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Integrated Groundwater Management: An Overview of Concepts and Challenges

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Abstract

Managing water is a grand challenge problem and has become one of humanity's foremost priorities. Surface water resources are typically societally managed and relatively well understood; groundwater resources, however, are often hidden and more difficult to conceptualize. Replenishment rates of groundwater cannot match past and current rates of depletion in many parts of the world. In addition, declining quality of the remaining groundwater commonly cannot support all agricultural, industrial and urban demands and ecosystem functioning, especially in the developed world. In the developing world, it can fail to even meet essential human needs. The issue is: how do we manage this crucial resource in

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an acceptable way, one that considers the sustainability of the resource for future generations and the socioeconomic and environmental impacts? In many cases this means restoring aquifers of concern to some sustainable equilibrium over a negotiated period of time, and seeking opportunities for better managing groundwater conjunctively with surface water and other resource uses. However, there are many, often-interrelated, dimensions to managing groundwater effectively. Effective groundwater management is underpinned by sound science (biophysical and social) that actively engages the wider community and relevant stakeholders in the decision making process. Generally, an integrated approach will mean "thinking beyond the aquifer", a view which considers the wider context of surface water links, catchment management and cross-sectoral issues with economics, energy, climate, agriculture and the environment. The aim of the book is to document for the first time the dimensions and requirements of sound integrated groundwater management (IGM). The primary focus is on groundwater management within its system, but integrates linkages beyond the aquifer. The book provides an encompassing synthesis for researchers, practitioners and water resource managers on the concepts and tools required for defensible IGM, including how IGM can be applied to achieve more sustainable socioeconomic and environmental outcomes, and key challenges of IGM. The book is divided into five parts: integration overview and problem settings; governance; socioeconomics; biophysical aspects; and modelling and decision support. However, IGM is integrated by definition, thus these divisions should be considered a convenience for presenting the topics rather than hard and fast demarcations of the topic area.

1.1 Introduction

Managing groundwater has all the features of "wicked or messy" problems (Rittel and Webber 1973), which have multiple stakeholders and decision makers with competing goals, and where the systems of interest are complex, changing and multifaceted – having interactive social, economic, and ecological components – that are subject to a range of uncertainties caused by limited data, information and knowledge.

It is also a grand challenge problem in its severity, pervasiveness and importance. Stores of groundwater represent over 90 % of readily available freshwater on earth (UNEP 2008). However, historically, groundwater has been out of sight and thus underappreciated. Moreover, the time for groundwater system degradation to reach thresholds of concern, even if recognized, is typically longer than many timeframes used in societal decision making. As a result, despite its importance groundwater remains a minor player in water resources management. This relative inattention is changing. Groundwater usage surpasses surface water usage in many parts of the world, which is expected to increase further with advances in drilling and pumping. As well there is a growing awareness of the crucial connectedness of freshwater systems (Villhoth and Giordano 2007), and competition for all types of water has intensified across the globe, driven by the growing world population, and increased agriculture, industrial and economic development. Finally, the hidden nature of, and difficulty in characterizing, groundwater systems mean that once a groundwater system is degraded it is not quick, cheap, or easy to remedy. In this way a precautionary principle applies: an ounce of prevention truly may be worth a pound of cure.

The dependence of human and ecological communities on groundwater and their respective challenges varies substantially across the globe, but in no location is groundwater not utilized. The dependence of communities on groundwater can be seasonal or episodic; for example the resource may become critical to survival during severe drought when surface water resources run dry. There are countries, such as Belgium, Denmark, Saudi Arabia and Austria, where over 90 % of total water consumption is sourced from aquifers (Zektser and Everett 2004). However, on average, groundwater comprises approximately 20 % of the world's water use. In many humid regions, such as Japan and northern Europe, groundwater is mostly used for industrial and domestic purposes (Villhoth and Giordano 2007). In most countries outside the humid inter-tropical zone, groundwater is predominantly used for agricultural purposes, especially irrigation (Zektser and Everett 2004). Many large aquifers vital to agriculture, notably in India, Pakistan, Saudi Arabia, USA, China, Iran and Mexico, are under threat from overexploitation (Gleeson et al. 2012; Wada et al. 2012).

Where groundwater abstraction exceeds recharge over long periods and over extensive areas, the subsequent decline in watertable level affects natural groundwater discharge, which in turn may have harmful impacts on groundwater dependent streams, wetlands and ecosystems (Wada et al. 2010). Furthermore, lowered groundwater levels can reduce well yields and increase pumping costs, as well as lead to land subsidence on large scales (Konikow and Kendy 2005). The last can be particularly important. When sufficiently dewatered, accompanying aquifer compaction cannot be reversed, and no options are available to regain the lost aquifer storage. The groundwater in this case is truly "mined" and non-renewable. Partly due to its hidden nature, groundwater usage in many regions has been less monitored than surface water resources. Groundwater managers are typically "flying blind," especially in less advanced countries. Impacts of groundwater overexploitation and pollution can remain undetected for decades or even centuries, presenting further challenges for managing today's resource.

In addition to the poor scientific understanding of groundwater systems, other drivers of poor groundwater management practice have included suboptimal governance, short time horizons of management, and the resource being undervalued and underpriced. More practically, even seemingly small technology shortcomings such as the difficulty and lack of metering hinder implementation of integrated groundwater management. Declines in groundwater quality have also adversely affected use, reuse, and management efforts. As a result, the major threats to groundwater are multi-faceted. The wide range of interests that contribute to groundwater problems illustrates that groundwater issues are not a sector, state, or national issue, but a human issue. Given the complex nature of groundwater systems and their increasing importance as a source of water, there is broad consensus that an effective integrated approach to groundwater management is essential.

1.2 Integrated Groundwater Management

Integrated Groundwater Management (IGM) is viewed here as a structured process that promotes the coordinated management of groundwater and related resources (including conjunctive management with surface water), taking into account non-groundwater policy interactions, in order to achieve balanced economic, social welfare and ecosystem outcomes over space and time.

A valuable meta-discipline for such a process is that of integrated assessment (IA) (Risbey et al. 1996; Rotmans and van Asselt 1996; Rotmans 1998). IA is defined by The Integrated Assessment Society (www.tias-web.info) as "the scientific meta-discipline that integrates knowledge about a problem domain and makes it available for societal learning and decision making processes." Also "Public policy issues involving long-range and long-term environmental management are where the roots of integrated assessment can be found. However, today, IA is used to frame, study and solve issues at other scales. IA has been developed for acid rain, climate change, land degradation, water and air quality management, forest and fisheries management and public health. The field of Integrated Assessment engages stakeholders and scientists, often drawing these from many disciplines." In terms of water resource management, Jakeman and Letcher (2003) summarise key features and principles of IA (Table 1.1) and highlight the role of computer modelling in the process. The latter will be expanded upon in Part IV of this book. It is noteworthy that IA can bridge multiple topics; for example: although water and energy assessments are distinct threads in the IA literature, the meta-discipline offers a way forward to capture multiple issues and their interactions/interrelations.

Table 1.1 Common features of integrated assessment (Adapted from Jakeman and Letcher 2003)

A problem-focussed activity, needs driven; and likely project-based
An interactive, transparent framework; enhancing communication
A process enriched by stakeholder involvement and dedicated to adoption
Linking of research to policy
Connection of complexities between natural and human environment
Recognition of spatial dependencies, feedbacks, and impediments
An iterative, adaptive approach
A focus on key elements
Recognition of essential missing knowledge for inclusion
Team-shared objectives, norms and values; disciplinary equilibration
Science components not always new but intellectually challenging
Identification, characterisation and reduction of important uncertainties in predictions

To produce outputs that are useful for an intended purpose such as decision making, it is essential that IGM and IA address all important dimensions of integration. Below we discuss ten key dimensions of IGM based on a framework applied to Integrated Modelling proposed by Hamilton et al. (2015). These dimensions correspond to the integration of multiple, often disparate, topics: issues of concern; management options and governance arrangements; stakeholders; natural subsystems; human subsystems; spatial scales; temporal scales; disciplines; methods, models, tools and data; and sources and types of uncertainty. This book covers a wide range of challenges relating to groundwater management and the integration across and within the ten dimensions, as well as potential solutions to addressing such challenges.

1.2.1 Issues of Concern

IGM recognises that many issues are interrelated and thus cannot be solved in isolation. For instance, the modernisation of traditional gravity irrigation systems reduces groundwater recharge important for other uses; economic incentives (subsidies) provided by agricultural or energy policies can thus drive groundwater use. Similarly, policy interventions initially designed to solve a groundwater management problem may interfere (positively or negatively) with other policies or groundwater activity. For example, the enforcement of pumping restrictions to ensure that the sustainable use is not exceeded may lead to drastic changes in agricultural production and competiveness of a local agroindustry.

Clearly, addressing groundwater issues in isolation can inadvertently create or exacerbate other problems. Therefore, a joint assessment and treatment of issues across the policy sectors in Fig. 1.1 is important to avoid adversely offsetting actions. A holistic treatment of groundwater related issues is also needed to ensure that all stakeholder views are included and conflicts considered. The essence of IGM consists of clearly articulating and making trade-offs to limit adverse impacts and balance the needs and values associated with competing objectives. This process can involve selecting appropriate environmental, social and/or economic indicators as evaluation criteria, and using integrated assessment and modelling to assess the system performance under different scenarios (Hamilton et al. 2015).

1.2.2 Governance

The governance dimension of integration is ubiquitous yet is often a primary stumbling block to effective IGM. Groundwater governance comprises the promotion of responsible collective action to ensure control, protection and socially sustainable utilisation of groundwater resources and aquifer systems. This is facilitated by the legal and regulatory framework, shared knowledge and awareness of sustainability challenges, effective institutions, and policies, plans, finances and incentive structures aligned with society's goals (GEF et al. 2015). Governance can

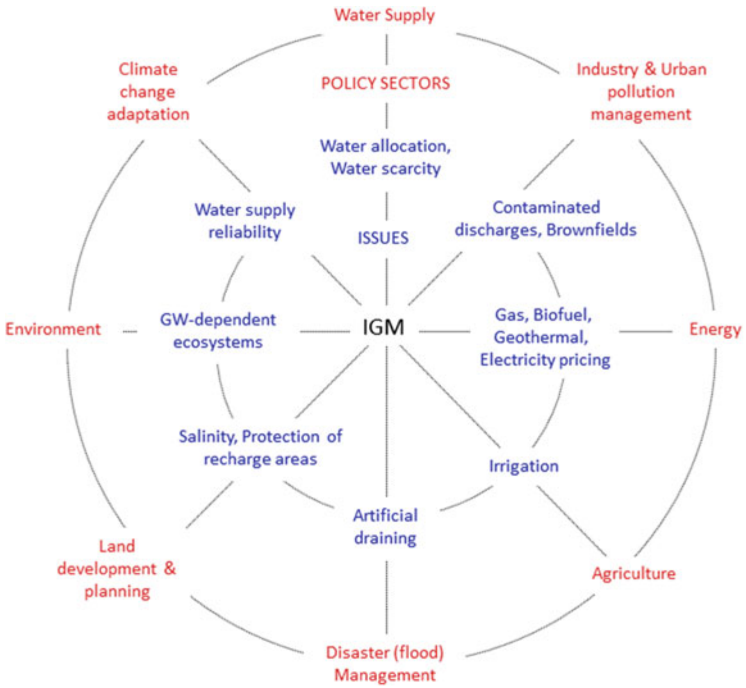

Fig. 1.1 Examples of diverse issues related to groundwater and their relevant policy sectors

be examined from various perspectives including institutional architecture, who is involved, and who is accountable for what to whom.

Such discussions include a mix of policy approaches, including the five types of instruments (Kaufmann-Hayoz et al. 2001):

- Command and control instruments such as regulatory standards, licences, and management zones; these tools aim to improve the behaviour of a target group through State intervention.
- Economic instruments such as taxes, subsidies or water markets, which influence micro-economic choices towards a desirable state, by influencing the costs and benefits of possible actions.
- Collaborative agreements which aim at strengthening cooperative behaviours between groundwater users, by enhancing non-economic motivations (altruism, reciprocity, trust, concerns for future generations)
- Communication and diffusion instruments, to distribute information aimed at influencing the knowledge, attitudes and/or motivations of individuals and their decision making (e.g. related to individual water consumption)
- Infrastructure instruments/investments, which describe the public sector investments intended to improve groundwater management such as those used to initiate managed aquifer recharge.

Ideally, decision makers should develop strategies and institutions that effectively combine these instruments to deliver acceptable environmental and socio-economic outcomes, and are also robust under potential changes to the natural and human settings (e.g., climate change, population increase). One of the main issues is ensuring the consistency of the interventions. Implementing one instrument may facilitate or inhibit the effectiveness of other instruments; it is important to consider possible synergies. IGM should provide a process for identifying intervention options and instruments and assessing their effectiveness under different scenarios. Groundwater governance is a complex process, where its effectiveness is influenced by challenges related to determining and implementing policies for groundwater allocation, and coordination of responsibilities across geographical, sectoral and jurisdictional boundaries.

1.2.3 Stakeholders

It is increasingly recognised that successful treatment of any wicked problem engages stakeholders appropriately. This particularly applies to groundwater management due to the invisible nature of the resource and the expense and related lack of high-quality information. Stakeholders are individuals or groups involved or interested in the problem – for example local/regional/national government, groundwater users, community groups, the water industry and those with relevant expertise (e.g. hydrologists, hydrogeologists, environmental modellers, agronomists, social scientists, ecologists, etc.). Though often avoided by groundwater scientists, the stakeholder engagement process is critical for effective IGM because it ensures that a broad range of interests, knowledge and perspectives are considered, shared and understood. Stakeholder engagement is also a valuable process in mutually educating, reducing conflict and building trust among researchers, decision makers and other stakeholders. Stakeholder engagement helps to develop a better understanding of demands on the resource and assimilates and publicizes scientific information used by managers. It also promotes mutual learning between users, managers, and policy makers in different domains (agriculture, water supply, energy, etc.). Perhaps most importantly, it can be considered as a necessary condition to gain acceptance of proposed management strategies needed for effective implementation by as many as hundreds or thousands of individual groundwater users. That is, those that are not included in the discussions about the groundwater resource are often those least likely to accept solutions proposed.

1.2.4 Human Setting

IGM operates within the human setting, including the social, political, cultural and economic characteristics of the stakeholders. One key role of groundwater managers is to make trade-offs between demand for water use and demand for groundwater sustainability. The demand for use is determined by prevailing market conditions and economic policies and to a lesser extent by societal values, including market conditions, policies and values concerning connected resources. The demand for groundwater sustainability and protection is determined by social drivers, including concerns for ecosystems and future generations. These drivers can in turn be influenced by the existing political context. Social drivers also shape the evolution of the institutional set-up, already described in the governance section above.

To effectively management groundwater systems it is necessary to understand how the human setting directly and indirectly relates to the groundwater system. This includes human responses to management interventions and other drivers like climate, and the socioeconomic impact of reduced access to groundwater or reduced groundwater quality. The human setting also underlies behavioural and socioeconomic factors that influence the adoption of better practices or new technologies identified by IGM.

1.2.5 Natural Setting

Most importantly, the natural setting forms the extent, limits, and service area of the natural resource from which all IGM must stem. This dimension relates to the integration and communication of the relevant scientific underpinnings and biophysical components of the system. The natural setting includes any substantive connection between aquifers and other natural features such as rivers, lakes, wetlands and springs. It also includes intra-aquifer connectivity within heterogeneous aquifers and inter-aquifer connectivity in multi-aquifer groundwater systems. The natural setting may encompass non-freshwater resources; the hydraulic connection between groundwater and the sea can be important as in estuary health and saltwater intrusion into pumping centres. IGM can also include joint consideration of groundwater and surface water systems with climate, vegetation, fauna and soils. It is increasingly being recognised that these compartments cannot operate or be managed in isolation, as demonstrated by the recent greater demand for conjunctive management of surface and groundwater resources.

1.2.6 Spatial Scales

The biophysical and socioeconomic processes related to groundwater systems occur at different spatial scales, ranging from global and regional scales (e.g. climate processes) down to the local scale (e.g. practices of individual farmers, endangered species restricted to a single spring, drinking water well protection zone). A single groundwater system can range from less than 10 km^2 to over 100,000 km^2 in size, and processes can operate at vastly different scales depending on the system. Biophysical processes can also operate at very different scales and boundaries than socioeconomic processes because groundwater flow is driven by gravity, not political boundaries. One of the key challenges of integrated assessment and modelling is accommodating the multiple spatial scales of system processes and interests. The stakeholders may also focus on scales that differ from the actual system processes, for example policy makers might have to develop strategies for groundwater management at a state or national level. Process upscaling/downscaling is commonly required to resolve potential mismatch of scales in integrated assessment frameworks. In many cases, mixed spatial scales are needed depending on what part of the system is represented.

1.2.7 Time Scales

Temporal aspects also operate at different scales – as might be expected when groundwater system processes typically occur over much longer time than human timeframes. The mismatch of temporal scales in IGM presents a considerable challenge in characterizing, understanding, and communicating aspects of groundwater systems, as well as how to manage them. Cause and effect may not be readily apparent due to substantial time lags between an action and its result; for example in some systems the effects of overexploitation of groundwater or poor land management may not be apparent in streamflow quantity or quality for several years or even decades. Similarly, even if extraction is reduced to sustainable limits, it may take decades before the effects are noticeable at land surface. Accurately attributing the effect of disturbance or management is further complicated by other confounding disturbances in the intervening period (e.g. extreme climate) and legacy effects from past practices (e.g., aquifers with low hydraulic diffusivity). The appropriate choice of time horizon (extent) and time step (resolution) is ultimately driven by the purpose of the IGM activity, and typically is selected to ensure important processes and responses can be captured.

1.2.8 Disciplines

To provide a holistic understanding of the system, IGM typically requires integration of knowledge and competencies from a broad range of paradigms (e.g. positivistic, interpretive) and disciplines (e.g., geology, hydrogeology, hydrology, hydrochemistry, engineering, ecology, law, economics, computer science, sociology, political science and psychology). Integrating disciplines involves challenges associated with incorporating divergent views and interests, theories, assumptions, types and formats of information, languages, research methodologies and tools (e.g. Hunt and Wilcox 2003; Hancock et al. 2009). IGM calls for a new breed of research, one focused on teams who are much more interdisciplinary and systems focused in their approach. Moreover, the interdisciplinary focus requires investments of time to communicate and understand points of view outside of one's field of expertise.

1.2.9 Methods, Models, Other Tools and Data

This dimension relates to the technical integration of different methods, models, tools and data from various disciplines and/or representing different processes or perspectives. There is a wide range of modelling and analytical tools that can be integrated to develop a comprehensive framework to facilitate IGM – both for the groundwater system itself as well as the socioeconomic drivers that act on the groundwater system. Integrated modelling is the common platform used for performing integrated assessment as it can support a systematic and transparent approach to integration (see Sect. 1.3 below). Combining diverse tools and data is a challenge in interfacing, interoperability, and appropriate distribution of limited available resources and effort. Such challenges have been the focus of work involving model and data standardisations and information exchange, work that is ongoing.

1.2.10 Uncertainty

No environmental system (natural and/or socioeconomic) can be perfectly characterized, especially when many of its key characteristics are inferred and imperfectly sampled. Handling the lack of detailed understanding of groundwater systems is one of the key challenges to their effective management. Uncertainty is embedded in all aspects of IGM, from our ability to represent the biophysical systems to the social systems in which they are embedded. Though the system cannot be perfectly characterized, the presence of uncertainty is well accepted and thus cannot be ignored. Effective IGM recognizes the source, nature and level of uncertainties associated with problem definition, social/political context, communication, and models and tools used in the assessment process. Due to the inherent and often large uncertainties associated with managing groundwater systems, there is a need to communicate decision making in the context of uncertainty and, when possible, develop robust management strategies that perform well under a range of plausible conditions.

1.3 Integrated Assessment, Modelling, and Other IGM Tools

Many tools can be used to support the development of policies in IGM. The development of conceptual models amongst stakeholders is a common starting point to frame the relevant issues, define outcomes, and manage complexity. A vital first step is to draw system boundaries wide enough to encompass the interacting influences, while keeping the conceptualisation only as complex as necessary to conduct useful analysis (Bazilian et al. 2011). Integrated models are generally considered the primary tool to articulate and test such conceptualisations because they can represent potential scenarios of policy interventions, uncontrollable drivers and uncertainties, and outputs that capture trade-offs or impacts of alternative actions. When properly constructed, they can also allow exploration of system feedbacks and linkages within a single framework. Because IGM encompasses a wide variety of drivers, feedbacks and spatio-temporal scales, integrated models that couple component models representing different system components (often from different paradigms) are often required (Kelly et al. 2013). For example, in exploring the socioeconomic and ecological impacts of reduced water allocations and adaptation options by farmers, Jakeman et al. (2014) developed an integrated model that couples surface-groundwater models with social Bayesian networks, crop metamodels, economic optimisation of production values, policy rule models, and ecological expert opinion. On the other hand, integrated models typically include one modelling methodology (e.g. Bayesian networks, system dynamics, agent-based models, expert systems) rather than a combination to represent the whole system. Including multiple methods is a topic of ongoing work.

The nature of integrated assessment, including the need to integrate perspectives from different disciplines and stakeholder groups, requires a process and modelling framework that is adaptive and facilitates participatory procedures. Often there is a flow of information from stakeholders on their knowledge of the system and preferences about the policy environment. This information, along with scientific knowledge, supports the conceptualisation, construction, and use of a model (Fig. 1.2). Model conceptualisation includes elements such as issue definition, specification of system boundaries and identification of measures, criteria, indicators and processes. The model, in turn, provides insight on the possible impacts and trade-offs under selected scenarios, which then flows back to inform stakeholder and policy preferences and system understanding. Scientists gain understanding from the modelling process as well through their interactions with stakeholders.

There are several important considerations handled when constructing integrated models. The purpose of the model drives the selection of system

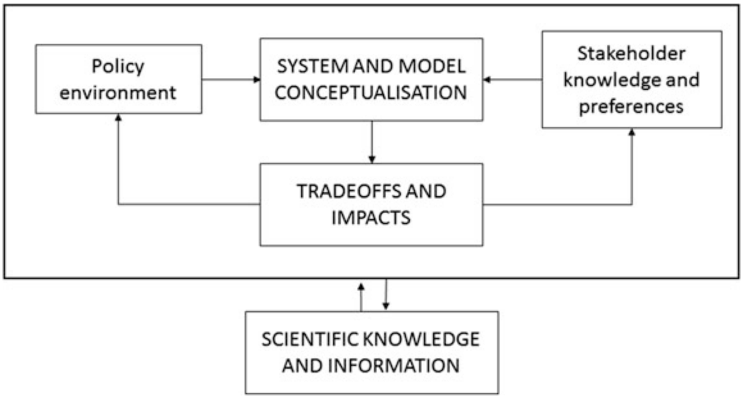

Fig. 1.2 Integrated modelling framework

processes, which in turn dictates the model structure that is applied and evaluated (Jakeman et al. 2006). Appropriate modelling takes into account the spatiotemporal detail required in the modelling, the nature of the data (qualitative and/or quantitative), the level of ability to represent uncertainty and feedbacks (Kelly et al. 2013). The choice of approach may also be dictated by human and computational resources. For example, Bayesian networks may be suitable when data is sparse or system understanding is limited but quickly interrogated; and process-based models may be suitable if system processes are understood and important for the IGM activity. The system dynamics approach may be appropriate when dynamic processes or system feedbacks are of interest, whereas agent-based models are appropriate when interactions between individuals are of interest (Kelly et al. 2013). Scenario analysis is useful when future conditions are difficult to estimate and underpin overarching uncertainty (e.g. climate change – See Anderson et al. 2015, Chap. 10). In summary, integrated assessment and modelling is often best supported by a suite of tools, with individual tools applied to leverage different information that is then compiled to provide an encompassing assessment of the system. The challenge is then ensuring effective communication between tools.

The outputs of integrated models are not a crystal ball defining one future. Rather, they are typically a heuristic tool that provides insights to support decision or policy making, a tool that articulates the trade-offs inherent to IGM. When properly used, these tools facilitate IGM through: (1) improving and articulating understanding (regarding potential impacts as well as system feedbacks and interactions); (2) educating scientists, decision- and policy-makers and other stakeholders; (3) limiting options explored to those that are feasible; and (4) building interaction and rapport between stakeholder groups, which can influence the range of policy changes considered.

1.4 Book Overview and Key Messages

The book is divided into five parts. An overview of each part and associated key messages are provided below.

1.4.1 Part I: Integration Overview and Problem Settings

This first part of the book provides a broad examination of integrated groundwater management and associated issues and challenges. As we have seen in Chap. 1, Integrated Groundwater Management is a grand societal challenge, perhaps the most urgent as many societies and ecosystems depend on the sustainability of their groundwater systems. Effective IGM considers the dimensions discussed in Sect. 1.2, and the effectively tailors the wealth of model platforms and tools available to support IGM to a specific problem context. Scientists and decision makers need to engage extensively with stakeholders and think and plan for the longer term inherent to all groundwater systems. Chapter 2 examines the international scale of groundwater issues, both in severity and extent. It points to the need for understanding the interconnections among aquifers, surface water, ecosystems, and human needs, especially given the complexities of social-ecological systems dependent on the resource. Chapter 3 discusses the interactions within components of groundwater-dependent and social-ecological systems, and proposes a conceptual framework to describe their complexity.

Chapters 4 and 5 examine the challenge of groundwater management under global change. Chapter 4 focuses on the water-energy-food nexus whereas Chap. 5 considers potential climate change impacts on groundwater, in addition to potential feedbacks of groundwater on the global climate system. Energy demand management measures have positive synergies in reducing consumption of water, but the impacts of new energy technologies on groundwater are mixed. The direct impacts of climate change on groundwater will vary with different combinations of soils/aquifer materials, vegetation, and climatic zone. Long-term monitoring of natural systems (groundwater, surface water, vegetation and land use patterns) provides a critical baseline to identify and evaluate effects of future change. Climate change mitigation and adaptation policies are expected to change, and in some cases (carbon sequestration in the landscape, some renewable energy technologies) exacerbate, the challenges associated with groundwater use and management.

1.4.2 Part II: Governance

Here six chapters deal with issues related to the governance of groundwater, focused on three case study regions: Australia, the European Union and the USA. It begins in Chap. 6 with a comparative study of groundwater governance in the three regions, classifying groundwater governance issues into the five blocks used in the Earth Systems Governance Framework. Strengths and weaknesses are elucidated as well as the governance difficulties and dilemmas faced in these three regions. A review of the fundamental legal principles relating to groundwater in the three regions, including the challenges of these legal frameworks in a cross-boundary context is discussed in Chap. 7. Australia, the western United States, and Europe display key differences in how they conceive of fundamental aspects of groundwater regulation, such as ownership and principles for permitting groundwater withdrawals. Yet they face very similar challenges in relation to integrating regulation of groundwater and surface water, groundwater and dependent environments, and groundwater across boundaries. Commonly, they deal with similar challenges in different ways, where a range of potential legal tools are used across the globe. In Chap. 8, groundwater challenges are examined through integrated management and planning approaches, with specific examples of policy frameworks for water management adopted in parts of the three study regions. From these examples, integrated groundwater management appears a “living” or iterated mechanism that is updated, refined and (if necessary) changed as new information and experience are gained. Chapter 9 explores the opportunities and challenges of delivering conjunctive management of water resources through collective action by governments and water users. Australia, Spain and the United States have made some progress in pursing conjunctive management through collective action, but their experiences have highlighted a number of practical and policy limitations. Conjunctive management through collective action is more likely where social and environmental crisis arise and where there is institutional recognition of hydrological connections (between groundwater and surface water), and where management tools are devolved to local water users.

Groundwater governance challenges, and associated potential social and environmental injustices, are addressed in Chap. 10, including how equity in water use is considered and how it has been translated into practice. The rationale for sharing or allocating groundwater is guided by the principle of *equitable and reasonable utilization*. Environmental justice is a useful lens in the arsenal of researchers, policy makers and natural resource managers that can be used to highlight the importance of a systems approach when dealing with common pool resources such as groundwater. In the last Chap. (11) of Part II, social justice and different groundwater allocation rules are contrasted in a French case study. It analyses the acceptability of rules for apportioning groundwater resources among agricultural users in over-used / over-allocated groundwater basins. The study highlights that acceptance of new water allocation rules is not only determined by how stakeholders perceive these rules in terms of distributive justice. Farmers' judgment is also influenced by their perception of the legitimacy (moral, pragmatic and cognitive) of the policy in which the question of allocation rule is embedded. Another determining factor is the perceived implementation difficulties that are expected to result from allocation rules.

1.4.3 Part III: Biophysical Aspects

The biophysical aspects of IGM are examined in Part III. It begins with a background to ecohydrology in Chap. 12, which considers how ecology and hydrology interactions are critical for determination of groundwater availability and sustainability, and once articulated, can be incorporated into effective groundwater management. In many cases, success of integrated groundwater management is measured by how well the interaction between ecology and hydrology aspects is articulated and addressed. Groundwater dependent ecosystems (GDEs), their structure and function, are reviewed in Chap. 13, and are discussed in terms of the potential threats resulting from over-extraction of groundwater. Defining the response function of ecosystems to groundwater extraction is a key research challenge for the future, with major implications to policy, legislation and sustainable management of GDEs and groundwater resources. Chapter 14 uses examples to illustrate how natural and anthropogenic water quality issues can drive IGM and its implementation – factors that can in some cases eclipse water quantity issues that may also exist. Water quality concerns can come from naturally occurring or human induced contaminants; moreover, such concerns are often based on public perception, which can limit the use and availability of groundwater. In this way, "acceptable" water quality is not a static definition, but changes with time with increasing analytical precision and increased knowledge on effects on human and environmental health. Chapter 15 examines the processes and issues around salinization and drainage in irrigation schemes. As the salinization of shallow aquifers is closely related to root-zone salinization, the two are considered together. A case study of root-zone salinization was taken from a developing country (Pakistan), whilst that of shallow aquifer salinization was taken from a developed country (Australia). Both case studies underscore how mitigation strategies to overcome groundwater salinization need to be integrated with policy.

In Chaps. 16 and 17 the promise and challenges of managed aquifer recharge (MAR) are explored, including opportunities to save excess water underground and reduce evaporation losses. MAR can augment groundwater with available surface water and can act alongside conjunctive use of surface waters and groundwater to sustain water supplies and achieve groundwater and surface water management objectives such as protection of ecosystems. Chapter 16 argues that specific local characteristics of each MAR site, precludes a single universal solution for all settings, suggesting existing legal frameworks must take this into account. Moreover, MAR function and the impacts on water availability, water quality, sustainability as well as on the local and downstream environment, need to be communicated to promote cost-effective implementation. Chapter 17 further describes the potential role of MAR in IGM for conserving surface water resources, improving groundwater quality and increasing groundwater availability. MAR may be used to replenish depleted aquifers, in association with demand management strategies to bring aquifers closer to hydrologic equilibrium needed for sustainable use. In suitable hydrogeologic locations, MAR options have been shown to be economic when compared to other sources such as seawater desalination.

1.4.4 Part IV: Socioeconomics

Part IV focuses on the social science and economic considerations of IGM. Chapter 18 examines groundwater management in modern-day China, which is facing unprecedented challenges that reflect many social, cultural and political drivers. The chapter examines how changes to the legislation system, institutional reforms and better management instruments can help China progress towards more integrated groundwater management. Chapter 19 explores the social dimensions of groundwater governance and how social sciences, including stakeholder engagement, social impact assessment and collaborative approaches, contribute to the IGM process. Difficult or 'wicked' natural resource management issues are often best addressed by engaging stakeholders in processes that involve dialogue, learning, and action to build and engage social and human capital. Human and social capital underpins much of the capacity of any community to respond to the challenges of sustainability. When conducting integrated research, it is critical for social researchers to be engaged from the outset in problem definition and setting research priorities.

In Chap. 20 the use of groundwater trading as a management strategy is investigated, where attempts in Australia and the USA to establish groundwater markets are used to frame important underlying issues. Before groundwater markets can successfully develop, institutions and regulations have to exist at some level. For fully efficient and effective policy, there is a need to invest in high quality economic and scientific research, where social concerns are not the sole important drivers for efficient and effective groundwater markets. In Chap. 21, assessment of the benefits of groundwater improvement and protection is addressed from an economic viewpoint of contingent valuation. Such economic analysis integrates benefits for present and future generations, and includes the "bequest" or "heritage" value, defined as the value of satisfaction from improving groundwater resources for future generations. Potential and limits to this approach are discussed using literature review and two case studies from France and Belgium. Chapter 22 evaluates strategies for groundwater management through economic instruments, current practices, challenges and innovative approaches. The last Chap. (23) of Part IV examines the expanding groundwater economy in North Africa, where aquifers have commonly been overexploited as a result of the short-term interests of private entities and the absence of effective governance.

1.4.5 Part V: Modelling and Decision Support

Lastly, Part V focuses on concepts of modelling, data management, and decision support for facilitating and informing IGM. Chapter 24 discusses the use of systems thinking, particularly soft- and critical-systems approaches, for incorporating human aspects (i.e. cognitive, social, cultural, and political) into groundwater management and research. It stresses the value of a multi-method approach to accommodate different perspectives using four international case studies, and suggests that practitioners and researchers need to be aware and explicit about their theoretical and methodological stance, but also creative about how they adapt and localise their approaches. Chapter 25 examines the use of decision support processes and models for articulating and improving groundwater management policies and trade-offs. Decision support systems (DSS) provide a means for water managers to evaluate complex data sets that include hydrogeologic, economic, legal and environmental elements. Although distributed groundwater modelling approaches are improving, examples of integrated groundwater DSS or participatory processes are not widespread. Nevertheless DSS are well suited for integrated groundwater problems because they can provide a set of applications, methodologies, and tools to communicate and cope with inherent complexity and uncertainty.

Chapter 26 discusses challenges that ripple to data management needed for IGM as new technologies in monitoring and computing, including data networks, are developed. Integrated studies typically have large data requirements, which not only need to be well stored, but also well described, easily discoverable and accessible, and in consistent form for use in integrated groundwater studies. Data networks are increasingly being used to provide access to large national data holdings in a consistent open standards based manner, which facilitates their use in integrated groundwater studies. Chapter 27 reviews the use of hydro-economic models as decision support tools for conjunctive management of surface and groundwater. It considers technical challenges involved in incorporating aquifer dynamics, stream-aquifer interactions, nonlinearities and multiple objectives into integrated frameworks. Hydroeconomic models can provide a useful insight into a more efficient operation of conjunctive use and the economic implications of different conjunctive use strategies. The final Chap. (28) relates IGM to uncertainty – uncertainty that resides in managing groundwater systems and in groundwater system models. A range of methods for exploring uncertainties and how they can be applied are discussed. Because no one approach is appropriate for all applications, techniques are often decided by the judgement of the modeller. As the scientific method cannot prove correctness, making predictions of uncertain outcomes needs to focus on eliminating the impossible and incorrect potential outcomes, and focus on elucidating alternative models and conclusions. One does not need to be able to use all possible alternatives, but it is important to be aware of alternatives that have not been used but could affect associated conclusions.

And perhaps one final message is warranted. Difficult problems and crises involving groundwater will only increase. Opportunities for IGM will then operate on two levels, the first being steadfast application of standard approaches to problems well recognized. Less predictable, come windows of opportunities for reform and more effective IGM. The challenge for all parties – decision-makers, water managers, scientists and other stakeholders – is to be prepared to seize opportunities to implement more sustainable and effective groundwater management. The aim of this book was to prepare the reader for such windows of opportunity by laying out the major disciplinary and interdisciplinary components, challenges, and opportunities, for integrated and sustainable management of groundwater.

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