, as extensive experience in decision-support modelling is a prerequisite for advising others on its principles and applications. Perhaps consideration should be given to establishment of an informal group of advisors composed of individuals from government and industry that can be contacted by federal, state and territory regulatory agencies when high-end advice is required.

11.Guidelines and Checklists

11.1 From the Web Meetings

When asked about the extent to which attendees rely on the Australian Groundwater Modelling Guidelines (AGWMG – Barnett, 2013) to do their jobs, responses varied greatly.

Some attendees informed us that they seldom refer to the AGWMG, for they already possess the knowledge that they require to assess proponent modelling work. Others informed us that the AGWMG does not provide guidance in asking project proponents the questions that really matter. These questions do not necessarily pertain to the details of groundwater modelling; rather, they pertain to the repercussions of modelling for proposal assessment.

Other meeting attendees hold the AGWMG in high esteem. They see its precepts as aligned with their own. However, because their knowledge of groundwater modelling is sufficient for them to have strongly held opinions, their assessment of proponent modelling does not rely on advice provided by the AGWMG; rather the AGWMG provides official endorsement of what they already require from proponents.

Still other attendees voiced confusion. Implied in the AGWMG is that some models can be relied upon to make good predictions, particularly if they are complex. When presented with proponent models that are complex, but whose inability to replicate the past impugns their ability to predict the future, some attendees wondered if an expansion of the AGWMG model confidence classification scheme is warranted in order to accommodate situations such as these.

Referring to the AGWMG model confidence classification scheme, some attendees ruminated that it should be mandatory for some critical environmental protection issues to require construction of a class 3 model instead of a class 2 model. They note that by far the majority of models that cross their desks are class 2 models (and have been endorsed as such by proponent peer reviewers). Others wondered what implications for predictive uncertainty should be drawn from the fact that a model is of class 2. They can only conclude that the uncertainties associated with its predictions may be moderate, but probably not too high. They declared that making a decision on this basis is somewhat unsatisfactory.

Most attendees agreed that much has changed in the industry since writing of the AGWMG. Analysis of uncertainty is now on everyone's radar. In response to this, the IESC commissioned a guidance document to help modellers understand this issue; see Middlemis and Peeters (2018). When asked about whether they found this text useful, some attendees replied in the affirmative. However others noted that the link between this document and the AGWMG is not very clear.

Despite mixed reactions to existing guidelines, most attendees believe that, as regulators, the existence of guidelines is fundamental to their job. Implied in a set of groundwater modelling guidelines is that a proponent's modelling work should reach or exceed a certain standard. Many regulators do not have the expertise to understand the implications of this standard for model design, history-matching, deployment and uncertainty analysis, However the existence of this standard is more important than its details. It gives them the right to require quality, however "quality" is defined.

Likewise, many attendees see checklists that are provided in the AGWMG and IESC Information Guidelines (IESC, 2018) as fundamental to their assessment duties. While acknowledging that modelling to address complex environmental issues is more nuanced than a checklist can express, a proponent's respect for a checklist provides an assurance that their modelling has met at least some basic standards. Checklists provided by the AGWMG and IESC Information Guidelines save regulatory agencies from having to develop their own checklists. Meanwhile, checklists protect regulators from criticism that they approved a proponent's model despite the fact that it "does not tick all boxes". In summary, checklists provide a necessary (but not sufficient) condition for assurance of quality of proponent modelling.

11.2 GMDSI Perspective

The above discussion raises a number of important issues. They include the following:

- the need for guideline documents;
- the most useful contents of these documents;
- whether guideline documents such as AGWMG are serving current needs.

We discuss these issues in reverse order.

11.2.1 The Australian Groundwater Modelling Guidelines

A central theme of AGWMG is its model confidence classification scheme. This scheme awards a class of 1, 2 or 3 to a model in accordance with (among other things) care taken in its construction, its representation of local hydrogeology, and the quantity and quality of data that support its design. Modellers are required to endow their model with a classification level so that those who make decisions based on its outputs are aware of the credibility of these outputs. Peer reviewers are required to assess whether a proponent modeller is correct in assigning a particular class to their groundwater model.

Problems with the AGWMG model confidence classification scheme include the following.

- Confidence is not something that can be assigned to a model. It is something that can only be assigned to a prediction made by a model. It reflects availability of information as it pertains to that prediction. A model may possess moderate credibility in making one type of prediction, but mediocre credibility in making other types of prediction.
- Presumably, predictive confidence falls as predictive uncertainty rises. As is discussed extensively herein, a model should be capable of quantifying the uncertainties of any of its predictions that are used in support of decision-making. A decision-maker should not have to rely on a model's confidence level classification which yields only a qualitative, and prediction-agnostic, assessment of decision-salient predictive integrity.
- Even where a simple model is used for regulatory assessment, it is still incumbent on a modeller to acknowledge predictive uncertainty. This can be done by endowing a model with pessimistic parameters when using that model to explore risks associated with a proposed development. The modeller must then convince decision-makers that predictions made in this way are indeed worst case. This conforms with metrics for decision-support modelling that are described in Section 3 of this document and references cited therein.
- As is also discussed in Section 3 of this document, reduction of predictive uncertainty, and of predictive bias, is often best served when model construction and history-matching is tuned to the making of a specific prediction. The awarding of a confidence class to a prediction-specific model makes little sense.

The authors of the present document view decision-support modelling as simulator-based, environmental data processing. The manner in which environmental data is best processed is context-specific; it may also be prediction-specific. It comprises a continuous spectrum that varies from back-of-the-envelope calculations to construction of a complex environmental model. If the imperative to quantify predictive uncertainty is taken seriously, and if a modeller ensures that a prediction made by a simple model is accompanied by a safety margin that guarantees conservatism, then it follows that the principal benefit of model complexity is an ability to reduce the uncertainties of at least some decision-critical predictions. However this can be achieved only if:

- the model is numerically stable and can run reasonably fast;
- the model is used in conjunction with data assimilation software such as PEST and PEST++.

If these conditions are not met, predictive uncertainty becomes difficult to reduce and even more difficult to quantify when using a complex model. The risk of understating uncertainty therefore rises. This conclusion is at odds with the implication that is inherent in the AGWMG model classification scheme that simulation is somehow independent of, and superior to data processing, and that mathematically based relationships between data availability and predictive uncertainty do not apply when a prediction is made by a complex groundwater model.

11.2.2 Guideline Contents

As described in Section 9 of this document, implied in the regulatory imperative as it pertains to a particular development proposal is a hypothesis. This hypothesis is that the proposed development will precipitate environmental damage. In accordance with the Popperian falsification view of the scientific method, a proponent’s task is to demonstrate to regulators that this hypothesis can be rejected at a high level of confidence, possibly through adoption of an adaptive management regimen. A proponent attempts to do this by processing all available site data. These data are used to develop a conceptual model, which then forms the basis for numerical calculations. An hypothesis of environmental damage can be rejected if processing of site data reveals incompatibility of the damage hypothesis with system processes, system properties and/or measured system behaviour.

Depending on the circumstances, the hypothesis-testing process may be complex. Often it will require conjunctive deployment of simulation, data assimilation and uncertainty analysis software. In some circumstances a hypothesis can be rejected if it lies outside the uncertainty range of a complementary model prediction. In other circumstances, model-based hypothesis-testing may be more direct. It is fair to say that the groundwater industry still has much to learn about this process.

Regulators too have much to learn in order to fully understand this process, and in order to guide proponent modellers in implementing it at a particular site. The need for a guidelines/checklist document to which regulators can refer when assessing site-specific, model-based hypothesis-testing is easy to understand.

The point is made in Section 3 of this document that decision-support modelling failure occurs when a hypothesis of environmental damage is falsely rejected. This can occur if the model-calculated uncertainty that is attributed to a particular decision-critical prediction is understated. Or if a simple model is deployed, it can occur if worst-case hydraulic properties are not actually worst case. In these and other cases, a regulator’s primary task is to ensure that decision-support modelling failure is avoided.

It follows that a guideline document on which the regulatory process can be based should assist a regulator in providing this assurance. In doing so, it should enable a regulator to convince the general public that the scientific method has been implemented at a particular site. Issues that guidelines appearing in this document should address may include (but should not be limited to) the following:

- early identification of hypotheses that require testing, these pertaining to environmental assets that may be impacted by development;
- design of one or a number of conceptual models that collectively allow exploration of all impact pathways;
- the manner in which calculations based on these impact pathways are undertaken;
- assessment of proponent assurances that the uncertainties of decision-critical model predictions are not understated;
- the possibility that history-matching may expose deficiencies in the current conceptual model, and that history-matching has been conducted in a way that does not preclude this possibility;
- demonstration that an adaptive management scheme has the potential to relegate environmental impact to a low level of probability.

A problem with current regulatory guidelines is that they do not draw their inspiration from the scientific method. Nor do they provide guidance on how it should be implemented at a particular site. Instead, documents such as the AGWMG focus on the tools through which the scientific method should be implemented, rather than on ensuring that the scientific method is actually implemented. This does not invalidate the value of advice that they provide. However technical advice and methodological guidelines are two different things. They are not interchangeable.

11.2.3 Educational Resources

In common with other professions, regulators must regularly update their knowledge. Regulator expertise is addressed in a previous section. Fields of study in which regulators require at least cursory knowledge include the following. (Note that this list pertains to groundwater matters only; it does not address ecological/biological issues with which the authors of this document are unfamiliar but with which regulators should have at least passing familiarity.)

- principles of groundwater flow and solute transport;
- software packages which undertake groundwater-pertinent calculations and/or simulate groundwater processes;
- the practicalities of groundwater simulation, including the costs and benefits of model complexity;
- the benefits and drawbacks of hydraulic property upscaling;
- highly parameterised, regularised inversion (i.e. model calibration);
- basic geostatistics;
- the principles and practice of history-match-constrained, model predictive uncertainty analysis.

A regulator may not have expertise in all of these (and other) matters. However they should possess enough knowledge of these matters to recognize suboptimal proponent work when they see it. A regulator’s knowledge must also be sufficient to recognise when expert advice is needed. As is discussed in Section 10 of this document, this requires that regulators have access to appropriate educational resources, and to personnel from whom they can seek advice.

Educational material on which regulators may draw to update their knowledge should not be confused with government-sanctioned methodological guidelines, as is presently the case. Similarly, the status that is awarded to education material should be that of educational material, and nothing more. This material should be regularly updated, and therefore fluid. Furthermore, given the wide range of issues that it must cover, and the sometimes conflicting views on these issues that are held by industry modellers, contributions to a repository of educational material should be sought from many sources. As has already been discussed, industry and stakeholder groups would also benefit from such a resource.

11.2.4 Assistance

The need for regulators to have access to expert assistance when negotiating with proponents, and when assessing their work, has already been discussed.

There may be occasions where expert assistance is also required to adjudicate a dispute between project proponents and a regulatory agency. The complexities of applying the scientific method in an inexact science where conceptual model development may be challenged by data scarcity, and where simulation and data assimilation must be used conjunctively to assess the uncertainties of decision-critical predictions, creates fertile ground for methodological disagreement. Ideally, the regulatory context should provide opportunities for both sides of a disagreement to present their case to a disinterested third party if this proves necessary.

12. Peer Review

12.1 From the Web Meetings

Generally, a proponent's modelling report is accompanied by the report of a peer reviewer. The peer reviewer is normally selected by the proponent. When asked how much influence a peer reviewer's report has on their deliberations, meeting attendees were nearly unanimous in declaring that its influence is small. It was remarked that the peer review process probably benefits the proponent more than it benefits the regulator.

Rarely, if ever, does a peer reviewer express misgivings about a proponent's modelling work. Its inevitable conclusion is that a proponent's model is "fit for purpose" (with "fit" and "purpose" left undefined). Additionally, a peer reviewer generally endorses the AGWMG class that a proponent has bestowed on their model.

Attendees note that the peer review process is normally continuous, and that a proponent and the proponent's reviewer probably discuss modelling strategy and outcomes at different stages of the modelling process. They find some solace in the notion that "two pairs of eyes are better than one".

However attendees also note that a modeller is hardly likely to choose a peer reviewer whose approach to modelling is very different from their own. They also note that the consulting industry is small, and that it would be unwise for a peer reviewer to antagonise another modeller with a critical review, for an offended party will have ample opportunities for revenge.

Some attendees suggested that the peer review process would be better served if peer reviewers were selected by regulators rather than by project proponents. It was even suggested that a regulator-selected reviewer should have the option of remaining anonymous like peer reviewers of scientific journal publications. This would enable them to express adverse opinions without fear of reprisal. (We note, however, that the groundwater industry is so small that the opinions and writing style of a peer reviewer would probably unmask them.)

12.2 GMDSI Perspective

It is unlikely that peer reviewers will damage their reputations by aligning themselves with shoddy work. So it is probably better that a proponent's modelling work be peer-reviewed than not.

Expertise in some important aspects of decision-support groundwater modelling, such as data assimilation and uncertainty analysis, varies greatly between modellers. There are also some important differences of opinion between modellers on the roles that these should play in the decision-support modelling process. Hence, while the peer review process may forestall gross modelling errors, a proponent's approach to modelling will probably be endorsed by a handpicked, like-minded peer reviewer, even if that approach omits some important components of the decision-support modelling process.

Previous sections of this document discussed early regulator involvement in the approval process. This gives regulatory personnel the opportunity to collaborate with proponents in identifying risks and setting modelling goals. If a regulator is assisted in these tasks by a modelling expert of their choice, that same expert should be asked to peer review the proponent's modelling work.

We note that the reference point for peer review should be the same as that for regulatory review. That is, it should be a government-endorsed guideline document that recognises the importance of the scientific method in decision-support environmental modelling, while providing advice on how to implement it in the regulatory framework. The worth of the peer review process therefore depends in part on the quality of regulatory guidelines and accompanying educational material. See Section 11.

13.Cumulative Impact

13.1 From the Web Meetings

Cumulative impact assessment was discussed at all meetings. It is seen as desirable by most attendees. However many attendees drew our attention to the many logistical problems that it raises.

The Queensland government's response to the need for cumulative impact assessment was establishment of the Office of Groundwater Impact Assessment (i.e. OGIA). This, together with accompanying legislation, overcomes problems associated with access to proprietary data that are held by gas and mining companies who are all operating in the same area. At the same time, its employment of capable personnel have won it the trust of these companies. Nevertheless, technical problems remain; these are briefly discussed below.

Northern Territory regulatory personnel have commissioned the construction of a number of large-scale, complex models that they use as a basis for many of their regulatory decisions. These models account for the impact of multiple groundwater users.

The situation elsewhere is evolving. There is widespread recognition that assessment of cumulative impact requires that a single institution, with capable modellers, have access to monitoring, management and development data belonging to a suite of operators. Either a group of mining companies must jointly commission a third party to undertake cumulative impact assessment modelling work on their behalf (after confidentiality protocols have been put in place), or the government must take the lead role.

13.2 GMDSI Perspective

Cumulative impact assessment is more easily said than done. The domain of a cumulative impact assessment model must often be large. Upscaling of hydrogeology and system stresses is therefore required in order to preclude excessive run times and numerical instability, both of which obstruct data assimilation and uncertainty analysis. As has already been discussed, data assimilation and uncertainty analysis are essential components of model usage in decision support. This is especially the case where data are plentiful and may therefore have the capacity to reduce the uncertainties of decision-critical predictions, as is often the case where a groundwater system plays host to many developers.

When considering the need for, and the nature or, cumulative impact assessment modelling, it should be borne in mind that environmental vulnerability is often just as reflective of local conditions as it is of regional impact pathways. Local conditions may comprise a fault, or an alluvial system that may, or may not, be fully replenished at irregular intervals by high rainfall events. Assessment of cumulative impact may therefore require the construction of multiple models. One of these models may simulate regional aquifer depressurization in an upscaled manner, while the other may explore how regional depressurisation affects the complex temporal and spatial nuances of a local groundwater system. Assessment of impacts on biotic health may require that the latter model calculate alterations to streamflow duration statistics, and uncertainties associated therewith, as the former model will be incapable of this.

If most impact receptors of importance are close to sources of groundwater stress, then calculation of cumulative impact may achieve little beyond that which calculation of local impact achieves. The large domain of a cumulative impact assessment model may compromise its ability to assimilate data that can reduce uncertainties associated with predictions of local impact. In these circumstances, environmental protection may be better served by construction of a series of local impact models than by construction of a large model. The former series of models may already have been developed to support approval and compliance of individual projects.

Problems associated with the mixing of scales are endemic to cumulative impact assessment modelling. Innovation is essential in addressing these problems in order to protect the data assimilation and uncertainty analysis imperatives of decision-support modelling. The groundwater industry is still acquiring the necessary skills. Meanwhile, documented case histories would make a valuable learning resource.

In common with all decision-support modelling, cumulative impact assessment modelling should adhere to a workflow which begins with identification of risks posed by development, together with sources of information pertaining to those risks. Modelling can then be tuned to the harvesting of this information so that the uncertainties of impact-pertinent predictions can be quantified and reduced; the level of environmental risk can thereby be established. Where a region is subject to multiple developments, each of which poses its own local risk while possibly contributing to regional risk, cumulative impact assessment may require considerably greater sophistication than the construction of a giant model that attempts to simulate all of the stresses and impacts that prevail within the entirety of its domain.

14.Community Engagement

14.1 From the Web Meetings

The relationships between regulators and the community was addressed at a number of meetings.

Regulators are well aware that the eyes of both industry and the community are upon them. Some attendees admitted that this may affect their assessment of proponent modelling. In particular, it may induce them to require that the complexity and expense of proponent modelling rise in accordance with the size of a proposed development, and/or with the level of antagonism that some elements of the public may feel towards a proposed development.

A number of meeting attendees pointed out that a complex model can provide a powerful didactic tool. Stakeholders are more likely to be convinced of the merits of a certain management strategy if they can see for themselves how and why it works. They also pointed out that the importance of stakeholder education should not be undervalued.

14.2 GMDSI Perspective

It is true that modelling that accompanies highly visible and/or controversial projects is likely to be heavily scrutinized by academic and other reviewers. The results of this scrutiny will be well publicized. The “low hanging fruit” when criticising someone else’s model is that simulation integrity is compromised by (among other things):

- omission of important processes;
- limited size of the model domain;
- failure to represent important nuances of subsurface hydrogeology;
- insufficient number of layers;
- failure to simulate the temporal and spatial details of recharge;
- failure to simulate flow in streams; and
- over-simplified representation of contaminant transport (for example through use of particles instead of the advection-dispersion equation).

These criticisms may be based on arguments whose cogency extends little deeper than alluding to the differences between “subsurface reality” and a computer graphic. Nevertheless, they may resonate with stakeholders who understandably interpret the word “model” to mean “replica of a system”. Unfortunately, many within the groundwater industry attach the same meaning to “model”.

The authors of this document agree with meeting attendees who stress the importance of stakeholder education. However they note that the scientific method is no less worthy of didactic attention than the mechanics of groundwater flow.

As is discussed elsewhere in this document, decision-support modelling should attempt to implement the scientific method. The level of complexity and expense that is required to do this depends on many factors. In some cases, the imperatives of scientifically based decision-support may be best served by a structurally and parametrically simple model. In many cases they may be best served by a structurally simple and parametrically complex model. Occasionally, they may be best served by a structurally and parametrically complex model. Rarely are they likely to be well served by a model that is structurally complex but parametrically simple. However, the last of these model types may be of greatest didactic worth to stakeholders who seek a better understanding of the principles of groundwater flow as these apply to a site that is the focus of their concern.

The role of regulator guidelines is discussed in a preceding section. As well as assisting regulators to ensure that decision-support proponent modelling is scientifically based, these can also comprise a powerful instrument for community engagement. Inclusion in regulatory guidelines of a strong statement of their commitment to the scientific method, the importance of this commitment, and how recommendations embodied in their guidance are inspired by that commitment, would be of considerable didactic worth to stakeholders who rely on government to safeguard important environmental assets.

The authors recognize that topics such as data assimilation, inversion, regularisation, geostatistics and uncertainty analysis are foreign to many environmental stakeholders. In contrast, the idea that simulation “accuracy” rises with simulation complexity is alluring, for it seems to work in other branches of science and engineering. However, succumbing to stakeholder expectations should not compromise regulatory adherence to the scientific method. Any perceived conflict between these pursuits identifies a need for educational resources that can benefit both regulators and the general public; see Sections 10 and 11 of this document for a further discussion of this issue. At some sites it may also require that a purpose-built groundwater model be dedicated to public education.

15. Simple is Beautiful

15.1 From the Web Meetings

We conclude our reporting of web meeting conversations by remarking on the number of times that phrases such as “in simple terms” or “simple explanation” were uttered (sometimes in almost despairing tones) by meeting attendees.

Regulator frustration is understandable. A regulator’s job is unique. It places them at the intersection of a number of mathematical, numerical and scientific disciplines. It also places them at the boundary between scientific, governmental and community expectations. It is not possible for a single person to possess expertise in all of these matters. Nevertheless, regulators must understand complex scientific concepts in order to assess sometimes substandard technical work. They do this in order to make important decisions under the arresting gaze of a sometimes sceptical public.

15.2 GMDSI Perspective

The authors acknowledge the many difficulties that regulators face. In doing so, we state our belief that some of these difficulties can be redressed.

Section 11 of this document discusses the possibility of developing regulatory guidelines, rooted in the scientific method, that can help regulators to ensure that their actions are based on the scientific method. At the time of writing, regulatory adherence to the Australian Groundwater Modelling Guidelines (AGWMG) is recommended. As has been discussed, despite the practical advice that AGWMG offers, enshrined in its model classification scheme is a view of modelling that conflicts with that of the scientific method. It is noteworthy that “scientific method” is not mentioned once in the AGWMG document.

It is our belief that a science-based approach to environmental problem-solving is not difficult to implement. Nor is it difficult for the general public to understand. The general public is already familiar with terms such as “hypothesis-testing”, as well as related phrases such as “onus of proof” and “beyond reasonable doubt”. Phrases such as “risk management” are also familiar to most. Terms such as these can be readily turned to the task of justifying scientifically based decision-making.

Admittedly, other concepts such as inversion, history-matching, stochasticity and uncertainty analysis are more difficult to understand. Nevertheless, it is our opinion that they can be explained to the non-scientific public using terminology with which they are familiar. After all, mathematics does nothing other than implement logic, and logic is little more than common sense.

The notion that we cannot predict the future, especially as it pertains to poorly understood processes that operate in unseen places, is easily understood. So too is the notion that certain rules apply to these processes – rules which allow us to simulate them. So too is the idea (encapsulated in Bayes equation) that information resides in measurable and mappable system properties on the one hand, and in observations of system behaviour on the other hand. Furthermore, this information can be harvested in order to reduce the uncertainties of decision-critical predictions. These basic principles underly all decision-support modelling. Their careful explanation to the general public should not precipitate feelings of disempowerment.

In contrast, “business as usual” provides no mechanism for alleviating regulator frustrations, industry misgivings nor stakeholder scepticism, for “business as usual” lacks a coherent intellectual framework. “Business as usual” requires a continuation of regulatory decision-making based on guidance documents whose underlying principles are difficult to comprehend because they cannot be explained. While recognising the utility of simulation, they ignore the imperatives of information harvesting and transmission. While explaining the significance of software which implements modelling, they do not explain why models should be partnered with software of equal sophistication which creates pathways for flow of information. Nor do they explain how failure to use simulation and data assimilation packages in concert erodes the scientific basis of environmental protection.

Groundwater science is inexact. Experts will always argue with each other. However with the help of modern software, disputes can be focussed on issues that can be resolved through acquisition of data. Meanwhile, if lack of resolution of a particular issue raises the spectre of environmental damage, then a proposed project should be delayed until the necessary data are acquired. This simplifies the regulatory process and discussions that are associated with it. It obviates the need for tortuous arguments, delivered in an office or in a courtroom, concerning whether a particular model is “fit for purpose”, so that its predictions can therefore provide a basis for expensive and irreversible decisions.

The simple truth is that no model can simulate processes that are operative in a natural groundwater system very well. However, if deployed in conjunction with model-partner packages which implement data assimilation and uncertainty quantification, numerical simulation can comprise an essential component of a process that harvests information, and transmits that information to where it may reduce the uncertainties of decision-critical predictions.

Model-based processing of environmental data, conducted in this manner, will sometimes reveal that development-induced environmental damage is “unlikely” or “manageable”. If this is the case, then a proposed development can proceed. If it is not the case, then a proposed development cannot proceed. These are simple concepts.

16.Conclusions

This document reports regulator concerns and viewpoints that were expressed during a series of web meetings that took place between and including November 2021 and March 2022. For the sake of clarity these concerns and viewpoints have been grouped according to issues. We acknowledge that these issues overlap to some extent (perhaps more than is commonly realised).

We repeat our regret, expressed in the first section of this document, if any viewpoints have been misrepresented or ignored. We also reiterate our gratitude to those who attended these web meetings, and who spoke to us so freely. This is truly appreciated.

Some of the points that were made in the second part of each of the above sections are summarised below. These subsections contain our own reflections on issues that were raised by meeting attendees. Our views on many of these issues were informed and clarified by those expressed by meeting attendees.

- Interactions between regulators and proponents should begin early in the approval process.
- Initial meetings between regulators and proponents should identify risks, and set modelling strategies and goals.
- The primary task of decision-support modelling, including that which is done for regulatory purposes, is implementation of the scientific method. This requires that predictive uncertainties be accommodated, and quantified where necessary. Uncertainties should always be overstated rather than understated. It is a regulatory imperative to ensure that this occurs.
- Decision-support modelling is a form of environmental data processing. This task should be compromised by neither inadequate nor inappropriate model complexity.
- A government-sanctioned regulatory guidelines document is required that explains the principles and implementation of the scientific method in the regulatory framework.
- A comprehensive suite of educational material, targeted at regulators but benefiting the public at large, would constitute a useful regulator resource which complements this primary guidelines document.
- Regulatory personnel should have ready access to expert help if/when they require it. Ideally, a group comprising industry and government personnel could comprise a pool on which regulators can draw for expert assistance.
- Regulatory oversight of both the approval and compliance processes is often compromised by lack of baseline data. Far-sighted gathering of such data at locations where development may proceed in the distant future would be a worthwhile government commitment.
- Community trust in the regulatory process is of great importance. Ideally, this should be inspired by guidelines which describe the philosophy on which regulatory oversight is based. Sometimes stakeholder confidence may be assisted by development of a special-purpose didactic groundwater model.
- Cumulative impact assessment is fraught with technical and logistical problems. In principle, logistical problems can be overcome through government and/or industry action. Some of the technical problems may never be fully overcome. However they should be recognised when determining whether and how cumulative impact should be assessed at a particular site.
- Model-based data-processing demonstrates that uncertainty is pervasive, and that risk is omnipresent. However decision-support modelling, if properly conducted, may inform design of an adaptive management strategy that can reduce risk to a manageable level.

- Links between model-calculable quantities and risks that are faced by ecosystems are often vague. Development of stronger numerical linkages between model outcomes and environmental risks is an area of much-needed research.
- Environmental risks posed by development are rarely zero. Governments, and society at large, must accept this. In doing so, governments should provide regulatory personnel with guidance on how to accommodate this when making decisions on society’s behalf.

Responsibilities that the regulatory process imposes on both regulators and project proponents are considerable. We understand that tensions may sometimes arise between these two groups as they exercise their respective responsibilities. We recognise that modelling is a common source of these tensions, and that difficulties in resolving them are made no easier by constantly changing technology.

In commenting on the many modelling-related issues that were raised by regulators at the series of meetings that are described herein, the authors of this document have attempted to support the regulatory process by offering a scientific critique of that process. It is our belief that adherence by proponents and regulators to the scientific method can resolve many of their modelling concerns by providing a strong foundation for proponent modelling on the one hand and regulatory assessment of proponent modelling on the other hand. Project proponents, regulators, and society in general, should expect nothing less.

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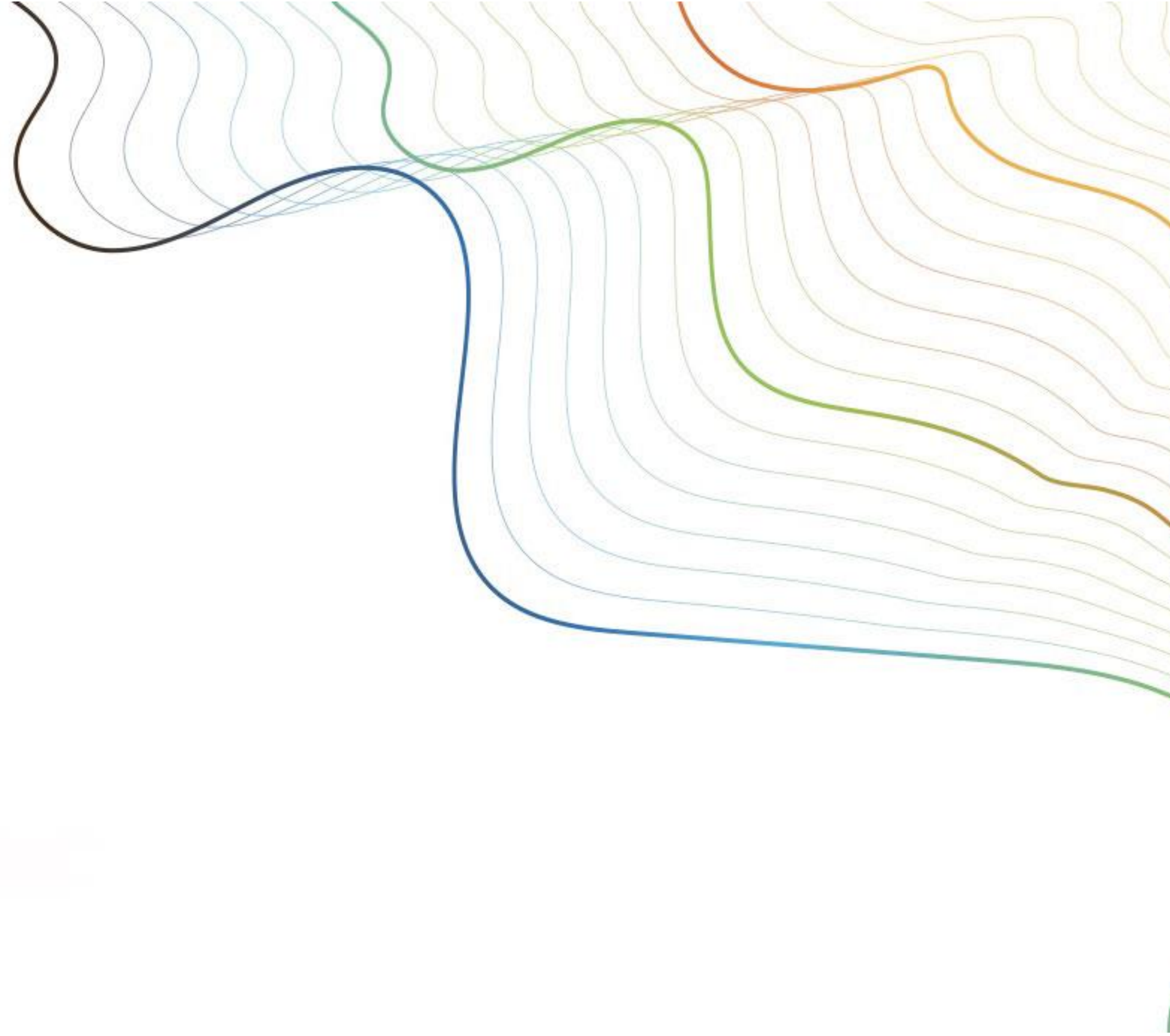

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