

Ecohydrology and Its Relation to Integrated Groundwater Management

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Abstract

In the twentieth century, groundwater characterization focused primarily on easily measured hydraulic metrics of water storage and flows. Twenty-first century concepts of groundwater *availability*, however, encompass other factors having societal value, such as ecological well-being. Effective ecohydrological science is a nexus of fundamental understanding derived from two scientific disciplines: (1) ecology, where scale, thresholds, feedbacks and tipping points for societal questions form the basis for the *ecologic* characterization, and (2) hydrology, where the characteristics, magnitude, and timing of water flows are characterized for a defined system of interest. In addition to ecohydrology itself, integrated groundwater management requires input from resource managers to understand which areas of the vast world of ecohydrology are important for decision making. Expectations of acceptable uncertainty, or even what ecohydrological outputs have utility, are often not well articulated within societal decision making frameworks, or within the science community itself. Similarly, “acceptable levels of impact” are difficult to define. Three examples

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are given to demonstrate the use of ecohydrological considerations for long-term sustainability of groundwater resources and their related ecosystem function. Such examples illustrate the importance of accommodating ecohydrogeological aspects into integrated groundwater management of the twenty-first century, regardless of society, climate, or setting.

12.1 Introduction

Groundwater resource characterization in the past was typically based on relatively easily estimated hydraulic metrics of water storage and flows within aquifers (see Chap. 3). This characterization occurred on smaller site scales to larger regional assessment, and employed well-established “classic” hydrogeological methods (Fig. 12.1). In the twenty-first century, however, such accounting approaches can miss a fundamental societal decision-making issue – there is no “unused” water in the environment (Hunt 2003). Because of mass balance, what is taken for a new use comes at the expense of an existing one. Recognizing the need to include this trade-off, groundwater resources are now evaluated in terms of water *availability*. In such a view, a more holistic view of the groundwater system is required, one that includes non-hydraulic factors such as ecological degradation. For example, although a shallow unconfined aquifer might have a saturated thickness of 100 s of meters, even small drawdowns can markedly change groundwater discharge to surface water features and associated ecological functions valued by society (Reilly et al. 2008). Thus, the system is characterized by large groundwater storage, but the storage actually *available* for use, as decided by non-hydraulic factors, is much less (Alley 2007).

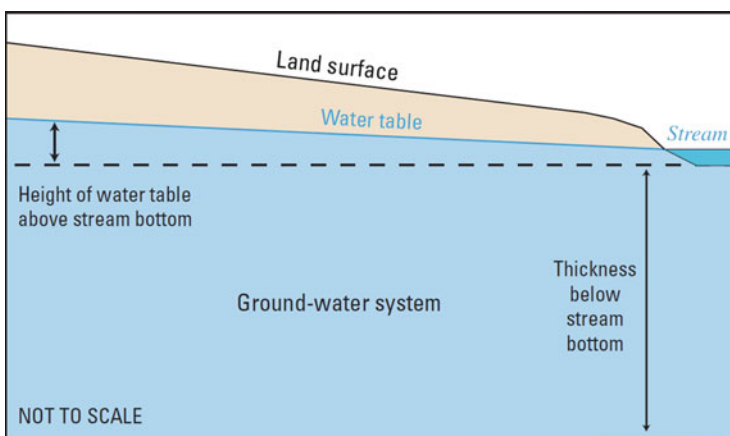


Fig. 12.1 An example of differences in water *stored* in an aquifer (large arrow on right) and the smaller amount of water *available* (small arrow on left) as determined by a societal desire to maintain surface water flow (Modified from Reilly et al. 2008)

Unconsolidated sediments in humid climates typify this issue. These deposits are commonly characterized by a high water-table elevation and high degree of connectedness/interaction between groundwater and surface waters, and in turn, associated ecosystems. Groundwater withdrawals from unconfined aquifers not only intercept groundwater that would discharge to surface waters and associated ecosystems, but can directly capture water from the stream under certain pumping conditions (Fig. 13, Alley et al. 1999). In either case, associated diversion of groundwater by drainage and well abstraction can be expected to stress local groundwater-dependent ecosystems (GDEs). In arid areas, the importance of groundwater is also seen, where the landscape singularities of higher moisture drive high levels of ecosystem production (Springer and Stevens 2009). Thus, a very small portion of the land surface can be responsible for the majority of the arid ecosystems' value. In these ways, groundwater is not only a resource to be exploited, but is also a hidden connector across the landscape (Hunt 2003). This connection transmits stress within the aquifer itself, and across and between surface waters (Winter et al. 1998) and many aquatic and terrestrial ecosystems. For GDEs, where the water table intersects or comes close to the land surface, the timing and magnitude of groundwater flow and related nutrient fluxes can be critical to ecosystem formation and persistence. Consider that precipitation is the dominant source of water in nearly all wetland systems in humid climates, yet the influence of the groundwater flow component can be sufficient (from an ecological perspective) to yield an entire new type of wetland community often valued by society, the fen (e.g., Amon et al. 2002). Influxes of groundwater to lakes, rivers, and wetlands can change whole-system physico-chemical properties (e.g., Anderson and Bowser 1986) including temperature and salinity, while also providing more subtle influences on microenvironments and ecological processes such as (e.g., Hurley et al. 1985). Infiltration of water from surface aquatic ecosystems also has a significant effect on aquifer ecology, especially on microbes and invertebrates (e.g., Hunt et al. 2006). Moreover, surface ecological processes such as evapotranspiration have long been recognized as potentially influencing hydrological responses (e.g., Meyboom 1964, 1966) and related hydrochemical function. Thus, the relation of groundwater hydrology to patterns and processes in ecology is a 'two-way street' where understanding the feedback of one to the other serves as a powerful lens through which to evaluate and explain the functioning of natural ecosystems (Hancock et al. 2009).

One difficulty for standard application of broad ecohydrological concepts to integrated groundwater management is that types of groundwater-ecology links can be wide-ranging – they can include the well-recognized relations found at the groundwater/surface-water interface such as water-plant interactions or groundwater-temperature-fish relations, but also less well-known topics such as microbial community characterization at the periphery of a contaminant plume. Thus, it is perhaps not surprising that standard ecohydrological procedures and metrics do not exist, and the significance and power of this ecohydrological tandem has not always been followed with effective interdisciplinary science. That is, the encompassing ecological, hydrological, and physico-chemical links between

groundwater, surface waters and associated ecosystems are seldom fully understood, even though true characterization and optimal management may require such an encompassing multidisciplinary view. Shortcomings in our ability to perform true characterization notwithstanding, overarching concepts of application to integrated groundwater management can be developed, and much can be learned from successful (and unsuccessful) attempts at ecohydrology.

One way to characterize the overarching interplay between ecology and hydrology is this: consideration of ecohydrological issues enhances understanding amongst biologists, as hydrogeology provides the abiotic “box”, within which ecological processes play out. Biologists and ecologists articulate defining characteristics of groundwater flows required for their societally relevant target – insight that requires the skills of hydrogeologists to attain. Hydrogeologists, in turn, must understand how and why groundwater influences ecological processes so that their expertise is effectively brought to bear on the ecological question (Hunt and Wilcox 2003a, b). Moreover, hydrogeologists have to recognize that the ecological system can influence the groundwater system most notably by evapotranspiration from shallow groundwater (Batelaan et al. 2003). Ecological factors help define important spatial and temporal scales, which in many cases are smaller than classical hydrogeologic characterization. In addition, ecological factors facilitate identification of qualitative levels of certainty needed in abiotic characterizations. Learning about ecological *thresholds* and *tipping points* for the societal question at hand helps define the work needed, and ensure it is tackled efficiently. An ecological threshold can be described as a system condition whereby a small change in external conditions causes a rapid change in an ecosystem, and passing the ecological threshold leads to rapid change of ecosystem health. An ecological tipping point is where the change moves from one stable state to another stable state, often irreversibly. To understand how a threshold can influence decision making, consider the selection of a pipe sized to convey a well’s pumpage that is somewhat uncertain (Hancock et al. 2009): pipe sizes come in a set range of diameters so estimated pumpage is evaluated with the pipe-size thresholds in mind. If one is relatively certain that a pipe diameter (threshold) will not convey the estimated pumpage, then a larger diameter of pipe is chosen. Knowledge of pipe-size thresholds simplifies and directs the question into a form much different than trying to estimate the exact rate of well pumpage itself. In a similar ecohydrological context, the ecological threshold of a stream drying up is a very different abiotic forecast than estimating various degrees of low flow in a perennial stream. Therefore, the ecological threshold can simplify and direct the types of hydrogeological investigation brought to bear to characterize the system appropriately.

Identification of which thresholds and tipping points are societally important is often provided by the resource managers, and thus can be considered an important link for effective integrated groundwater management. A societal context for science has become increasingly important (e.g., Boland 2010; Guillaume et al. 2012); resource managers are better acquainted with competing needs and rank of societally valued ecosystem services. Thus, they are critical for including in the discussion of tradeoffs of one *versus* another, and ranking which areas of

ecohydrology are societally relevant for decision making. Their input elucidates connections between groundwater and terrestrial/subterranean ecosystems that facilitate holistic management of natural systems, and helps create a complete listing of the threats and mitigation opportunities. Such input moves discussions of water availability to long-term *sustainability* of the resource and its ecosystem goods and services. Such a multi-discipline approach is needed to effect true integrated groundwater management.

In this chapter a historical background and examples of ecohydrology and integrated groundwater management are provided with these considerations in mind. Because the range of potential societally relevant ecological endpoints is vast, we focus on transferable elements contained within the examples rather than problem-specific insight. The chapter concludes with discussion of concepts and approaches for including ecohydrological considerations into integrated groundwater management. Using the dimensions of integrated groundwater management outlined in Chap. 1, ecohydrology can be seen as integration of multiple disciplines assessing natural and human systems across multiple scales of space and time. This integration, in turn, gives an encompassing foundation for discussion involving stakeholders, resource managers, and decision-makers. It should be noted that the topic of groundwater dependent ecosystems is sufficiently large and important for integrated groundwater management that it warrants its own chapter (Chap. 13). Therefore, these important systems are discussed only cursorily here.

12.2 Background of Ecohydrology and Water Management

In the last 10 years ecohydrology has been developed as a new scientific discipline. Recently its importance has been stressed in relation to hydro(geo)logy and ecology but also a wider range of ideas within the broad field of “ecohydrology”. Elements of the history of ecohydrology are described here, which provide a foundation for the role of ecohydrology in groundwater management.

Several definitions of “ecohydrology” have been published:

- Wassen and Grootjans (1996): ‘An application driven discipline aiming at a better understanding of hydrological factors determining the natural development of wet ecosystems, especially in regard of their functional value for natural protection and restoration’.
- Baird and Wilby (1999): ‘Eco-hydrology is the study of plant-water interactions and the hydrological processes related to plant growth’.
- Eamus et al. (2006): ‘Ecohydrology is the study of how the movement and storage of water in the environment and the structure and function of vegetation are linked in a reciprocal exchange.’
- Rodriguez-Iturbe (2000): ‘Eco-hydrology seeks to describe the hydrological mechanisms that underlie ecological pattern and processes’.

- Nuttle (2002): ‘Eco-hydrology is . . . concerned with the effects of hydrological processes on the distribution, structure and function of ecosystems, and on the effect of biological processes on the elements of the water cycle’.
- Hunt and Wilcox (2003a): ‘ecohydrology (is) defined . . . as tightly coupled research in which both (ecology and hydrology) disciplines are equally involved in the formulation of the research objective, design of the work plan, and on-going interpretation.’

The range of definitions clearly shows an imprint of the background from which different authors approach the field of ecohydrology, ranging from wetlands (nature protection), plant-water interaction, and, more recently, emphasis on bi-directional understanding provided by integrated application of hydrology, micrometeorology, and ecology.

Since 2000, ecohydrology has become popular in hydrological literature, including both dryland hydrology such as soil moisture-limited evapotranspiration processes (Rodriguez-Iturbe 2000; Eagleson 2002; Rodriguez-Iturbe and Porporato 2004), effects of streamflow and temperature on temperate climate biotic communities (e.g., Boulton and Hancock 2006; Hunt et al. 2006; Olson and Young 2009), and even using viruses as tracers of groundwater flow (Hunt et al. 2014). This recent interest in ecohydrology notwithstanding, much is to be gained by consideration of pre-2000 ecohydrological research roots, some of which have clear groundwater, and groundwater management, origins.

Early humans undoubtedly had some ecohydrological consciousness, as the recognition of certain plant species warned him of dangerous places where he could drown, or offered opportunities to find food. One of the earliest transcripts reporting on the topic comes from the Bible. Ross (2007) interprets and translates the Hebrew bible text of Isaiah 44 in modern language as: ‘I will pour out My spirit as suddenly and overwhelmingly as a rainstorm in the desert. After such a storm, the willow does not fade like grass, but is kept green for many years by groundwater that recharges in the storm’. Obviously, this expresses some form of early ‘ecohydrological’ observations relating rainfall-recharge-groundwater with plant species occurrence. Vitruvius (15 BC) (1913), roman architect and engineer in the first century, wrote this concerning exploration of drinking water: ‘One of the indications where groundwater can be found is the occurrence of small rushes, willows, alder, vitex, reeds and ivy’. Moreover he remarks: ‘one must not rely on these plants if they occur in marshes, which receive and collect rain water’. Hence, he was well aware of the relativity of the plants as indicators for good quality groundwater, differences between sources of water, and the usefulness of ecological indicators for groundwater-drinking water management.

In tenth century AD, Mohammed ibn al-Hasan al-Hasib al-Karaji included a more holistic consideration of the subsurface into ecohydrology. Karaji was a mathematician and engineer who mainly lived and worked in Baghdad. In an effort to support the water resources exploration of his native Persia during the later stages of his career, he wrote the book ‘The Extraction of Hidden Waters to the Surface’, which is regarded the oldest textbook in hydrology/groundwater science (Nadji and

Voigt 1972; Pazwash and Mavrigian 1980). In the book, Karaji includes techniques for the exploration of groundwater such as wells and qanats – techniques still used today in many parts of the Middle East and Asia. He also examines how plants indicate the presence of groundwater by studying the roots of plants and how they grow towards the water table, and includes a report of a well digger who found roots at a depth of 50 m (Nadji and Voigt 1972; Pazwash and Mavrigian 1980). From this treatise, it is clear that Karaji had a surprising good understanding of groundwater and hydrological processes, and used this understanding to further develop ecohydrological relationships with vegetation.

In the mid-nineteenth century, the famous work of engineer Henri Darcy revolutionized this early understanding of groundwater flow. Often overlooked in the pioneering work of Darcy (1856), however, is the fact that it contains a description for the search for drinking water by spring seeker Father Paramelle, in addition to the much better-known column tests. Darcy relates how Father Paramelle infers the probable presence of water, and even the approximate depth of the water below the ground surface, from the nature and strength of the plants. Paramelle (1859) documents his methods in detail, which are notable for using a multidisciplinary approach that includes careful observation and evaluation of geology, mineralogy, topography and vegetation. His methods provided water for many communities in France, where he identified more than 10,000 springs.

Later in the nineteenth century, botanist A.F.W. Schimper focused on the detailed knowledge of plants and their specific habitats, and illustrated an important distinction between wet, hygrophyte and dry, xerophyte plant species. The difference lies in the plant physiology: if a soil contains too much salt, the plants cannot absorb the water and hence it is physiologically dry. All soils which are physically dry are also physiologically dry; and hence only the physiological dryness or wetness of soils need be considered in ecology of plant communities near the ends of this gradient (Schimper 1898). O.E. Meinzer, the father of modern groundwater hydrology, was the first to define the term phreatophyte as a plant that habitually obtains its water supply from groundwater (Meinzer 1923). In 1927, he wrote an entire book about these phreatophytes (Meinzer 1927). In it, he describes the principal phreatophytic species, like common salt grass (*Distilchlis spicata*) and their occurrence in the arid and semi-arid regions of the US. With this understanding, Meinzer and other groundwater hydrologists could then use plants as indicators for locations of groundwater resources.

After the first half of the twentieth century, the use of phreatophytes in groundwater studies became less prominent in the hydrogeological literature; however, ecologists continued the study of plant habitat requirements (Londo 1988; Ellenberg et al. 1992). Ecologists interested in plant community composition, development, and species relations (“phytosociologists”) started to research the relationship between vegetation types and groundwater dynamics in the 1950s. Ellenberg (1948, 1950, 1952, 1953, 1974) and Tüxen (1954) systematically studied the relation between groundwater level and the occurrence of vegetation types. More recently, interest in phreatophytes again became a prominent topic of study following the interest and formal need for protection (European Union 2000, 2006)

of groundwater dependent ecosystems (Batelaan et al. 2003; Witte and von Asmuth 2003; Loheide et al. 2005).

The first publication in which the word ‘ecohydrology’ is mentioned is from the Dutch author van Wirdum (1982), and came about through a groundwater management concern. In van Wirdum’s annual report of the activities of the Dutch National Institute for Nature Research, one sees a growing recognition for ecological values of wetlands (Grootjans et al. 1988; Wassen et al. 1990; Mitsch and Gosselink 1993). This recognition was driven by an observed deterioration of high ecological functions of wetlands due to poor water management. For example, desiccation resulting from groundwater abstraction and agricultural drainage, along with water pollution (Schot et al. 1988) were identified as important factors reducing biodiversity. Hence, even with this early use of the word ‘ecohydrology’ it was understood that groundwater management could significantly influence ecological values.

12.3 Examples of Ecohydrology and Water Management

Groundwater has well-recognized ecological functions including: (1) sustaining stream base flow and moderating water-level fluctuations of groundwater-fed lakes and wetlands, (2) providing stable-temperature habitats, (3) supplying nutrients and inorganic ions, and (4) providing moisture for riparian and other groundwater-dependent vegetation (Hayashi and Rosenberry 2002). The importance of these functions is being incorporated in water management policies of European countries through the Water Framework and Groundwater Directives (European Union 2000, 2006), and has been gaining recognition in other parts of the world over the past decade or so. The following three examples explore how the considerations of the interaction of the ecosystem with the groundwater system influenced management of the resource.

12.3.1 Temperate Climate: United Kingdom

The European Water Framework and its progeny Groundwater Directive require assessment of the status of groundwater bodies with respect to various criteria including the condition of a groundwater-dependent terrestrial ecosystem. Using wetlands as an example of a groundwater-dependent ecosystem, Whiteman et al. (2010) describe a screening tool to assess wetland condition by examining three factors: (1) condition of source groundwater (rate of abstraction, concentration of contaminants, etc.), (2) connectivity between groundwater and the wetland, and (3) ecological response of the wetland to changes in hydrological condition. By assigning scores to the three criteria at 1,368 test sites in England and Wales, they identified 63 wetlands as having high risk from abstraction pressures and 117 from contamination pressures. Once a potentially high-risk site is identified, site-specific

investigation is initiated to assess the actual condition of groundwater and, if poor condition is confirmed, potential mitigation measures are explored.

For example, Hurcott and Podmore Pools is a series of pools and marginal wetlands within a large alder wetland/woodland in Worcestershire (Whiteman et al. 2010). The main sources of water for the pools are surface water inflows from the upstream catchment and groundwater discharge from a major sandstone aquifer, which is also an important public water supply. Unsustainable groundwater abstraction from the aquifer caused a wide-scale drawdown of water levels in the aquifer (poor condition of source water), which significantly reduced stream inflows to the site and eliminated direct groundwater discharge to the site (poor connectivity), and which in turn resulted in a measurable change in vegetation community composition (ecological response). Detailed site assessment suggested that summer maximum water-table depths should be less than 0.45 m to support the ecosystem; however, water-table fluctuations up to 0.7 m were observed. Based on these observations and numerical groundwater modeling results, a Water Level Management Plan (Whiteman et al. 2010) was proposed and implemented to raise the water table and to potentially change the groundwater abstraction regime.

12.3.2 Semi-Arid Climate: Kansas, United States

The State of Kansas in the USA has a long history of integrated groundwater management, which provides a useful case study to demonstrate the paradigm shift in groundwater management. The following summary of the Kansas case study has been largely drawn from a major body of work by Marios Sophocleous at the Kansas Geological Survey. Irrigation is the largest user of water in Kansas, accounting for 80–85 % of total water use (KWO 2009), most of which comes from groundwater extracted from the High Plains aquifer. Groundwater abstraction rapidly increased after the enactment of the Kansas Water Appropriation Act in 1945, which permitted water rights to users for “beneficial use” (Sophocleous 2011). By the late 1960s, too many water rights had been permitted, enabling over-development of the High Plains aquifer resulting in the mining of groundwater resources (Sophocleous 1998). To prevent further mining of groundwater, five Groundwater Management Districts (GMDs) were established, covering most of the extent of the High Plains aquifer, and a “safe-yield” management policy was adopted in the GMDs (Sophocleous 2000).

The aim of this management policy was to balance groundwater withdrawals with aquifer recharge by limiting the total water abstraction in a 3.2-km circle around any proposed new abstraction to be less than the long-term average annual recharge (Sophocleous 2000). This policy had an effect of slowing the rate of water-table declines in the aquifer, but the policy did not stop the decline. More importantly, the safe-yield concept was known to be problematic in practice (e.g., Thomas and Leopold 1964) as it gives no consideration to maintaining naturally occurring groundwater discharge that sustains the perennial flow of streams (Sophocleous 1997). As a result, stream flows and associated riparian and aquatic

ecosystems in western and central Kansas steadily declined and the related ecosystem deteriorated (Sophocleous 1998).

Recognizing that streams and aquifers are closely linked and have to be understood and managed together, in the early 1990s some of the GMD's moved toward *conjunctive* stream-aquifer management by including baseflow in the evaluation (Sophocleous 2000). In other words, baseflow is considered a societal value that it has been given a water right on its own. This shifts the focus from the problematic *aquifer* safe-yield paradigm to a more holistic sustainable *system* water management paradigm. It was hoped that the new measure, together with the legal establishment of minimum-desirable streamflow standard in 1984, would provide needed protection to the riverine-riparian ecosystem (Sophocleous 2011). As a result of GMD actions, pumping rates of groundwater in Kansas leveled off after decades of increases. However, the aquifer had already been mined to a significant reduction of saturated thickness and many streams had deteriorated due to earlier over-development (Sophocleous 1998). The long-term goal of the GMDs is to reduce the rate of water use in order to prolong the life of the aquifer and maintain the remaining groundwater-dependent terrestrial ecosystem. Towards this goal, Intensive Groundwater Use Control Areas (IGUCAs) were established in locations where unfavorable conditions existed, including situations where groundwater use was adversely depleting streamflow and adversely affecting ecology (Sophocleous 2011). Such a tiered designation is a powerful tool that allows the use of a variety of measures, including the reduction in existing water rights, to solve groundwater and ecological issues.

In addition to the revised safe-yield policy explicitly considering baseflow and the use of IGUCAs, Kansas has been using innovative measures to enhance the riverine-riparian ecosystems. For example, private, not-for-profit water-bank systems are used to provide open-market approach for temporarily moving water rights from inactive users to active users (Stover et al. 2011). The Conservation Reserve Enhancement Program is used to give economic incentive to owners of irrigated land to retire lands located in sensitive areas, for example along river corridors of drying streams (Leatherman et al. 2006). In order to enhance integrated water management of groundwater-dependent ecosystems, Sophocleous (2007, 2011) suggests that: (1) the definition of "beneficial" water use must be expanded from traditional irrigation and other consumptive uses to include water conservation and instream flow needs; (2) domestic and other wells that are currently exempted must be included with regulated uses; and (3) increased flexibility of regulatory requirements regarding transferring water rights is needed.

12.3.3 Arid Climate: Australia and United States

The above examples demonstrate groundwater management efforts to support riverine-riparian ecosystems. In some water-scarce regions, however, riparian trees were deemed harmful to stream ecosystems because they take up and transpire groundwater that would otherwise be available to sustain baseflow. Doody

et al. (2011) present a review of case studies from the western USA and south-eastern Australia, where removal of non-native riparian vegetation has been attempted to reduce transpiration diversion and enhance stream flow. In the western USA, non-native phreatophyte, saltcedar (*Tamarix spp.*) had spread along many river bottoms by the 1950s and became a primary target of water “salvage” projects (Robinson 1965). Contrary to the original perception that saltcedar had a higher water use compared with native species, many years of studies including large-scale tree removal experiments have shown that the reduction in evapotranspiration by the removal of saltcedar had no measureable effect on streamflow. This surprising finding was due to similar transpiration rates between the non-native saltcedar and the vegetation community that was established after the saltcedar was removed. In this case, unexpected ecological aspects confounded the expected hydrologic response. Other ecohydrological work showed similar results: no large-scale removal experiments in arid settings have shown the expected return of increased stream flow.

In the Murray-Darling Basin in south-eastern Australia, colonization of the non-native phreatophyte, willow (*Salix spp.*) has also been associated with a number of undesirable impacts on stream ecosystems, including increased water uptake and transpiration, and subsequent reduction in streamflow. Similar to the United States saltcedar, site-scale studies have shown that willows growing in the riparian zone have evapotranspiration rates similar to native *Eucalyptus spp.*, suggesting that removing willow from stream banks will have little effects on net stream flow (Doody et al. 2011). However, unlike saltcedar, willow growth has other hydrologic effects beyond capture and transpiration of groundwater that would discharge to streams. That is, it also grows *within* wet stream channels and reduces flow velocity. The reduction in velocity facilitates water capture, and because the willow is rarely water limited, they can transpire at a higher rate than open-water evaporation (Doody and Benyon 2011). Because the native *Eucalyptus* more commonly grows on river banks and not in the channel, the removal of willow from within stream channel is expected to result in significant water salvage. These examples indicate the importance of understanding eco-hydrological processes specific to the problem – in this case water uptake by trees – to design effective methods of integrated groundwater management.

12.4 Incorporating Ecohydrology into Integrated Groundwater Management

Taken as a whole, concepts and approaches discussed above lead to salient insight into how ecohydrological considerations can be integrated with groundwater management.

1. Groundwater *availability* constraints in highly connected groundwater and surface water systems are a function of both ecosystem degradation *and* water-use

needs. Even though the latter is often an initial primary driver, aspects of the former often become key drivers for decisions of allowable water use. Therefore, *sustainability* of the groundwater resource can be expected to be tied to ecohydrological drivers.

2. Hydrologic measurements (e.g., streamflow statistics or water-table depth in a wetland) allow decision makers to obtain quick snapshots of the system of interest. These “sentinel metrics”, however, are often an indirect measure of what is considered valuable. Therefore, these sentinels need to be formally recognized by stakeholders as surrogates for societally-relevant system qualities. The identification of a set of surrogate sentinel metrics is critical for integrated groundwater management because full system characterization after each management change is not feasible. Moreover, the real-time insight of properly identified sentinel metrics can move an adaptive management plan from simple monitoring to proactive actions that can mitigate ecosystem degradation.
3. Many integrated groundwater management questions are complex – both in ways systems interact as well as feedback mechanisms that mitigate or exacerbate the effect of potential change. Such questions may require hydrologic or ecologic characterizations that are more holistic and comprehensive than sentinel metrics. The goal of this higher level of ecohydrological work is development of a quantitative framework for how much degradation can be expected for differing levels of groundwater withdrawals (or diversions). This allows quantification of the trade-offs inherent to ecohydrology, which in turn can inform cost-benefit analyses conducted by stakeholders. Characteristic functions of ecosystem response, such as response curves (e.g., GCAC 2007; Chap. 6), thresholds, and tipping points, for species of interest give language and help visualize tradeoffs between water use and ecosystem degradation – evaluations inherent to integrated groundwater management.
4. There is a need to translate each science and resource manager concern into terms and metrics that are understandable to all involved. Ecologists may resist having their science being held to the precision that hydrogeologists routinely report, yet are comfortable focusing on thresholds and tipping points for their ecosystem. Successful integrated groundwater management will, in large measure, be a reflection of how well the interaction between ecology and hydrology aspects is articulated.
5. Similar to an adaptive management framework, integrated groundwater management must recognize that many of the underlying feedback loops and system complexity will never be fully understood, especially given the relatively short timeframe of most decision-making. Yet, just as with the adaptive management approach to handling confounding uncertainty, the integrated groundwater management framework can form the crucible of hypothesis testing, where it distills all possible ecohydrological research topics to a subset that can be prioritized. In this way, integrated groundwater management provides a relevance that may be missing in simple academic ecohydrological endeavours. An effective integrated groundwater management plan is expected to include aspects of applied research that focuses on spatial and temporal scales relevant to both the hydrogeological

and the ecological process being studied. This is important to note since historically, hydrogeological studies often are performed on the aquifer or site scale, thus using approaches and generating data too broad for understanding many ecological processes on a site or smaller scale. Moreover, both hydrogeological and ecological foci may have not been optimally tuned for the resource management question of primary interest.

12.5 Summary

In summary, the demands of twenty-first century integrated groundwater management might be considered to precede the maturation of ecohydrological science, a view that might be concluded from the lack of dominant textbooks published or widely accepted common guidelines. However, we believe there are many necessary and common elements in current science methods that have direct application to today's integrated groundwater management. Moreover, formally including societal drivers as the basis for ecohydrological action provides an important foundation for effective ecohydrology in the twenty-first century. Such a focus can only help move the societally relevant and necessary science of ecohydrology into effective integrated management.

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