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Effective modeling for Integrated Water Resource Management: a guide to contextual practices by phases and steps and future opportunities

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ABSTRACT

The effectiveness of Integrated Water Resource Management (IWRM) modeling hinges on the quality of practices employed through the process, starting from early problem definition all the way through to using the model in a way that serves its intended purpose. The adoption and implementation of effective modeling practices need to be guided by a practical understanding of the variety of decisions that modelers make, and the information considered in making these choices. There is still limited documented knowledge on the modeling workflow, and the role of contextual factors in determining this workflow and which practices to employ. This paper attempts to contribute to this knowledge gap by providing systematic guidance of the modeling practices through the phases (Planning, Development, Application, and Perpetuation) and steps that comprise the modeling process, positing questions that should be addressed. Practice-focused guidance helps explain the detailed process of conducting IWRM modeling, including the role of contextual factors in shaping practices. We draw on findings from literature and the authors' collective experience to articulate what and how contextual factors play out in employing those practices. In order to accelerate our learning about how to improve IWRM modeling, the paper concludes with five key areas for future practice-related research: knowledge sharing, overcoming data limitations, informed stakeholder involvement, social equity and uncertainty management.

Keywords: decision making, social learning, stakeholders, uncertainty, calibration, integrated modeling, IWRM

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1. Introduction

Integrated Water Resources Management (IWRM) is above all a process (e.g. Molle 2008; Ibisch et al. 2016); one that "promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (GWP 2000). IWRM principles, also known as the Dublin principles, have functioned to serve public participation in water resource decision processes and increasingly this encompasses participatory, or the related collaborative, modeling (Basco-Carrera et al. 2017). Indeed, an IWRM project typically includes substantial stakeholder engagement and is supported by at least one jointly-developed model. Such participatory modeling has recently been defined by Voinov et al. (2018) "as a purposeful learning exercise for action that engages the implicit and explicit knowledge of stakeholders to create formalized and shared representations of reality."

Modelling for IWRM represents interactions between humans and their environment and therefore has much in common with social-ecological systems modelling and the more recent concept of socio-hydrology. "Social-ecological systems modeling" often focuses on sustainability (Ostrom 2009) or resilience (Folke 2006), while "socio-hydrology" focuses on how coupled human-water systems interact and co-evolve (Sivapalan et al. 2012). IWRM is distinguished by a practical focus on supporting water management or policy decisions in a context that typically involves stakeholders from multiple sectors. IWRM is underpinned by water balance and hydrological modelling adapted to a specific policy or planning setting. This requires connecting hydrology with other socio-environmental knowledge and component models (see e.g. Croke et al. 2014 for a case study in the Murray-Darling Basin).

The term 'model' however has many connotations; here we define a model as an explicit representation of features and relationships of a target system (Badham 2015). Within this definition there are many types of models, including process, physically and/or behaviorally based, gaming, actor-based, conceptual, and flowcharts. Each can have a range of characteristics such as static/dynamic, statistical/empirical/probabilistic, and distributed parameter/lumped parameter. An IWRM process can utilize any of these.

Here we emphasize quantitative models because they provide an appropriate framework for cost-benefit and other trade-off analyses, as well as playing a key role in understanding, managing, and negotiating solutions for integrated socio-environmental issues. Quantitative models: 1) can serve as boundary objects to encourage and facilitate focus in communication among participants; 2) help in problem framing and explicit boundary setting, which bridge gaps in understanding that can divide participants and bring together multiple perspectives; and 3) determine which actions out of all those possible are in fact being evaluated (i.e., which hypotheses are tested) (Falconi and Palmer 2017). Although these benefits also arise with other types of models, the rigorous process of converting qualitative statements and broad understandings (i.e. mental models) into quantitative, or at least categorical, relations allows for testing the veracity of perspectives.

Successful IWRM modeling can be effective in many ways and to varying degrees (Merritt et al. 2017). In this paper, we view success in a holistic way as the ability to embed the modeling process in a social process that connects scientists, decision makers and stakeholders, and achieves impact in accordance to its purpose, which may vary from a shared understanding of a problem to policy analysis (Hamilton et al. in review).

Our starting point is that the degree of IWRM modeling success can be enhanced by the use of effective practices throughout the model development-application lifecycle, from framing key questions and defining objectives all way through to using the model to satisfy its intended purpose(s). Adoption and implementation of effective IWRM modeling practices need to be informed by practical and fit-for-purpose driven guidance on how to mobilize the IWRM concepts and techniques towards successful outcomes for decision making and stakeholders. Although scholars have made strides in fleshing out IWRM (e.g. Tortajada, 2016), conceptualizing modeling methodologies, and reporting case studies, there is still limited documented knowledge on the modeling workflow, and the role of contextual factors in determining this workflow and the practices to employ. Practice-focused guidance may help explain at a micro-level some of the nuances experienced by those involved in IWRM modeling.

We aim to contribute to bridging this knowledge gap by describing the actions needed to develop a successful IWRM modeling project. This focus on detailed steps and activities motivates the need to develop an in-depth understanding of the IWRM process, in particular seeking to understand how integration will be implemented, how stakeholders are effectively involved, and linking the modeling decisions to the variety of factors that make up the problem and system context. We draw on findings from literature and the authors' collective experience to articulate what and how contextual factors play out in employing those practices. The guidance synthesizes findings about the modeling process drawn from literature reported in overlapping areas, including: environmental and hydrologic modeling (Jakeman et al. 2006; Anderson et al. 2015; Harmel et al. 2018), engaging stakeholders (Vennix et al. 1990; Voinov and Bousquet 2010; Voinov et al. 2018), and general modeling (Banks 1999).

In the next section, we summarize some key literature on the notion of IWRM, including main criticisms, arguing that these are concerned with the challenge of its implementation in a practical context, and that operationalizing IWRM is assisted by a good modeling process. The Phases and Steps that constitute an effective IWRM modeling process are later described in Sections 3 to 7. This is followed by an outline of key areas for future development in IWRM modeling (Section 8).

2. Background: The concept, the criticisms and the operational role of modeling in IWRM

It is a well-accepted premise that modeling has a crucial role to play in the implementation of IWRM (Soncini-Sessa et al. 2007). Yet, the effective use of modeling for operationalization of IWRM still faces important challenges for the future in terms of integration and implementation of knowledge. These challenges are inherent to the nature of the IWRM concept itself and how it can be implemented in practice. In this section, we give an overview of those challenges, and how they motivate this paper.

The first challenge is the difficulty of managing wicked problems in water policy, when there are multiple pressures, conflicting stakeholder values, competing goals, multiple decision makers, limited resources, and deep uncertainty. In the context of integrated groundwater management, Jakeman et al. (2016) bring together some 74 contributors to elucidate the governance, biophysical, socioeconomic, and decision support aspects of IWRM. The three IWRM goals of economic efficiency, equity and environmental sustainability often conflict, and so require trade-offs (Molle, 2008). Criticisms of IWRM often focus on the practical challenges of implementation. Perhaps the most strident critic has been Biswas (2004) who considers the definition of IWRM itself amorphous and questions whether integration across so many aspects is achievable. Tortajada (2016) responds to these criticisms by clarifying IWRM as a concept, as a goal in itself, and as a strategy to achieve development goals. Practical high-level guidance on what to integrate is given by Hamilton et al.

(2015) who flesh out ten dimensions of integration (e.g. issues of concerns, stakeholders, spatial and temporal scales, uncertainties, etc).

As an extension of this challenge, there has also been discussion in the literature about the water-energy-food nexus as either a competing paradigm to IWRM or one that could inspire improvements in the concept and operationalization of IWRM (e.g. Benson et al., 2015; Keskinen et al., 2016; Müller, 2015). But while representing a set of issues to be considered in many IWRM problem settings, the water-energy-food nexus concept may focus attention on the food and energy sectors and draw attention away from the natural environment, and possibly other social and economic water values. Climate change, environmental change and adaptation also are being increasingly recognized as a component to be integrated with IWRM, especially in regard to the planetary effort towards sustainable development and its goals (including a specific target, SDG 6.5, on the implementation of IWRM at all levels; Giupponi and Gain, 2017).

The second challenge relates to handling the human element in IWRM and reconciling the conflicting agendas involved with water management (Grid 2016). For example, IWRM has been criticized in that: stakeholder engagement has been perfunctory; the concept has not been accepted and practised by local water managers (Funke et al., 2007); and technical integration in analyses has not coincided with a balanced institutional integration (Fischhendler, 2008); or the modeling has not been convincing (Middlemis 2000). On the other hand, Grid (2016) argues that while IWRM is challenging because of the human element, no other process can reconcile the conflicting agendas involved with water management.

The primary challenge therefore is in building guidance on how one implements IWRM, or tackles the integration dimensions in the implementation of IWRM for a given problem. Whereas the literature includes some prescriptive guidance on how to implement an IWRM modeling process, there is still a gap in linking this advice to practice. For example, Hamilton et al. (2015) take a step towards operationalizing integration by offering a framework for mapping research methods that can be used to implement each of the integration dimensions throughout the modeling process. However, the framework remains mainly prescriptive, and work is still needed to document and reflect on the lessons from the actual execution of the modeling processes.

In summary, we are well aware of the difficulties of operationalizing IWRM. Whilst Ibisch et al. (2016) have recently examined 14 IWRM projects and given a synthesis of lessons learnt from them, we agree with Giordano and Shah (2014) that the lessons from attempts to implement IWRM are otherwise not well-documented and have impeded its development beyond a concept for dealing with wicked water problems. If we are to add substance to carrying out successful IWRM, we need to begin to document systematically how IWRM projects are being carried out and evaluate the lessons. Being systematic will require a template that includes a set of categories defining the context of a problem so that patterns and anti-patterns of IWRM operations in specific contexts can emerge for future guidance on what and how to integrate. There is no alternative to us as a community than “learning by doing” IWRM, while reporting on it and explicitly accruing the lessons.

In recognition of this need,we have been associated with a “Pursuits” project at the National Socio-Environmental Synthesis Center (SESYNC) (https://www.sesync.org/for-you/educator/research/themes-pursuits), funded by the United States National Science Foundation. We come from a range of backgrounds spanning science and social science of water resource management as well as public health modeling and computer science. The Pursuit project aims to address the overarching research question of “identifying the core practices that should be employed in developing and using models to support IWRM.” Thus, we argue for effective IWRM through a modeling lens. But it recognizes that such modeling needs to be a process that is well-grounded in the needs of the IWRM problem at hand, hence we also focus on guidance for applied problems. Following good practice, modeling can bring many benefits to the IWRM process including: elicitation, systemization and sharing of otherwise fragmented knowledge; management of uncertainty; clarification of tradeoffs; facilitation of capacity development; transparency; and participation and inclusiveness.

The paper does not delve into the necessary institutional and governance reforms advocated by many for IWRM. Moreover, we feel that there is still much progress to be made by working within whatever current governance constraints exist but also using modeling to infer and communicate how new arrangements and approaches might improve the effectiveness of water resource management. At its core, our paper's main aim is to address 'the how' of IWRM modeling by guiding modelers and commissioners of projects on what questions to ask and what issues to address, thereby prompting decisions through a model-grounded process for an IWRM problem.

3. Introducing Phases and Steps for effective IWRM modeling

IWRM modeling actions can be broadly grouped into four phases (cf. Hamilton et al. 2015). The *Planning Phase* identifies what is to be achieved, how this is to be accomplished, and what resources can be brought to bear. The model is built and tested during the *Development Phase*, and then used in the *Application Phase*. Finally, models that become part of the ongoing policy or decision-making process, or are for routine operational use, require a *Perpetuation Phase*. These phases are sufficiently general that they typically apply to the widest range of IWRM activities and model types.

Within these general phases are more specific steps (see left side of Table 1) or activities associated with the IWRM modeling process, which may be implemented in different ways. We provide a modeling-centric view of an IWRM decision support process. A policy-centric or stakeholder-centric view might identify and emphsize phases somewhat differently, connecting to these to varying extents – depending on the level of (policy maker or other) stakeholder involvement. In the broader IWRM arena, different authors have separated the modeling process into distinct actions. For example, Black et al. (2014) focus on the use of models to analyze water resource planning scenarios and their guidance is principally intended for modelers. We step back and focus on what fundamentally is to be considered and achieved in each of the four phases and accompanying steps for the context in which the IWRM process operates. The framework described here emphasizes flexibility and directs project attention to key points and questions as a way to facilitate better access to the IWRM concepts and tools available.

Here we define 'context' as the social and project characteristics that influence which steps are brought to bear and how they are implemented; in any application, specifics of what happens within the steps may differ. Important contexts for the model development include the general role of the modeling, the funding levels for the effort, level of stakeholder conflict, type of governance setting, relevant scales of the problem, and tolerance for uncertainty.

Description of each step within a phase is elucidated in the following sections using brief examples drawn from a range of IWRM settings, typically based on quantitative water management modeling with substantial stakeholder involvement. Given the broad nature of IWRM problems, examples alluded to here are necessarily illustrative rather than comprehensive.

Although the phases are broadly chronological, ordering is not intended to imply that the steps are necessarily sequential. The steps presented in this paper are not intended to form a rigid checklist, but capture key practices that should be considered and performed as needed. A great deal of overlap and iteration between phases and steps can be expected, some steps may be conducted concurrently whilst in particular projects others may not be needed at all. For example, tasks undertaken in the first *Planning Phase* might be revisited during the *Development Phase* if data are found to be of poorer quality than expected or the desired model outputs change. Similarly, there is likely to be overlapping parallel progress between data collection, model construction and testing, as testing reveals weaknesses in the model and identifies additional data that would be required to reduce uncertainty in important model outputs. Such concurrent cyclic iteration is widely understood to be a part of hydrological (and other) models, where the *Development* and *Application* phases of modeling provoke revisiting of previous efforts.

Each step of the model can be seen as a path which has 'forks' where alternative choices can be made. The choices made by the modeling team can affect the quality of the modeling results. For example, choosing one stakeholder group over another can affect the relevance of the information included in the model. Lahtinen et al. (2017) have developed a checklist to help modelers "evaluate alternative paths, and recognize and act on situations where changing the path may be desirable." While not discussed further here, it is a useful complementary tool.

Table 1: Phases and steps in the modeling process in IWRM and desired results.

Step	Desired Results
Planning Phase	
Problem definition and scoping	Concise and sufficiently complete picture of modeling objective(s); including whether these are scientific understanding, decision making and/or social learning at the highest level. Articulation of what is to be integrated especially if these are water issues only or also cross-sectoral issues
Stakeholder Planning	Description of stakeholders to be involved in the IWRM process, and how and when they are to be engaged; identify sectoral interests and jurisdictional levels; identify how modeling results will be integrated into stakeholder processes
Project management planning	Negotiated workplan of project activities and resources, including time and cost; good understanding of cost-benefit of different levels of effort on data collection and modeling regarding hydrology, water use and management, depending on nature of their integration with stakeholder processes; also includes decision-support processes.
Preliminary conceptual model	Broad description of the characteristics, relationships and processes important to solve the IWRM problem; IWRM outcomes of interest at relevant spatial and temporal scales – hydrological, ecological, social, economic indicators; controllable (policy) and uncontrollable drivers (climate, boundary conditions); helps define "bounding box" of what processes the model will include
Development Phase	
Data collection	Compilation of available data including evaluations of data quality (hydrology, water use, socioeconomic and management); ensure leveraging of existing knowledge and avoid "reinventing the wheel" (e.g. using existing water databases)
Construction	Efficient development of one or more quantitative tools that provide a concise but appropriate representation of the system of interest, typically including some elements of the hydrological, water use and water management system
Model Calibration	Model inputs and processes refined so that output is similar to, or consistent with, observations and/or qualitative information in known situations (especially water availability and water use); maximize the flow of information from the observations to the model inputs; adequately

	represent past and current conditions to foster acceptance of model predictions
Uncertainty analysis	Description of the reliability and accuracy of model predictions (e.g. water availability, ability to meet demand, ecosystem and socio-economic outcomes); provide stakeholders with a basis for discerning when one model output is different than another; articulate main sources of prediction uncertainty and suggest future data that could be collected if uncertainty is too high
Testing/evaluation	Model is correctly implemented and suitable for its purpose; verify that the model performs for conditions outside of those included in calibration (e.g., extreme drought), while taking into consideration the relevance of the model assumptions to the conditions outside the calibration.
Application Phase	
Experimentation	Learning biophysical and socioeconomic constraints on the system, exploring possible trade-offs among socio-economic and environmental outcomes, more trust/acceptance of modeling tool
Analysis and Visualization	Concise compilation of salient model outputs tuned for fulfilling the model objective, e.g. hydrological, ecological and socio-economic indicators; provide concise encapsulations of important model insights and outputs
Communication of results	Effective exchange of important insights and outcomes of modeling; tradeoffs of IWRM indicators; ensure that benefits of the work for different audiences are well justified
Perpetuation Phase	
Documentation	Provide the information to use, reproduce, adapt and update the model; maximize the efficiency of future models of the system; have defensible model for legal arena (e.g. in prior appropriations of water allocation regimes, or supporting water use permit decisions)
Process evaluation	Gain insight in what went right/wrong, why, and what could be improved for future IWRM projects from multiple project stakeholder viewpoints; leverage insights for more efficient IWRM efforts in the future
Monitoring and maintenance	Assimilate new information into model (e.g. more recent climate data, new ecological information, and socio-economic survey results), including data about predictive accuracy, and issues of hosting and end-user support addressed; provide approach to address uncertainty resulting from unknowable future

4. Phase 1: Planning

The *Planning Phase* defines what the modeling is intended to achieve within the context of the larger IWRM project, who should be involved, and what resources are required. It converts an initial need that 'a model or set of models is required' into a description of the model(s) and a plan for how to meet that need efficiently and effectively. Models may need developing or, if suitable, can be adapted from already developed models. This phase comprises four steps: *Problem Definition and Scoping*; *Stakeholder Planning*; *Project Management Planning*; and *Preliminary Conceptual Model*.

4.1 Problem definition and scoping

The first step is one of clarification and agreement about what are the objectives, and especially which water-centric issues and cross-sectoral issues (e.g. climate, food, energy, environmental, cultural) are essential to be addressed. This essentially determines what is (and is not) to be modeled. A key aspect is to identify the questions that the modeling should answer. However, the form and scope of these questions and their answers are shaped by the intended users of the model(s) and identified stakeholders, as well as the function (or role) that the model(s) and modeling process is to have within the broader IWRM project.

Clearly defining the problem, and how the model is to be used to address the problem, determines many of the decisions made during subsequent modeling steps. Some of these decisions are: whose views and knowledge are to be included, which functions and processes are required of the model(s), expected level of model accuracy and complexity, and how model utility will be tested.

Model function

Fundamentally, a model is a representation of knowledge about a system (i.e. past, present or future), and that representation can be used in different ways (Badham 2015; Kelly et al. 2013; Oxley et al. 2004). An IWRM modeling process is policy-oriented because the defining characteristic of IWRM, as outlined earlier, is its focus on the human and decision-making dimensions of issues, such as ways to equitably manage sources of water, or how to cost-effectively allocate volumes of water in a river system to different uses and the environment. Commonly, policy-oriented modeling is supported by quantitative models of a particular water resource or other aspects of the socio-environmental system, which form the foundation for exploration of options and constraints. A major component of these models tends to be physically based, but sometimes data based, models that advance scientific knowledge of, or improve scientific tools applied to, that resource. Typical examples include hydrology models (Beven 2012) which aim at understanding surface water behaviours, hydrogeological models (Anderson et al. 2015) to advance the knowledge of groundwater systems, and water quality models (Chapra 2008; Fu et al., 2019; Merritt et al. 2003) to comprehend the fate of nutrients and/or contaminants in water. But increasingly these are supplemented or integrated with modeling of the human dimensions (Noel and Cai 2017; Kelly et al. 2013), especially their behavior and decision making at various levels such as individual (e.g. farmer, household), industry (irrigation), community (rural, urban), and policy jurisdiction (local, regional, national).

Policy-oriented models can be further subdivided into those models used for policy support or decision making and those for conceptual thinking and (social) learning. Models used for policy support and decision making extrapolate from knowledge and behaviour to estimate potential consequences, or a range of consequences, of potential actions. While everyday use of water models can include forecasting for operational objectives (e.g. reservoir real-time operational decisions for flood control; Hsu and Wei 2007), IWRM modeling is typically for longer-term strategic, and/or multiple, objectives such as assessing spatiotemporal tradeoffs of impacts resulting from alternative management options (e.g. for licensing abstraction volumes and locations under a varying climate). These models are used either directly by the decision maker (or their advisors), or the modeling team may summarize the model's outputs for different scenarios as advice for decision makers.

Models for thinking and learning are used to communicate, visualize, and explore the system to inform the diverse groups concerned with a project. Such models can also integrate knowledge elicited from those groups (e.g. see Elsawah et al. 2015 for cognitive mapping of stakeholder system understanding). In this process, the model acts as a translator, or boundary object, between groups with different understanding and languages about the problem. The emphasis is on restricting all imaginable system behaviours to those that are reasonably likely, while at the same time providing insights, improving mental models, and fostering interaction and communication among stakeholders. The modeling process itself is often an important part of this role, with possible cognitive or social outcomes including systems thinking, consensus building, and conflict reduction (Belt and Blake 2015). For example, Pahl-Wostl and Hare (2004) describe benefits of a learning activity that included gaining insights into complexities of the system, and greater understanding of the actors' own perspectives and the role of other actors. In addition, the openness of the process fosters the discussion of innovative ideas.

Although presented as somewhat distinct in this discussion, the purpose of a modeling exercise may be manifold. A model that promotes social learning may also be taken further and used for policy support. Likewise, scientific models may be harnessed by a modeling system in order to provide policy support. Furthermore, the role may change during an IWRM process, with different aspects of the model emphasized at different points; for example, social learning when generating options, but then policy support when the options are being compared.

Although developing a model or models may be the main deliverable of an IWRM project, some complex projects may involve drawing on several sources of evidence and methods, perhaps with the model playing a relatively minor part (Bots and van Daalen 2008). For example, there may be formal legal hearings and submission processes to obtain the views of members of the public as well as key stakeholder organizations. In such a situation, the modeling process needs to complement and interact with the non-modeling activities and sources of information. Consider for example the objectives of the Murray-Darling Basin Plan in Australia where the objective was to determine a sustainable limit of water extraction in the basin (CSIRO, 2008). Largely existing hydrological and ecological models were adapted to address this objective, supplemented by socioeconomic analyses (Croke et al. 2014).

Model question and scope

Clarification of the modeling purpose, role and use triggers the first model design decision: what are the questions the modeling is answering? Questions can be framed around a set of inputs and outputs. IWRM inputs typically include drivers that impact water systems (e.g. climate change, water use needs for energy, urban or agriculture demands), stressors (e.g. over-exploitation of water resources), and management and policy options (e.g. riparian buffer management, water allocation policy), where financial and socioeconomic impacts are associated with each driver. Outputs of interest feed IWRM outcomes that need to be improved or maintained to address the identified issue(s). An example question is 'which management interventions acting in which locations are most likely to lead to desired outcomes?' A typical output would be the nature and magnitude of change in the physical water resource. Examples include 'how much water reaches the end of the river given a rainfall, population and abstraction scenario?', or 'how much is some measure of pollution reduced, and perhaps at what cost, given a specific change in policy?' The modeling may generate several outputs that each answer a different question, or multiple outputs might be used to answer a single question.

As IWRM projects typically involve researchers and stakeholders from different disciplinary backgrounds and experiences, there can be different perspectives on what key questions need to be investigated (Brandt et al. 2013). Coherent framing of questions can be challenging and time-consuming, but the process of (re)framing the modeling questions is an essential exercise for building a shared understanding about the modeling inquiry and its implications for the system. The process also sets relationships between stakeholders that will be active during the remainder of the IWRM process.

Problem definition facilitates subsequent boundary setting and scoping of the problem domain, identifying what aspects of the system are to be included/excluded from the model in terms of its relevance or contribution to addressing the question of interest. Of course some elements of the setting may change over time. Challenges to problem definition are inevitable as IWRM is a wicked problem characterized by multiple, and often conflicting, viewpoints about the problem, possible solutions, who will be affected by the problem, and who should take part in solving the problem. Based on the plausible interpretations of these issues and questions, there are multiple problems to be defined and boundaries to be set (Walker et al. 2003). Dewulf and Bouwen (2008) offer an example case study where three actors (i.e. water power plant, water management authority, and sand miners) have divergent problem frames about water management problems in their region. The water plant, which provides electricity to the region, defines the goal as reducing soil erosion and resulting sediment flow to the reservoirs. On the other hand, miners do not frame sediment as a threat but as an economic opportunity. Problem definition is not a straightforward exercise, but an organic process through which stakeholders reflect on their existing problem frames, negotiate differences, and ideally re-construct their views to reach a shared representation of the problem.

Although many IWRM applications are typically confined to the physical boundary settings of targeted water systems, emerging concepts, such as 'virtual water' which involves the role of food trade in compensating water deficit, can stretch beyond the biophysical boundary (Yang and Zehnder 2007). Social and economic considerations can also stretch the physical boundary; for example, income used to sustain a regional community may be derived not just from activities within the IWRM zone but may be supplemented from additional work outside a catchment. 'Nexus thinking' is another driver for expanding system boundaries by promoting the importance of attending to the food-water-energy-environment linkages and cross-sector impacts (Hussey and Pittock, 2012). Framing water problems using a nexus lens extends many of the aspects that need to be attended to, including stakeholder groups to be involved, goals and risks to be considered, governance and regulatory framework, and the interdependencies among the modeled systems.

However, different problem interpretations are not only attributed to different stakeholder views and systems of interest. The disciplinary background of the research team can be another challenge. Whereas diverse disciplinary teams are often cited as beneficial for problem definition and even critical for the success of an IWRM modeling process, the assumption that any interdisciplinary team will effectively work together to develop an integrated problem cannot be taken at face value (Nicolson, 2002). Interdisciplinary teams do have their challenges and can stumble over their differences (Bark et al., 2016), such asdifferent views about what constitutes data, different research agendas, etc.. There is still a need for more guidance into how interdisciplinary teams can work together in IWRM modeling projects to negotiate their differences and reach an integrated understanding of the problem.

4.2 Stakeholder Planning

IWRM inevitably involves multiple stakeholders and interest groups that include domain experts. Effective stakeholder engagement leverages diverse knowledge and perspectives in order to inform what water-related issues are addressed, the subsequent construction of realistic input data, scenarios, and potential management solutions (Elsawah et al. 2015). The extent of stakeholder involvement, however, depends on both the project needs and the interests of the particular stakeholders. The purpose, timing, ways and mode of engagement may also differ for different stakeholder groups. Stakeholder planning steps must consider several questions such as:

- Which stakeholders to engage, separately or together, and when (disciplines, domain knowledge, relevant interests)?
- What role does the main client or funding agency play relative to other stakeholders?
- Are there cultural or other sensitivities to consider?
- How much authority should the stakeholders have in making decisions about the model?
- At what points in the modeling process is their input most important?
- Will stakeholders be involved as individuals or part of a group?

- How will information flow from/to stakeholders and the model?
- How does the project provide value to the stakeholders?
- What is required to enable the stakeholders to engage effectively?
- What commitment is required from the stakeholders and are they sufficiently interested and available to make that commitment?
- What is required to build trust?

Plans for stakeholder engagement should be developed, monitored, and adjusted in concert with the stakeholders who are to be engaged (Barreteau et al. 2010). Four forms of engaging IWRM stakeholders in modeling have been identified (Hare 2011): (1) front- and back-end modeling where stakeholders are involved at the early and last stages of the project; (2) co-construction where stakeholders are involved throughout the model development process; (3) front-end modeling where participation is limited to the early stage; and (4) back-end modeling where stakeholders are brought in at the end of the modeling process. In general, it is best to engage representative stakeholders as early and as often as possible (Langsdale et al. 2013), checking in with regular status discussions at all stages of the modeling effort. Extensive engagement is particularly important in projects oriented towards promoting social learning and collaboration, and requiring high levels of trust. However, the early stages of a project typically involve more abstract discussions; hence, there is a tension between involving stakeholders early and consuming their time with little progress, or later and running the risk of them feeling that key decisions have already been made. Developing and maintaining stakeholder interest is key to resolving this tension.

4.3 Project management planning

Like all substantial projects, the modeling process requires resources such as time, funding, data (see *Data collection* step below) and skilled personnel. In some cases, there can be externally imposed deadlines or funding constraints that must be met, which in turn can drive problem definition, choice of model used, and the modeling process. Even without fixed constraints, government or regulatory authorities are likely to contribute much of the funding and some technical skills, and may have a different role in supporting planning from other stakeholders.

Stakeholder engagement discussions should cover what support is desired and what is available, and then be revised as more is learned as the IWRM process progresses. Key decision points in the modeling process should be coordinated with stakeholders to ensure agreement on what is (broadly) being done, when and with whom. This typically is a negotiated process between (some) stakeholders and the modelers and can be aided by developing a workplan of activities that is revisited throughout the project to allow response to changing priorities, resource constraints, or leveraging opportunities. In the context of IWRM, more resources are typically required for larger projects in order to facilitate the communication and collaboration that typically include a greater variety of stakeholders with different perspectives, disciplinary backgrounds and experiences (van Asselt and Rijkens-Klomp, 2002).

4.4 Preliminary conceptual model

The preliminary conceptual model forms the basis for transitioning between the *Planning* and *Development* phases. It is a broad, qualitative outline of the model design and identifies the main features that must be included in the model(s) that is (are) to be constructed. Conceptual models typically include:

- desired outputs of the model, which are those that represent the effects of controllable and uncontrollable drivers on the societally relevant resources and indicators;

- key entities or system components that drive the desired outputs of the model (such as land and water use behaviour; policy that influences how water is extracted; ecosystem impacts; river flow, aquifer responses of interest, and water quantity and quality)
- broad relationships and connecting processes between these entities; and
- uncertain elements that are to be explored during the decision-making process, such as policy options and those exogenous factors outside of policy control (e.g. climate, other sectoral influences such as from energy or agricultural policy).

The objective of the preliminary conceptualization is to describe aspects of the IWRM issues and the influences that contribute to these issues. These elements are then refined to those that are relevant to the output for IWRM outcomes and scenarios, and to the comparison of those scenarios for any negotiation or recommendation. A conceptual model defines connections between important components of the IWRM issue, and includes model inputs and model outputs, and intermediate states and processes that are relevant.

Some entities and processes do not influence the relevant output but may be important to stakeholders to improve relevance and make the model more accessible to end users (Elsawah et al. 2017). Therefore, the development of the preliminary conceptual model can also be a useful activity for building a shared understanding among the project stakeholders about the system drivers, and how they will be addressed in the model (Bertone et al. 2016).

Throughout the conceptualization process, substantial discussions are indispensable regarding how the model will be used, what limitations might need to be overcome, what alternatives should be considered, and how multiple models will work together. The conceptual model design step focuses on higher-level views of the IWRM problem, for example determining boundaries of the problem (e.g. what is in, what is out), temporal and spatial scales and extent and general level of complexity required for the intended decision level (e.g. whether short term operational, medium term management, or long term planning). Determining the appropriate scales can be challenging because the components of socio-environmental models in the IWRM domain can have different spatial boundaries and characteristic process time scales, and the stakeholders may be interested in issues that occur at different scales. For example, farmers are likely to be interested in impacts at the spatial scale of an individual farm and the temporal scales of both a single season, and a span of several years, while water resource planners are more likely to be interested in sustainable watershed spatial scales over a decadal planning horizon. There may also be a mismatch between stakeholders' scales of interest and the scales of relevant biophysical and socioeconomic processes (Hamilton et al. 2015).

Conceptual models are typically constructed with some sort of diagram using arrows to mark influential relationships and flows (Argent et al. 2016; Robinson 2008; Jakeman et al. 2006). Narratives or other visual and textual descriptions of 'what happens if' may also be useful (e.g. rich pictures). Data collection and knowledge elicitation methods are commonly used to develop the preliminary conceptual model, such as desktop literature review, expert and stakeholder interviews, and workshops (Vennix et al. 1990).

The components and processes should be broadly described in terms suitable for stakeholders who are not modeling experts. Qualitative descriptions regarding how a change of one component or process can change the state of another can be valuable, and can provide insight regarding the direction of change, whether it is a relatively small or large effect, and what other factors may influence that relationship (Liu et al. 2008). Quantitative measures and the detailed rules and equations specifying relationships are established in the *Development Phase*.

Conceptual models are also useful when adapting and/or integrating pre-existing models, which may well be required by the water management sector because of their legacy of, and commitment to, their previous investments in hydrological model types in particular. Here revisiting the conceptual model relates the existing model(s) to what may be a new problem, as well as identifying and resolving any conceptual differences between the adopted model and the problem as perceived by the modeler and stakeholders (Belete et al., 2017). This is an essential step before further resource investments are made.

Modeling technique

As the conceptual model is clarified, the type of modeling technique to be used must also be decided. There are usually many different possible techniques that could be selected, each with different strengths (Kelly et al. 2013; Fulton et al. 2015; Hamilton et al. 2015). Selection is influenced by factors including the level of knowledge about the system of interest, the level of spatiotemporal detail to be represented, the type of processes to be represented, and the nature of the data to drive and calibrate the model (see Badham 2015; Kelly et al. 2013; Anderson et al. 2015 for guidance). Broadly, however, conceptual, or toy models, or serious games, are typically more suitable for social learning and communication-oriented purposes (Argent et al. 2016; Van der Wal et al. 2016). Decision-support, on the other hand, typically requires mathematical or computer models, which require more quantitative data and different skills to develop.

Method selection may also involve trading off among the 'best' method, modeling effort, and participation in the model development (and possibly also model application). Sophisticated physically-based mathematical models, for example, can be difficult for non-specialists to understand the model's structure and relationships between model input and output, and thus explore. Adapting an existing computer model for a new IWRM objective can reduce the need for skills and time, and the model may be already familiar to some participants, but this may be at the expense of overall engagement. The experience of working with some form of a model can assist non-specialists to contribute to IWRM more effectively than discussing the specification of the expert knowledge to be embedded in the model. For example, Monks et al. (2014) describe a modeling effort where those involved in conceptualizing and developing the model had less time for exploring with the model, but explored more adventurously than those who were provided with pre-prepared models and given more time for exploration.

5. Phase 2: Development

The *Development Phase* converts the preliminary conceptual model into a complete model, ready for its intended purpose within the project. This phase comprises five steps: *Data Collection*; *Model Construction*; *Model Calibration*; *Uncertainty Analysis*; and *Testing*. In this phase, the steps are particularly interwoven and some elements must be undertaken in parallel or iteratively. For example, testing (which is a challenge in multi-component IWRM models, especially those with system feedbacks) is an ongoing process during model construction, as it may be necessary to test, and re-test, each model element, its linkages and the full model itself to ensure that the new or modified element has not interacted incorrectly with existing elements (Bertolino 2003; Vale et al. 2016). Even steps that appear sequential may be revisited; for example, an unsuccessful attempt to calibrate the model might lead to amendments in the model implementation (revisiting construction), which could further require additional data to be collected. Nevertheless, it is useful to identify separate steps, to ensure all key activities are given due consideration in the modeling process.

For mathematical or computer models, much of this phase is technical, with the modelers working from literature, expert opinion, data, as well as with stakeholders to formalize the important processes and system properties (previously outlined in the conceptual model). Although not discussed in depth here, similar steps are performed in the modeling process for qualitative models for exploratory and communication purposes (Malekpour et al., 2016). These methods typically use knowledge elicitation processes and diagrams to describe relations between stresses and system responses, and validate the final model with stakeholders to ensure it reflects the shared understanding of the system.

5.1 Data collection

Data are required to implement the conceptual model and to test that implementation. In IWRM models, these data may be a mixture of numerical values as is commonly the case for hydrological components, and categorical information where measurements and knowledge are less precise or more qualitative as could occur with some social or ecological components. As well as measurements, relevant data encompass information from established theory, existing models, published studies, assumptions, stakeholders and expert opinion. Data collection involves compiling, cataloguing, obtaining and evaluating all of these forms of knowledge. This step also identifies the data and knowledge that are not available and considers potential proxies for those gaps.

Some of the specific questions to be considered in this step include:

- what data are needed to represent theories included in the model (for each relationship and overall)?
- how accurate do the data need to be?
- what quantitative data are available?
- what is the quality of the quantitative data?
- what are the temporal and spatial scopes and resolutions of available quantitative data?
- what qualitative data are available, particularly with respect to the social and ecological elements of the system?
- how can gaps between available and needed data be addressed?
- are there any privacy, intellectual property (IP) or other constraints on the use of relevant data?
- do any datasets contain sensitive information?

Once compiled, some of the data may need to be cleaned, transformed into another format, or rescaled to be compatible with the other data or the model requirements. Note that more data may become available throughout the modeling process as stakeholders gain understanding and interest.

5.2 Model Construction

The model construction step converts the conceptual model design into a functioning quantitative model or models. This involves rigorously developing the details of all the processes to be represented in the model(s). Each process must be formalized as a set of equations or rules that specifically describe what happens in the model(s) in situations likely to be encountered, and then implemented within the model(s). For example, deterministic differential equations could be used to simulate the way in which water availability changes over time due to extraction, evapotranspiration, or other processes. Alternatively, relations could be represented probabilistically, for example ‘if the population increases by more than 20%, then water requirements will increase by 20% (with 50% probability) or 10% (with 50% probability)’.

Development of the detailed equations or rules may need to consider alternate models, such as those including alternative ideas about system geometry or processes, which arise from discussion between stakeholders and the modelers. Considering alternative model concepts is often an extremely useful communication approach, especially if they are perceived to be rival or advocacy models (Ferré 2017). These contentious alternative models can help identify what future data collection might discriminate between the rival ideas, and allow all stakeholders to have their ideas considered and vetted within the framework provided by the modeling process.

Elements within the overall model(s) may require translation. For example, they may be at different temporal or spatial scales, which then require upscaling and downscaling to communicate (Hamilton et al. 2015).Moreover, there are aspects of the system that may be conceptualized with different paradigms or units, so inputs and outputs need to be transformed from one type to another. For example, water quantity may be required for some equations, and flows for others. One approach is to construct the quantitative model with several sub-models that address components of the conceptual model and overall system, which facilitates the use of different types of equations or rules where different considerations are important. The sub-models typically pass relevant information to each other and detailed description of the communication between sub-models is developed prior to model construction. Different approaches to variables (such as scales) must be reconciled for interoperability of the sub-models (Brandmeyer and Karimi 2000) and evaluated for conflicting assumptions between sub-models (Mackay and Robinson 2000). Such considerations are especially important for IWRM models, which include quantification of hydrologic, environmental, decision-making and other social processes.

Technical implementation of the model may be achieved by adopting pre-existing modeling platforms, libraries, or else developing the model from scratch. These options indicate, from least to most, the required amount of software development knowledge that has to be on hand. Platforms refer to software packages that allow a user to construct a model without any coding knowledge, often through the use of a graphical user interface. Libraries provide a pre-developed model or set of models along with utilities and toolsets, interaction with which often requires code to be written. Research is often conducted in specialized niche contexts not covered by generalized platforms and so it is not uncommon for additional code development to serve the modeling's specific purpose (Ahalt et al. 2014).

Development of an integrated model requires collaboration between domain specialists (e.g. surface and groundwater hydrologists, various types of social scientists including economists, social and policy domains, ecologists, etc.), and leadership from integrated modeling experts, regardless of the development approach adopted. Implicit assumptions or misunderstandings through the model development process will likely induce unrecognised limitations in the model functionality. Tests to identify these mismatches and other general errors should be designed and developed, preferably before any model construction begins but may also be created post hoc. Doing so communicates to others what the intended model limitations are, and provides confidence that the model functions as intended.. These tests may be modified throughout the model construction process. This subject is expanded further in Section 5.5 Testing of model robustness.

As well as the technical process of building the model, the model construction step includes consideration of broader model choices and constraints on the implementation. Such issues include:

- the limitations or assumptions associated with the modeling techniques being used and how these are to be managed; this includes the levels of abstractions and simplifications;
- whether there are licensing or other constraints on the tools used to develop or apply the model;

- accessibility and usability of the eventual model - including issues of interface design for computer based models;
- potential reusability of parts of the model; and
- the intellectual property rights that should be asserted for the developed model.

At the conclusion of this step, the quantitative model(s) is (are) 'run' and transforms model inputs into outputs of interest. However, how well these outputs represent the socio-environmental system is not yet evaluated, which is the focus of the remaining steps in this phase.

5.3 Model Calibration

Calibration adjusts model parameters and other model factors such as boundary conditions to best reproduce observational data, often done formally using a metric and possibly constraints in an objective function, though visual and other qualitative approaches may have value (Bennett et al. 2013). Qualitative approaches to parameter settings can be especially useful in non-hydrological components (e.g. ecological, social processes) of IWRM models where data on observations are more scant and expert knowledge is required. Some model components in IWRM, particularly of a hydrological nature, are capable of accurately representing major relations and predictions that reflect broad properties of the system. Typically, other predictions will have less certainty, such as those requiring knowledge of small-scale properties of the system (e.g., preferential flowpaths needed to accurately simulate groundwater travel times), or those related to the social components of the system. After initial model construction, model parameters and other model factors are varied to better fit what was measured or expected from a given system for a set of conditions, a process called history matching. The model output is compared to observed or expected equivalents in the data to assess how well the model is able to represent the system of interest. When the observed data themselves are inadequate to constrain all model parameters, theory and expert soft-knowledge can provide further constraints. If the modeling contradicts well-grounded theory, this may point to an error in the data or the model structure.

Model parameter reasonableness is usually not judged using exact values, as they are not typically available; distributions or plausible ranges are used instead. Observational data are subject to a range of uncertainties and biases, including measurement or sampling errors and spatial and temporal heterogeneity. History matching does not require, or even expect, an exact match between observed data and model output. Indeed, too close a match can suggest overfitting, where the model is fitting errors within the data, which commonly degrade the model's ability to make predictions in other conditions beyond those operating in the calibration period. Some level of tolerance or an acceptability threshold is therefore required. When a model both fits the observations (or conforms to expectations) and has reasonable values for model parameters and other factors, it is deemed calibrated (Anderson et al. 2015, Ch 9).

It is important to apply history matching with multiple criteria. These criteria should include many different observation types in order to break correlations between model variables. Different observation types in the hydrological component of IWRM models could for example include measurements of water balance terms – evapotranspiration, groundwater levels, streamflow rates etc. In addition, decisions related to how to weigh the importance of the different observation/expectation types, and constraints on them, directly influences the trade-offs in fit (Anderson et al. 2015). Diverse comparisons can also reveal different areas where the model is strong or weak (Haasnoot et al. 2014; Parker 2009); and many weak signals that each assess different aspects of reality can be more informative than strong performance against a single aspect of behavior (Grimm 2005). However, even with several criteria, judging calibration may not be straightforward.

Communication with stakeholders during calibration commonly includes discussing data or processes important to the model that may not have been sufficiently considered. It may also include showing how different calibration approaches yield different results, and if these differences may have different practical implications. Moreover, the calibration step should also clarify that many alternative models may fit or explain the same observational dataset(s).

Typically, a model is only useful for decision support if it is perceived to be credible by stakeholders; often model credibility is primarily influenced by its ability to simulate what has been observed in the socio-environmental system. This can be challenging as stakeholders often obtain an understanding of inherent uncertainty in the modeling process from their everyday experience of the weather report. However, rather than immediate evaluation being available, as it is for a weather forecast, the timeframe of IWRM processes represented may be combinations of months, years, decades, and even longer. Thus, continual evaluation of model outputs such as is done with weather forecasting is generally difficult to conduct. Rather, the IWRM model calibration functions best when it provides tests that are meaningful and intuitive to stakeholders, which in turn facilitates building the stakeholder trust required for adopting the modeling results.

5.4 Uncertainty analysis

Once a model is calibrated to what is known about the system it can become a generator for predictions in other situations, where data are typically not available. Model predictions portray the estimated effect of changes to model inputs that represent current stresses (such as land use management, or stream or aquifer pumping rates), and/or future conditions of which there could be many in IWRM cross-sectoral issues (such as changes in climate, energy use and demographic patterns, or policy changes like managed aquifer recharge opportunities, and water trading rules). However, a model's ability to create representative predictions is expected to be worse than its ability to simulate calibration conditions. There is uncertainty in the model that was constructed – not only in the ability of field, social survey and other observations to constrain the model inputs and the necessarily simplified structure of the model that represents the IWRM system being modeled – but also in how specified future conditions represent what actually occurs. An *Uncertainty analysis* describes the uncertainty in the model output under stipulated conditions, input data used to calibrate the model, model structure and other assumptions, parameterization, output data used for calibration and future scenarios used for simulation of the model.

If model outputs used for calibration are very sensitive to one or more model factors (that is, model outputs vary substantially), the plausible values of the model factors will be constrained in calibration, and their uncertainty is reduced. When those model factors are also important to model predictions, the prediction is expected to have less uncertainty. When calibration data do not appreciably constrain the model factors important for a prediction, that prediction is constrained primarily by soft-knowledge and may have a high degree of uncertainty.

There are many ways to assess and describe uncertainty in the predictions (Guzman et al. 2015); the best representation will depend on the context in which the IWRM problem operates, and the requirements and understanding of the stakeholders (Hunt 2017). In IWRM, where cost-benefit trade-offs are often assessed, a more quantitative approach to characterizing uncertainty can be valuable (Guillaume et al. 2016). Most straightforward is a simple reporting of model predictions under a few specific conditions (e.g., streamflow depletion, land use practices, water allocations or environmental flow releases under drought and wet conditions).

However, most approaches involve a large number of simulations under different conditions so that the uncertainty can be described over the full range of modeled behaviour. Basic investigation of uncertainty might include a sensitivity analysis (e.g. Hill and Tiedeman 2006; Norton 2015), which adjusts different model factors by some known amounts and examines the effects on the key model outputs. Higher level uncertainty investigation might include Monte Carlo methods that report uncertainty in terms of a probability distribution of predictions/simulations, which are generated by running the model many times using samples pulled from a probabilistic representation of the model factors (referred to as realizations). Monte Carlo is computationally expensive because there are many combinations possible, hence many model runs are required to characterize the behaviour of the model across the scenario and parameter space (Anderson et al. 2015, pp.471–476). This is especially the case for IWRM modeling where potentially a large number of input and output variables are of interest as the investigations expand to multiple systems that incorporate hydrological, ecological and socioeconomic systems. It may therefore be more appropriate to sample the model inputs more efficiently; Latin Hypercube, quasi Monte Carlo and constrained walking methods (Campolongo et al. 2007) are examples of pseudo Monte Carlo sampling methods. Emulation methods are increasingly being used to build faster-running surrogate models of those models whose runtimes preclude Monte Carlo type sampling (Asher et al. 2015; Razavi et al. 2012; Machac et al. 2018). In this way, sensitivity and uncertainty analysis can be undertaken using the response surface of the surrogate model (e.g. Yang et al. 2018).

There are two additional uncertainty approaches that are well suited for IWRM problems. One is scenario modeling, especially of plausible but extreme-case scenarios (Anderson et al. 2015, pp.458–460; Kwakkel, 2017; Guivarch et al. 2017; Mills et al. 2018; Anderson et al. 2018). In this case a set of model inputs is developed that represent factors that, when combined, simulate the conceivable extreme (but also intermediate) outcomes that might be reasonably expected. In this case, the analysis represents outer edges and intermediate points of the envelope of possible model forecasts, which can inform the IWRM decision making beyond simple reporting of expected outcomes. This approach is well-suited to simulating future conditions such as climate scenarios and cross-sectoral influences and can be undertaken in a flexibly prescribed robust decision-making framework. A second, more qualitative approach is quality assurance of the modeling process itself (Refsgaard et al. 2007) where checks are undertaken to ensure that a model has been properly applied, and decisions and choices are monitored and recorded to enable transparency and reproducibility of the process.

5.5 Testing of model robustness

Before it can be used in the *Application Phase*, the model should be tested in several ways. As the model is constructed, the individual elements must also be tested to ensure the construction correctly implements the rules as intended. Standard model testing includes debugging and unit-consistency checking (Balci, 1994; Jakeman et al. 2006). As new components are being added to the model, additional tests are run to ensure the new component has not generated errors in the already tested parts of the model. Tests of sufficient scale and scope increase confidence that model behaviour is as intended. In practice, this approach is similar to Bayesian inference – rarely can it be determined that model behaviour is 'correct' across all possible scenarios, but a large number of successful tests increases confidence (Davidson-Pilon 2015).

The ability to invoke these tests in an automated manner can help ensure a sustainable pace of model development. This is especially true for larger-scale projects as automated running of tests (which may be run after a change in a model for example) aids in reducing the time and resource costs that may be incurred as model complexity increases. Having such tests, and the requisite infrastructure in place assists in the model construction process, maintenance (see Section 7.3 Monitoring and maintenance), and may serve as further technical documentation of the underlying processes within the model (see Section 7.1 Documentation). However, effective testing is much broader than model verification, including evaluation against a model's intended purpose and assessing the accuracy of model outputs (Bennett et al. 2013).

Conditions simulated during calibration may not encompass the range of conditions that the model will use to generate predictions in the *Application Phase*. Tests of the model's robustness can build credibility in these forecasts, including checks such as:

- can the model successfully simulate extreme conditions (e.g. drought or flooding)?
- do test cases generate output that is consistent with manual calculations or other existing models?
- does altering a variable to an extreme value change model outputs in an expected way?

Such checks may also reveal issues with data sets in use such as:

- implausible positive/negative values (e.g. data sets were generated with interpolation)
- mismatch in expected spatial and temporal resolution and range across model elements
- mismatch in assumed value types exchanged between models elements, e.g. a categorical classification given as a textual representation ("one") as opposed to its numerical equivalent

A common form of qualitative assessment involves domain experts who review the model logic and simulated output details to assess the degree to which a model appears effective in terms of its stated aims (i.e., face validity) (van der Sluijs et al. 2005). There may also be the opportunity to quantitatively assess predictions directly, using a split-sample or cross-validation approach (where some data are not used during calibration, but instead provide test cases). If insufficient data are available for this, then a post-audit might be performed after sufficient time has passed that a prediction can be evaluated, or in an ongoing process as new observations are acquired such as those derived from adaptive management.

A final check involves revisiting appropriateness, or a model's fitness-for-use. This could include assessing whether the user interface is sufficiently easy to use by the intended users, easy to understand (from the user's perspective, not the modeler's), and sufficiently well explained in lay terms. For models developed for participatory or educational purposes, the criteria pertaining to its usefulness may be more important than achieving a high performance or accuracy (Elsawah, et al. 2017). Using the case study of the Chesapeake Bay coastal system, Allison et al. (2018) argue further that, for addressing wicked problems in socio-ecological systems, it is more important that one seeks holistic modeling of results yielding robust directions of system change than high numerical precision of outputs achieved through increasing model complexity. Jakeman and Letcher (2003) argue similarly that, in IWRM modeling, the broad objective should not be about treating system outputs as accurate predictions. It should be aimed at allowing differentiation between system outcomes under different conditions (e.g. policy drivers), at least with a qualitative confidence.

6. Phase 3: Application

Application of the model ensues according to the modeling purpose determined during the *Planning Phase*. For simulation games, mathematical models and computer simulations, using the model includes both running the model with various settings or options and analyzing the generated output. For diagrammatic and other models used for thinking and learning, application of the model is more qualitative and generally consists of one or more discussions and a report concerning the contents. Yet, such discussions are also critical for mathematical models and computer simulations, as this phase can enhance understanding of impacts of decisions made regarding model structure and input data from earlier steps.

This phase comprises three steps: *Experimentation*, *Analysis and Visualization,* and *Communication*. These steps are often iterative, with discussion about the results from initial model runs stimulating additional questions that lead to further experimentation, analysis and discussion. The modeling project is most effective when the *Application Phase* provides stakeholders with an understanding of how the model works, builds confidence in the model, and supports substantive discussion about IWRM trade-offs and issues.

6.1 Experimentation

There are two key considerations for practical experimentation in order to obtain robust results: which parameter and other factor combinations are to be used, and how many runs are required. Each modeling effort will have different responses, though some broad generalizations apply across most IWRM problems.

A mathematical or computational model will typically have two broad types of manipulation. The first selects between specific scenarios of interest, where scenarios reflect simulated system stressors or conditions different from calibration stresses and conditions. Scenario definition can encompass a range of possible changes, such as: different policy options (e.g. water trading rules, regulation of water quality, varying operating rules or conditions for a dam); and conditions (e.g. high or low rainfall, high or low farm input prices and product returns, land use set at historical patterns or allowed to vary over time); together with the parameter values or distributions that define the scenario (such as the amount of rain each day during a high rainfall year). The second manipulation goes beyond specific scenarios of interest by using computational methods to explore the plausible ranges of model parameters and other factors more broadly.

Efficient methods of parameter space sampling may be used to limit the number of simulations required, which is particularly useful when model runtimes are prohibitively long. Although the process is similar to the uncertainty analyses conducted during the *Development Phase*, the purpose and hence selection of input values and the analysis are different. Here, the model is manipulated to explore 'what-ifs' posed by stakeholders and to understand the uncertainty associated with specific scenarios rather than to characterize the robustness of the model.

6.2 Analysis and visualization

The objective of the *Analysis and Visualization* step is to distil the insights gained from model development and experimentation in order to identify those meaningful to the stakeholders, including decision makers. However, multiple scenarios and experimentation runs, combined with a likely diversity of interests and expertise of the stakeholders, can make the reporting lengthy and analysis complex. Simple analytical approaches such as regression methods are of limited use as there is typically no single equation for the overall system. Instead, multidimensional visualization methods (such as heat maps, box plots and arrays of charts) allow communication of important relations, insights and system responses. Communication may be further aided by contextualizing the presented analysis. Analyses may be contextualized by overlaying data on a map (providing spatial context), comparisons against historical events (temporal context) and simulated results (scenario context).

Some key questions to consider during the *Analysis and Visualization* step:

- how do outputs important for decision making respond to changes in inputs, parameters and other factors, including interventions?

- are there thresholds or tipping points in the parameter space?
- what are the likely outcomes to the questions addressed by the modeling?
- are the results sufficiently accurate?
- are some stakeholders more adversely affected by model shortcomings than others?
- in addition to the most likely outcome predicted by the modeling, what is the distribution of outcomes for individual stakeholders?

In addition, if comparing IWRM options:

- can any options be excluded because a better option exists that applies to all situations tested (referred to as dominance)?
- are best options in some situations undesirable in others?
- are there robust options that are good in all feasible (or even probable) situations even if there are no situations in which they are the best? (Lempert and Collins 2007).

Once all possible model results are culled to those that have utility and relevance for the IWRM decision-making process, they are finalized for distribution beyond the modeling team.

6.3 Communication

The final aspect of model application is to communicate the insights from the modeling process in a way that most effectively contributes to model credibility and to policy or other decision making. One of the key challenges in an IWRM process is how to communicate with stakeholders about model results in a way that enables the stakeholders to understand the system being modeled. At a minimum, the model's scope, assumptions and capacity should be clearly specified in terms of what the model can and cannot do, to help the audience understand the model limitations.

To achieve effective communication, the modeler should consider the needs and background of the stakeholders and tailor the results accordingly. Even a simple model may be difficult to explain, particularly when there is a large disparity with respect to technical knowledge between the modelers and the stakeholders. One must balance an inclination to relate too much detail against appearances of hiding important model information. Skilful meeting facilitation will often be required to ensure equity among stakeholders, which is more challenging where there are diverse or contentious stakeholder interests and with increased importance of decisions.

An audience analysis may be useful to help plan the communication. This analysis includes questions about the motivations for the stakeholders' participation, their understanding of the system, and their prior experience with models (Hall et al. 2014). It may be desirable to segment the stakeholders based on the audience analysis, for example by offering some groups tailored discussion beforehand, and therefore providing a better opportunity for all to contribute meaningfully when they all meet together.

One approach to communication is to focus on the issue for which the modeling was developed, presenting the key insights and connections as a narrative (Richels 1981). The objective is to be clear and concise, and assist stakeholders in understanding the relevant issues, with the modeling supporting the discussion. Once the essential story is clear, more detailed discussion is required about the critical modeling assumptions, limitations, and their implications for results and recommendations.

Another approach is to use iterative discovery, where the modelers and stakeholders jointly investigate a series of scenarios, particularly for complex problems that involve deep uncertainty (Fu et al. 2015). Rather than simply providing the results, this method involves running the model alternating with discussion to raise new questions and propose further scenarios to be run. The iteration fosters a knowledge partnership between modelers and stakeholders, including decision makers, enhancing the modelers' understanding of stakeholder needs and their understanding of modelers' knowledge, thus leading to more useful presentation of results. This contributes to stakeholder confidence in the modeling (and modeler) and therefore greater acceptance of the model results. Moreover, both the stakeholders and the modelers attain a better understanding of the modeling assumptions and how they could potentially impact any decisions.

To address confusion over terms or concepts in both the model and analytical techniques used, the verbal or written presentation of models should be carefully crafted so that key, but unfamiliar, terms are illustrated with examples and thought experiments, and feedback should be sought from the audience to verify that they understand. The presentation should utilise images, visual aids and strategies (Kelleher and Wagener 2011), as well as actual examples, say from similar systems, particularly when complex ideas are being discussed.

In addition to the potentially technical nature of the discussion, stakeholders may have a different perspective of the system that can lead to difficulty in forming a mental picture of how the model represents the system and dissonance with their pre-existing understanding of that system. If the modeling provides a different system view than that held by the audience, it is important to not dismiss their perspective, but to use their own relevant observations to begin to see the alternative perspectives (Hall et al. 2014). Such perspectives can form the basis for additional scenarios.

7. Phase 4: Perpetuation

The *Perpetuation Phase* plans for the future. This phase comprises three steps: *Documentation*, *Process Evaluation*, and *Monitoring and Maintenance*. Where relevant, this phase integrates the model into ongoing policy processes and ensures it is maintained and updated when required, and/or when new observations become available so that the model can contribute to future decisions.

Models for decision support often require a high degree of technical development and testing to provide appropriate estimates as meaningful input to decisions, especially those involving high risks and intensive investments. This development can incur large costs. Reuse of the model for future or similar applications can help to justify that cost. For example, an Australian multi-year basin-scale modeling investment assessed future water availability in the Murray-Darling Basin and the impacts of development, water extraction and climate (CSIRO 2008). Subsequent model outputs continued to provide scientific evidence to assist in later development of the Murray-Darling Basin Plan.

In contrast, some models are used only once. For example, models developed as thinking tools for a given stakeholder group and timeframe are required only during the participatory process, to generate the intended learning (Pidd 2004). Even in such cases, however, the steps in the *Perpetuation Phase* should be explicitly considered. For example, while a full process evaluation is unlikely to be appropriate, reflection on the modeling process and discussion with the stakeholders about what they found useful can improve future similar modeling exercises.

7.1 Documentation

The type of model documentation and the detail included depend primarily on who will use the model(s) in the immediate present and future. There are three common types of model documentation: user documentation, technical documentation, and the project report.

User documentation should assist users in running and interpreting the model outputs. It should be focused on providing clear instructions for the main model objectives. This documentation may include:

- user interface description (including screenshots)
- interpretation of each input and output along with sources of data
- tutorials with incremental examples for training and credibility
- examples that reflect real scenarios
- guidance for running the model and description of potential common pitfalls.

Technical documentation has two parts. The first is a model archive that includes machine-readable model input, output, executable, and source code (if available). The second provides detailed descriptions of the model(s) and justification for the choices made in the model design. It will typically include:

- choice of modeling type and method (including how limitations are managed)
- assumptions and their justification or reasons
- rules and equations
- scales of representation
- variable definitions and codes (data dictionary)
- calibration method and results, preferably with relevant uncertainty assessments
- data sources, including references to theory.

Such documentation serves two purposes: scientific credibility and support for future development. Model results must be able to be reproduced and replicated if they are to be considered part of the scientific method (Morin et al. 2012; Peng 2011). Technical detail about the modeling is therefore critical for credible model use in IWRM applications. In addition to demonstrating scientific rigour, such detail may be necessary to meet legal obligations associated with some decision support models.

If a model is intended to have an enduring presence, then technical documentation that includes description of code or software is necessary to allow a future developer to modify or add to the existing code base. Its role is to describe each function, method, routine, or class and why it was constructed in the way that it was. Modern code documentation is frequently done within the code of the model itself using a variety of tools available to auto-generate or extract that documentation. Examples depicting how the code can be used may be included and doubly serve as executable test snippets. The advantage of including documentation within the code itself is that it is more likely to be updated as the model is developed or modified.

Well-documented (and tested) code can be considered a necessary requirement to achieve full reproducibility and transparency and eases the maintenance burden. Often textual or narrative descriptions of the represented processes do not fully capture assumptions made during development (both conceptual and technical), which results in implementation differences. Subsequent implementations relying solely on descriptive documentation may have differing behavior, compromising model verifiability (Hutton et al. 2016). If elements of the model(s) were developed in a sufficiently abstracted manner it is possible to reuse these beyond the original use case. This is the underlying concept applied in component-based modeling practices which require models to be coded to a standardized specification (Peckham et al. 2013). Adhering to such standards may also allow semantic information to be extracted, enabling high-level comparisons between different models within a model repository.

Several guidelines exist that are intended to ensure adequate information is provided to enable replication and reproducibility. These include reporting for deterministic models (Anderson et al. 2015; Reilly and Harbaugh 2004), the ODD protocol (Overview, Design Concepts, and Details) for agent-based models (Grimm et al. 2010; Müller et al. 2013) and SD-Doc approaches for documenting system dynamics (Martinez-Moyano 2012).

The project report is written for the client who commissioned the modeling. It summarizes the analysis and provides a written form of communication focusing on the specific scenarios of interest. Key elements include: scenarios and results, selected graphical and other visualizations (interactive where warranted) to highlight messages, and information about the limits of the results (including assumptions, uncertainty analysis, and plausible parameter values that would generate different results).

Regardless of model purpose, model documentation should be continuously developed over the course of the project. Furthermore, it is difficult to conceive of a situation in which a single person is able to contribute all the requisite domain knowledge, model implementation details, model interactions, and data including sources, types, and pre- and post-processes applied. Documentation is therefore most likely to be developed collaboratively.

7.2 Process Evaluation

Evaluation of the modeling process assesses whether the desired role of the modeling was effectively and efficiently achieved within the broader project. A formal process evaluation informs future modeling projects and should consider issues such as:

- did the model and modeling process meet the role originally envisaged, and were changes to that role intended and appropriate?
- how effective was the engagement of stakeholders?
- who needs to be added to any future modeling process?
- did the project meet time and budget objectives?
- how much adjustment was required to the original plans?
- what would have improved the modeling process, and at which phase/step?

Depending on the modeling purpose, several criteria have been developed for evaluating a modeling exercise. For example, Haasnoot and Middelkoop (2012) suggested three criteria: predictive success (has the future turned out as envisaged), decision success/robustness (have 'good' decisions subsequently been made) and learning success (have scenarios enabled participation and learning). A different set of criteria was suggested by Alcamo and Henrichs (2008): relevance, credibility, legitimacy and creativity. In a post-audit, Merritt et al. (2017) identified 33 factors for realizing success in an analysis of 15 water resource projects. Of the four factors considered to be the most necessary —all of them largely non-technical—three related to aspects of stakeholder engagement in the modeling process, the other to critical thinking around problem framing and the role of models.

7.3 Monitoring and maintenance

The final step is to put into place the plans and mechanisms to ensure that, if needed, the model is updated as required and continues to be relevant for any policy process in which it is embedded. This can be particularly problematic if the policy organization does not have technical expertise or funds to maintain the model(s), or if a model has been developed by an outside entity so that a transition process is required.

If the model is to be maintained beyond its final documented form, the key elements of the maintenance plan are to establish a process for updating any input data, documenting new data sources, and deciding the timing and assigning responsibility for the updating. A succession plan is also required to provide continuity and maintain the knowledge base about the purpose and results of the model. This plan should include lists of materials (including documentation and training materials) and where they can be obtained.

Many models are revised and adapted for different but related policy questions (for example, a similar decision but located in a different area of the problem domain). Maintenance questions to be considered include:

- how easy is it to adapt the model (conceptualization as well as implementation), for example to another catchment or set of water resource issues?
- what expertise, data and other resources are required in order to make changes to the existing model?
- what changes in model design might be needed in the future (for example, boundary conditions, scales, processes, etc.)?
- who can approve changes?
- what are the implications for the policy process when important existing model outputs appreciably change as the model is changed?
- which steps in the modeling process will most likely need to be reiterated or revisited, and can any steps be excluded in specific situations?

8. Five key areas for future development in IWRM modeling

Although there is always room for improvement, IWRM is now endowed with a rich set of techniques for modeling both social and biophysical aspects of a system. As described in Section 2, there are also many authors providing different prescriptions and recommendations for operationalizing IWRM. We have argued here that the overarching challenge for the future is integration and implementation (Bammer, 2013) of the knowledge gained from experience. While the application of IWRM in regions with weak institutions is often seen to be challenging, the need to better tailor analysis to policy making contexts is universal – a key concern, for instance, in the field of policy analytics (Tsoukias et al., 2013; Daniell et al., 2016; De Marchi et al., 2016). We focus now on five key areas for future development: knowledge sharing, overcoming data limitations, informed stakeholder involvement, social equity, and uncertainty management.

Knowledge sharing

The ability of the IWRM modeling community to share and exchange knowledge about the practices employed throughout the modeling process is essential for growing the field and expanding its applications. Knowledge about how to frame a particular IWRM problem and perform particular modeling activities (i.e. knowledge-in-use) is valuable for beginners learning the craft of modeling, distilling information about learnt lessons, and promoting ideas about new solutions. Knowledge sharing of practices is also valuable to inform comparison across multiple dimensions (e.g. methodological design, case studies, issues of interest).

A prime challenge is to document systematically, and with sufficient detail, the approach taken in projects so that the knowledge of how to do IWRM modeling and lessons learnt accrue for future projects. It should be possible to document a wide selection of IWRM projects to form the basis for on-going knowledge sharing in the future. Systematic and consistent documentation practices and tools for this purpose still need to be developed. To support transparency and learning, documentation should not only be focused on describing the modeling process as 'what happened', but cover the reasoning (i.e. why did it happen) behind the decisions and observed outcomes throughout the process. And ideally, it should entail critical reflection on what could have been done differently (Lahtinen et al., 2017).

One promising approach is the use of patterns to elicit, capture, and formalize this knowledge (Alexander et al. 1997). A pattern is defined as a (representation of a) solution to a recurrent problem in a particular context. A pattern could be with respect to any component of the IWRM process where modeling-related decisions are taken. Patterns can be represented in different forms and presentation (i.e. diagram, template). Regardless of the presentation, a pattern must have the following elements: (1) a name to facilitate use and communication, (2) problem description, (3) solution, and (4) context. The premise of the pattern approach is that once the successful practice has been recognized as a pattern and expressed in some pattern form, it may then be reapplied to similar problems/contexts, which will eventually lead to improved practices, new observations, and new or refined existing patterns. Discovering and capturing the relationships among patterns results in a 'pattern language', which provides a shared lexicon for the community to communicate about the different contexts where patterns can be used.

Overcoming data limitations

Data can pose a challenge to IWRM, especially in relation to the multiple and diverse types of data (including quantitative and qualitative) representing the various system components, and their different scales and quality. The type of data for a given project can determine whether or not a certain type of model can be used, or how well it can be applied. To address this, there has been increased interest in more flexible, semi-quantitative modeling approaches, such as Bayesian networks (e.g. Ticehurst et al., 2007), as well as different couplings of multiple methods (e.g. Nikolic and Simonovic 2015).

Limited data can place a major constraint on IWRM modeling. Basic hydrologic and meteorological data can be patchy and unreliable in countries in developing regions and those where governments place a low priority on investment in monitoring networks. New forms of observations, such as remotely sensed data, provide promising opportunities for IWRM, particularly in data-poor environments. However, these require more efficient ways of extracting useful information from the raw data (Montanari et al. 2013). Poor availability of socioeconomic data, with the general exception of census data, is widespread, and presents a major barrier to understanding feedbacks between society and the environment, undermining many water management endeavours (McDonnell 2008). Social media present an opportunity for bridging at least some of these gaps. In addition, stakeholder involvement in the modeling process will continue to play an important role in capturing social variables and processes.

Informed stakeholder involvement

A common criticism is that stakeholder involvement is inadequate in decision support system (DSS) exercises generally, not just in IWRM (for example Zasada et al. 2017 in a survey of EU-funded research programs on DSS for agricultural and environmental issues). This is despite recognition (e.g. Merritt et al., 2017 for water resource projects, and McIntosh et al. 2011) that attention to associated non-technical issues (i.e. social and behavioral) is vital to success, in particular when the purpose is to support decision making and social learning. For example, as noted earlier, Merritt et al. (2017) identified aiming for open and transparent communication, good relationships and trust, and sufficient interaction between the development team and users as three of four main factors crucial to success. Thus, time spent in the design phase, where stakeholder engagement usually begins, is time well spent to avoid rushing into poor decisions that can lock the project onto the wrong path (Nicolson, 2002). Projects therefore require the will and resources for attending to these aspects. This may also require more flexible funding arrangements that recognize the value in fostering an evolving understanding of the problem, and imposing soft deliverables (e.g. problem formulation documents) rather than rushing into quantitative deliverables.

A more technical issue in this respect is integration of stakeholder interests, preferences, and attitudes to risk into the modeling process, for example in terms of indicators or objective functions. Variations in all these elements can lead to completely different results and negotiated solutions. Model output can be converted into indicators by filtering the uncertainty in many ways, e.g. using different robustness criteria (e.g. McPhail et al 2018), leading to different (rival) problem framings (e.g. Quinn et al. 2017). This is not as simple as just obtaining and providing data from/to the end user. More thought and effort needs to be paid to methods like interactive data visualization that meet stakeholders' information needs and empower them to explore the problem and devise possible solutions.

Bridging scales is a particular challenge in stakeholder engagement within IWRM. In principle, stakeholders are well placed to comment on their immediate problems and changes they wish to see. However, they may not be in a good position to account for their own future needs, let alone consider how best to achieve them given others' preferences and interactions within the system. Modeling plays an important role in supporting stakeholders in making sense of the IWRM situation at longer timescales and larger spatial scales, but connecting abstract strategic ideas to concrete operational concerns remains difficult. Rather than trying to determine an ideal scale to use in IWRM models, it will be important in the future to reflect on the range of strategies available for bridging scales in a way that brings the necessary stakeholders together to achieve meaningful progress when implementing IWRM.

Social equity

Social equity is often sidelined in IWRM models, especially compared with standard cost-benefit considerations of different trade-offs. The distribution of benefits from water and, in particular, whether the needs and rights of different groups are met (Peña 2011) warrants greater consideration. The need to better consider the totality of benefits and costs associated with water management (including indirect outcomes, non-use values, option values, etc.), and how these vary between each person and group, is a broader challenge for IWRM in general.

Social equity in water management is not just about equity of outcomes (benefits and costs), but also equity in the decision-making process, especially having a voice or opportunity to influence the process (i.e. procedural justice; Syme et al. 1999). Given that the equity dimension is typically poorly captured in models, its consideration in the modeling process then relies heavily upon interpretation of model results and implications (Stojanovic et al. 2016).

Adequately addressing issues of equity in modeling necessitates careful consideration in the *Stakeholder Planning* step to ensure fair representation of stakeholder groups in the process and consideration of social processes and alternate knowledge sources or potential solutions – particularly in the *Planning Phase* and *Application Phase* steps. Budds (2009) argued that failure to do so in the La Ligua river basin in Chile and reliance upon a "purely physical assessment in response to a situation that was predominantly socio-political" led to a positioning of the model-based assessment and its commissioning agency as the only legitimate knowledge source, which closed down a range of possible solutions. Decisions made using the assessment then disadvantaged poor farmers who had not created the groundwater scarcity problem (Budds, 2009). In the context of

IWRM, the modeling process should facilitate procedural justice and at the very least not be a further barrier to equity.

Uncertainty management

Uncertainty pervades the treatment of IWRM problems. Users and managers of a water resource deal with uncertainty every day, in a variety of ways. The use of modeling itself is a powerful way of organizing information to understand and reduce uncertainties. Measures for managing uncertainty in management and modeling are still mostly considered separately, rather than being integrated, though some research areas are making progress on this front, e.g. in the deep uncertainty literature (Kwakkel et al. 2016; Maier et al. 2016). Much of the attention to uncertainty in the water resources literature focuses on sensitivity and uncertainty analysis of the hydrological models. Unfortunately, these are among the most certain of integrated model components, and the human and ecological processes warrant much more attention (Hunt and Welter 2010). Here we see an opportunity to prioritize uncertainty sources and deal with those most crucial. Among other things, this will involve attention to uncertainty assessment of model components but also the propagation between the component linkages, where there are often feedbacks. Qualitative uncertainty assessment (e.g. der Sluijs et al. 2005; Refgaard et al. 2006) will be a necessary, perhaps even the main, ingredient.

A key issue is understanding how uncertainty accumulates and diminishes within an IWRM process (including the model itself), and therefore where efforts can be targeted to constrain it. Combining uncertainty in future conditions, system understanding and stakeholder preferences quickly leads to an explosion in possible system outcomes, which can be overwhelming for stakeholders to consider. In addition to obtaining additional information or facilitating consensus processes, uncertainty can be made more manageable, for example by using adaptive approaches and looking for robustness rather than eliminating uncertainty. Especially where uncertainty leads to disagreement, these techniques can be important to achieve progress in implementing IWRM without needing perfect understanding of a system. Work on these techniques has not, however, been completely synthesized and needs further efforts to support their implementation.

9. Conclusion

Despite promising benefits and high expectations, the potential of IWRM in translating integration aspirations to successful on-ground results has not yet been fully realized. It is well recognized in the literature that modeling has a crucial role to play in operationalizing and successfully implementing IWRM. This paper attempts to contribute to improving the implementation of an IWRM modeling project by providing practical and fit-for-context guidance of the practices employed through the various modeling phases and steps. These practices explain the details of employing IWRM modeling.

Our general approach identifies four broad phases that occur during the modeling process: *Planning*, *Development*, *Application* and *Perpetuation*. These phases are common to diverse IWRM projects. Each phase comprises several steps or tasks. While one or more steps may not be required for some projects, it is valuable to consider the relevance of each step so that omission is an explicit decision and not simply an oversight. In practice, there will be many ways to implement each step. Appropriate methods and level of stakeholder engagement depend on the specific characteristics of the IWRM problem - aspects of the system being modeled as well as other contextual factors (e.g. funding, institutional setting, data available or level of stakeholder conflict). We have therefore focused on the objectives of the step and guided how the step may be undertaken.

Finally, we identified some important gaps in IWRM modeling practice-related research, highlighting the need for advances in knowledge sharing, overcoming data limitations, informed stakeholder involvement, social equity, and uncertainty management as well as some potential methods for answering those questions.

In short, effective IWRM modeling should involve a process and set of practices that are fit for the given context and well-grounded in the IWRM problem at hand. The implementation of effective modeling practice can play an important role in facilitating the *what* and *how* of IWRM, by contributing to identifying and understanding of the elements that underpin the problem, and guiding the questions to ask and the issues to address.

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