Neil A. Coles is a professor and the director of the Centre for Excellence in Ecohydrology at the University of Western Australia, Perth, Western Australia, and a guest professor at Zhejiang University, Hangzhou, China. Neil spent his formative years in a coastal country town in the Spencer Gulf of South Australia, where he grew to become enthralled with the coastal and dryland landscapes of this region. He later moved to North Queensland in 1980 to undertake studies at James Cook University in geology and rainforest hydrology. On graduating, he accepted a position in the mining industry, exploring tenements in western and central Queensland, studying not only the geology of these regions, but gaining an understanding of the fragility and extremes experienced in these semi-arid regions. In 1988, he moved to Perth, where he now resides, to undertake postgraduate studies in catchment hydrology and soil physics and was awarded a PhD in 1995. Neil joined the Western Australia (WA) Department of Agriculture in 1998 as a senior research scientist, conducting, directing, and extending research on land and water resource management in the dryland agricultural areas in the southwestern Australia. He continued in this post until 2009, when was appointed as the director for the Centre for Ecohydrology. Under his leadership and direction, this center has become an internationally recognized leader in ecohydrology research with industry applications. Neil has continued to foster the interdisciplinary approach to improving agricultural production and protecting and understanding ecosystems and remains committed to achieving better outcomes for the myriad of environments on this unique and singular planet.
6.1 Introduction

Ecohydrology, considered as a broader more inclusive science, as defined by the UNESCO Hydrology, environment, life, program (HELP) is “a transdisciplinary and applied science.”* Furthermore, it is stated that ecohydrology

Uses the understanding of relationships between hydrological and biological processes at the catchment scale to achieve water quality improvement, biodiversity enhancement and sustainable development [145].

This concept is based on the assumption that sustainable management of resources can be achieved by restoration and maintenance of ecosystem function, enhancement of the system capacity and flux transference mechanisms, and using the basic properties of resilience as a water management framework [144].

Thus, the study of ecohydrology requires the necessary divergence from single discipline to multidisciplinary approaches, and a movement through the micro- to the meso-scale analytical techniques, to provide a broader understanding of landscape function.

Tress et al. go further to state the following:

Interdisciplinary studies as projects that involve several unrelated academic disciplines in a way that forces them to cross subject boundaries to create new knowledge and theory and solve a common research goal [126].

And furthermore

Transdisciplinary studies as projects that both integrate academic researchers from different unrelated disciplines and non-academic participants, such as land managers and the public, to research a common goal and create new knowledge and theory. Transdisciplinarity combines interdisciplinarity with a participatory approach [126].

From their perspective, a broader view of ecohydrology is given, with not only the science being studied, but also the social and economic aspects, combined with on-ground outcomes that involve affected stakeholders and the wider global audience through an understanding of broader implications of the research and the actions undertaken as a result of that research. This more wide-ranging methodology is adopted for purposes of this discussion on ecohydrology concepts.

6.2 Fundamentals of Ecohydrology

Water is critical to all aspects of life as we know it on this planet, and while there is an increasing demand for potable water resources for human consumption, for industry and agricultural production systems, this water comes at a cost to the environment and sustained ecosystem functionality (Figure 6.1). Therefore, there is a fine line between water allocation and ecohydrological functions, such that a trade-off is inevitable and a considered approach must be adopted. The difficulty arises when assigning “value” or “primacy” to a water resource and the potential “value” the water may realize through an alternate use (Figure 6.1). To improve the management of water resources and allocation to appropriate uses for food, industry, and environment on an equitable basis requires knowledge of the dynamic sciences, economics, governance, and regulation thereby harmonizing the transition (Figure 6.2). Ecohydrology by necessity therefore transcends the boundaries between disciplines and provides a more holistic approach to managing landscapes and the water that is transferred and exchanged within them [140,141].

The current perception that the environment or ecosystem has no net present value or is considered of lesser value than alternate uses of water reflects the long-term exclusion of ecosystem function from business models and considerations (Figure 6.1). Ecohydrology seeks to redress this anomaly through improved understanding of hydrological dynamics and ecosystem performance. By understanding the need for trade-offs and assigning primacy to water allocation on an equitable basis through an evidentiary-based system, better management decisions on allocation can be determined (Figure 6.2).

Scale is an important factor in this determination, as the scaling factors that impact on rainfall inputs (or climate) such as adiabatic effects, inversions, storm fronts, thermal systems, and atmospheric circulation are quite different to those impacting on landscapes, such topography, vegetation cover, land use, geology, and soils [9,81]. Thus, capturing global scale data from climatic observations is challenging, but classifying and analyzing shifts using models that are then downscaled to the level of
data application within a catchment, or single landscape unit, become increasingly difficult, much less relevant at fine scales [9,69,77].

Ecohydrology deals with functioning and process that surround hydrological dynamics in an ecosystem context [9,45,112]. Such knowledge is fundamental to understanding actors and drivers for change in these systems, and at what point pressures exerted on these systems through external forces will cause that system to adapt or fail (Figure 6.2). Available data and the consistent monitoring of system or catchment performance are required to unravel these relationships [20], and this datum is often unavailable, at an inappropriate scale and location, or fails to capture the key component of the dynamics or event processes that will provide the cogent understanding necessary to provide for informed decisions [14].
In part, modeling solutions are often limited by the data available to calibrate and validate appropriately, without undertaking some form of assumption on the part of the modeler, or the events and the landscape being modeled [20,31,32,69]. Such modeled outcomes are often applied, as a best approximation, to evaluate both impacts and to derive solutions. Thus, our understanding of the ecohydrology and the interrelationship network of the ecosystem go hand in hand in clarifying the affect of the human dimension, as both source and solution to ecosystem degradation [69].

6.2.1 Global Perspective

Aquatic ecosystems, both marine and freshwater, are under increasing pressure globally. Increasing water allocations to provide for food security and energy production, access to safe drinking water and sanitation, and industrial uses are contributing to degradation of aquatic ecosystems with inherent loss of biodiversity as well as their use as ecosystem service providers [20,92]. This loss is exacerbated by an increase in intensive urbanization through the creation of megacities and extensive urban sprawl, which is now compounded by climate change phenomena that generate divergence from the “norm” that is causing extremes in either too much or too little water, as highlighted in global forums and recent reports [49,50,130]. Water, energy, and food are inextricably linked (Figure 6.1), and they underpin the current global trade and productivity models that have an expansionary developmental nature at their core [136]. The “forever” nature of this exploitative approach, which relies on physically and organically limited resources, presents a future challenge to either find targeted niche technological innovations, or shift to a near zero growth as alternatives, or run the risk of catastrophic contraction [30].

Cumulatively, climate changes are affecting hydrological cycles and will pose threats to the security of the existing water and food production and allocations systems, and will particularly impact on water quality and quantity available in different regions [50,92]. In some regions, this will take the form of increased rainfall (e.g., humid subtropics), and in others, it will result in declining rainfall (e.g., semiarid regions). Each shift brings its own set of problems and issues to solve, from both environmental and engineering design perspectives. Aquatic ecosystems are very dynamic and can rapidly adapt or collapse depending on the external pressures placed on them. Invasions of nonendemic species pose significant bio-security risks and threaten the biodiversity values of rivers, estuaries, and coastal areas [25,142].

The tendency for human migration and congregation toward coastal regions and river systems increases the potential to induce stress and subsequent degradation in these systems. Forecasting scenarios and adaptive management frameworks as applied in recent times, such as Integrated Catchment Management (ICM) [7,48,137], Integrated Water Resources Management [13,83], and Integrated River Basin Management [1,11,16,94,124], as the naming convention would suggest call for integrated solutions for water quality, water quantity sustainability, and the maintenance of ecosystem performance. Therefore, these solutions, by default, are focused on an in-depth knowledge of ecosystem interrelationships and hydrological process [91].

In the Murray–Darling Basin (Australia), ICM is largely directed toward practical ecological outcomes such as flow and hydroperiod, water quality, biosecurity, and river health [36]. However, the social sciences, if they are considered, are often marginalized, but at the same time, social and natural scientists agree that social and cultural issues should be integrated into land and water management, promoting research collaborations [121]. This is contrary to the current opinion in which ecohydrology is focused on the physical sciences alone; therefore, as discussed previously, it is suggested here that the adoption of a wider and more inclusive approach will deliver better environmental and humanitarian outcomes.

However, there are significant hurdles to overcome if these essential collaborations are to occur. Research policy must move toward favoring projects that integrate disciplinary knowledge and involve nonacademic stakeholders, creating transdisciplinary opportunities in land and water research and planning. In addition, funding providers are required to account for the variable time-frames associated with integrative research, with research outputs delivered from different disciplines within
multiple temporal frameworks. For example, The European Union Water Framework Directive (WFD) [46] represents a new approach to the management of water across Europe. Integrated, catchment-scale plans for the protection and restoration of aquatic ecosystems are required to be developed within this framework [124]. By necessity, this will require the collaborative creation of new scientific knowledge, extracting expertise from multiple academic disciplines. Using existing scientific knowledge, to generate a new awareness that is incorporated into policy and practice, scientists and managers need to foster collaborative partnerships that promote both the coproduction and the bidirectional exchange of knowledge [124]. While there has been a fundamental shift in thinking, groups often struggle with the challenges of operational integration, refocusing on more extensive and expansive spatial and temporal scales, defining collective terminology, appropriate methodologies, and managing the expectations of stakeholders [126].

One conceptual approach developed by the UNESCO International Hydrological Programme (IHP) and the Man and Biosphere Programme is based upon the assumption that the sustainable development of water resources is derived from the resistance and resilience of the system to change. This theory is based on an ecosystem's adaptive capacity and its ability to cycle water, nutrients, and energy fluxes at multiple scales, from a farm plot to the basin scale [70,145]. This suggests that for ecohydrology to move beyond monitoring and sensing environmental health, transdisciplinarity is essential, such that boundaries between disciplines dissolve; disciplines such as ecology, biology, hydrology, geography, environmental engineering, and law and socioeconomics transform into a seamless evaluation continuum, achieving new insights into the true nature of the effect that human and natural interventions may have on aquatic ecosystem.

This transcendency process is essential to propose revised remedial solutions and alternate practices to industry, agricultural or rural communities, governments, and other stakeholders that will be impacted by the shift toward sustainable production and environmental systems [48,70,91]. The role of ecosystem engineering, for example, restorative river flows to control eutrophication or regeneration of forest ecosystem to manage erosion and flooding [5], restoration of estuarine habitat (i.e., mangroves) to revive fish nurseries [139], and provision of tree and shelter belts to manage livestock and soil stability [123], demonstrates the integrative nature of the ecohydrology approach [25,47,91] that will be presented.

### 6.2.2 Ecohydrology Dynamics

Knowledge of the interrelationship dynamics and the impact of scales associated with water allocation is not only one of the fundamental pillars of understanding ecohydrology but forms the basis of process and management frameworks in which to optimize resource allocation. A significant barrier to developing this framework is the range of spatiotemporal scales to be considered and the lack of available data to predetermine local and regional impacts of water redistribution [77]. The water balance at the basin scale based on Budyko principles [21] (Figure 6.3) illustrates that for a given time interval, the surface and groundwater that flows out of a basin, plus any changes in storage, are equivalent to the amount of water entering the basin through atmospheric discharge (e.g., rain, snow, fog), minus that volume returned to the atmosphere through evapotranspiration, from plants, soils, and water surfaces [20,57,146].

The water balance model provides a useful summary of the hydrological processes within a basin; however, it tends to gloss over the finer interrelationships at the water–plants–soils interface [21,123]. The ecohydrology approach leveres this dynamic interrelationship between hydrological and ecological factors. Zalewski [143] and others [70,128,145] propose to increase ecosystem’s robustness and resilience to external impacts by adopting this approach based on the proposition that water quality and biodiversity are managed through controlling hydrological parameters such as hydroperiods, by influencing residence times and/or discharge volumes, or through the use of biological parameters, such as biofilters in the case of riparian vegetation or filter feeders that can be merged into
existing systems and structures. Through these synergies, integrative strategies can be optimized and extended beyond single-use technologies or strategies, thereby encouraging innovative approaches to water sciences and engineering [128].

This ecohydrology approach is based on three principles that are expressed as sequential components:

**Hydrological:** The quantification of the hydrological cycle of a basin should be a template for functional integration of hydrological and biological processes.

**Ecological:** The integrated processes at river basin scale can be steered in such a way as to enhance the basin’s carrying capacity and its ecosystem services.

**Ecological engineering:** The regulation of hydrological and ecological processes, based on an integrative system approach, is thus a new tool for Integrated Water Basin Management and Integrated Coastal Management [128,140,145].

From this discussion, we can derive that linkages are important to understanding ecosystem performance, and water and energy fluxes are drivers of transition between components of these systems. Also that it is possible to engineer and enhance the performance of an ecosystem if we understand the fundamental and dynamic nature of these interrelationships. Using these principles to apply ecohydrology to real-world outcomes is the next challenge.

### 6.3 Ecohydrology and Ecoservices

The use of the collective term “ecosystem services” was assigned in the early 1980s to explain a framework for structuring and synthesizing biophysical relationships within an ecosystem setting that delivered benefits to human well-being [95]. Ecosystems provide hydrological services that are coupled with a range of essential services, including air quality, carbon dioxide exchange, and soil development. These systems and services, as outlined previously, are often interrelated in dynamic and complex ways, and establishing their functional relationships requires approaches spanning diverse fields of inquiry. This section, for the purposes of this discussion, is focused on the terrestrial freshwater hydrological services as an example of what an ecoservice is or what may be achieved through a greater understanding of ecosystems.
6.3.1 Ecosystem services: Value and Benefits

Ecosystem services, described as the benefits obtained from ecosystems [19,20], form the basis for the design and development of environmental policy, trading schemes, benchmarking performance, and monetization of natural resources and are a powerful tool in assessing the relationships that people have with their surrounding tangible environment and the more distant intangible global benefits. The inclusion of beneficiaries, as shown in Figure 6.4, links values intrinsic to ecosystem services, to both the fundamental economics of dollar value and the trade-offs required to realize that value. By closing the cycle of service delivered and exploited through benefits derived from reduced ecosystem performance, it provides a direct assessment process that may enable the value proposition to be revised in relation to service provision. Whether or not those values are monetized, this framework should provide for the opportunity to assess theoretical trade-offs based on alternative scenarios of water resource use, land cover, and land-use change through comparative value and degradation of service [20].

The ecosystem services framework (Figure 6.4) highlights the complex feedbacks and trade-offs among service providers and direct and indirect beneficiaries, such that service provided in one portion of an ecosystem is often at the expense of that system through functional degradation [20]. The complex interactive nature of the ecosystem defines the framework into which the ecohydrologist and engineer must plunge, in order to deliver informed decisions to their clients that may be at the expense of consumption by others, elsewhere and in the future. The role of the ecohydrology engineer is to identify that combination of services, support, and ecosystem resilience that will enable the long-term success of the planned activities with minimal immediate cumulative impacts on the ecosystem being evaluated. These terms have gained currency because of the values that they convey and the idea that ecosystems are “socially valuable” and may have “existential value” that is not yet apparent [19,41].

Beyond this simple terminology, there is limited accounting and measurement standardization between economics, ecology, hydrology, and what is defined as an ecosystem service [19]. Assigning and trading values are the key to this process and has been at the forefront of adaptive management frameworks in recent years, employed in assessing biodiversity or natural resource values [34]. An accounting system has been suggested by Boyd et al., which has broad-scale applications that deliver

![Ecosystem services framework](image)

**FIGURE 6.4** Ecosystem services framework: where services provided by the biophysical environment are valued and traded to beneficiaries, through policy, governance, and market instruments. Equity and benefits in service provision determine the level and value of service degradation in ecosystem performance.
both environmental accounting and performance assessment, which can be allocated to a broad "Green GDP"* [19]. The accounting system is designed to provide more exacting measures of service, quantifying service units, linked with both monetary values and ecological principles, but targeted at a narrower range of measurable parameters to enable the prioritization of monitoring and data collection [19]. De Fries et al. (2004) and others [75,106], following the same theme, indicate that by confining the focus of the parameters (and their interrelationships) used for accounting purposes, it will enable governments to set priorities, monitor the efficiencies of economic policies more precisely, enact targeted environmental regulations and resource management strategies, and design more efficient market instruments [43]. This will provide an opportunity to deliver a socially responsible economic and environmental framework that has been touted for the last decade at both national and international levels [62].

This framework will enable policy documents and statements to be underpinned by complementary statistical information, or via a scientifically affirmed database, creating an evidentiary-based system of accounting and monitoring that can be utilized to set meaningful qualitative and quantitative targets for these policies. By shifting toward an evidentiary-based policy approach to ecoservices creates opportunities on a number of discipline fronts, in aquatic (ecohydrology, biology), terrestrial (geology, pedology), marine (oceanography, coastal dynamics), atmospheric (meteorology) sciences with linkages to engineering, law, politics, economics, and business applications that will provide an understanding of ecosystems from the perspective of people as beneficiaries [41,122]. This approach has tremendous potential for protecting ecosystems and their ecoservices and brings the science of ecohydrology as a broad concept to the fore [20]. Thus, an ecosystem services framework that links conservation and development through science and policy, which has the basic fundamentals of environmental health, water, and food security and human health, at its core, will provide for a more sustainable future. For a candid review of environmental valuation, its history, and context, the reader is referred to [19,42,49,74].

However, while this idealistic framework is being developed, for ecosystem services to move from a conceptual to an operational framework for decision making, significant changes, not only within the evaluation fields of natural, social, economic, and policy science, but within national and international businesses and governments globally are required [20]. Both Brauman et al. [20] and Boyd and Banzhaf [19] have suggested accounting and assessment approaches that seek to define and apply value to ecosystems and the ecoservices they deliver. For the purposes of this chapter, the focus is on identifying the ecohydrological interactions to define processes, relationship, and functions that may deliver key parameters, indicators, or indices that can be assigned values for accounting purpose, resilience measures, or industry targets.

However, deriving these targets, measures, or metrics is not necessarily straightforward—as has been discussed—to then assign a monetary or service value to each of these is also problematic. With the advent of the "green consciousness" and the need to develop better management strategies for ecosystems, biodiversity, water, and food production systems, green companies offering services have also proliferated. A key U.N. update report [38] on biodiversity recommends massive economic changes to manage and conserve species and protect the natural environment. The study argues that the economic case for global action to protect biodiversity is now much stronger than the case for tackling climate change. Research by the economics of ecosystems and biodiversity (TEEB)† group has led to the increased recognition of the economic value of natural assets and the returns that can be generated through investing in natural capital. The EU Biodiversity Action Plan [38] has increased the understanding of the drivers of biodiversity loss (including climate change) and how biodiversity is linked

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* Note that Boyd and Banzhaf [19] suggest that the green GDP should be considered as national-scale environmental welfare accounting and performance assessment system such that the ecosystem measure employed here is thought of as a measure of nature’s value, not the value itself. Creating a uniform and consistent accounting system that can be utilized across a number of disciplines and represents the GDP of services delivered to people (e.g., as described by Peskin and Delos Angeles [106]).

with other sectoral activities. The implementation of the plan in 2006 has highlighted the basic role and fundamental importance of ecosystems and has strengthened the need for better managed outcomes to facilitate mitigation and adaptation to climate change.

Through economic incentives or tax concessions, companies and countries can be induced to implement best management practices for biodiversity and a range of ecosystem services that can engender an improved understanding of the value of ecosystems and the services they provide, creating both an economic and a societal framework to reduce overexploitation and generate a new market for ecoservices. Ecoservices is thus termed—the new approach to managing shared space [19].

Increasingly, therefore, the use of soft-engineered solutions—ecoservices approach—is being championed. Soft systems such as those that employ sustainable drainage systems [37] and soft flood defenses are more responsive to extreme events [120]. Projects linking reforestation and river reconstruction are prime examples of soft engineering reposes to manage altered ecosystems in an effort to reintegrate and repair these natural systems [5,110,135].

6.3.2 Ecoservices: Accounting and Decision Making

Daily et al. [41] and others [19,20,42,49,74] have emphasized that understanding and providing ecoservices requires not only a scientific basis for this determination but also a valuation and accounting process that enables the value proposition to be defined, commoditized, traded, and regulated. They suggest three fundamental steps to the decision-making process to integrate both ecological and economic terminologies. First, possible alternatives to the proposed land use, system modification, or exploitation should be considered. The alternative framework in which this decision is often made is guided by the narrow focus of service, for example, water treatment, made to be only examined from an engineering and economic perspective, with alternative natural options given scant regard. Therefore, alternative natural treatments that may be implemented are not even considered [42].

Second, all impacts that may arise from this decision need to be identified and measured for each alternative (including labor, capital, biophysical, and social impacts). These decisions are also often undertaken with incomplete knowledge, either due to the lack of data or a limited understanding of the side effects that may occur (or might be long term and cumulative). However, it is suggested that quantification of uncertainties and risks should be undertaken before proceeding [42].

Third, and most significantly, the assignation of value that will link the risk and uncertainty to the return on investment and the capacity to maintain the status quo, evaluating each alternative scenario in comparable units, nominally the change in human well-being, calculated for the short, medium, and long term [42]. These can be defined as resources that are forgone to obtain the goods, services, or other outcomes associated with any alternative. Predominantly, this is measured in monetary terms [19,20].

In using a monetary approach, often the end result is a system that may not suit our requirements but is one that we are willing to pay for. For instance, extensive commodity and trading markets exist for the products of land- and water-based industries, such agriculture, aquaculture, and forestry [85]. However, the benefits of ecoservices (i.e., protection, treatment, mitigation, and provisioning [93]) remain relatively unpriced and therefore have limited market value [85]. As existing markets rarely reflect the true material cost of production, established initially on the basis that natural resources are “inherently free,” and can be used at “no-cost,” the opportunity to recover degradation and reparation costs is limited. This also leads to inappropriate resource use, incorrect measures of scarcity and vulnerability for some ecoservices, and no measures for the majority [85]. During the last decade, there has been growing support to utilize market and policy fundamentals to increasingly account for the environmental costs of industry, urbanization, and agriculture [8,26,38,64].

Markets for trading in carbon emissions (e.g., Chicago Climate Exchange, EU Carbon Trading Exchange), Renewable Energy Certificates (REC), and Biodiversity & Forestry (Reducing Emissions from Deforestation and Forest Degradation—REDD) have been developed in one form or another. These schemes have gained some credence through market and political support but are still relatively small in scale and operation as measured on a global scale, with some additional support for environmental trading offered by the development of market-like mechanisms for the payment for ecosystem services (PES) schemes [85]. Through these mechanisms, governments and nongovernmental organizations are able to fund environmental recovery and conservation through habitat provision, watershed protection, or carbon sequestration [57,88].

While progress has been made, there are limitations to their effectiveness that include the high degree of uncertainty concerning greenhouse gas (GHG) emissions and climate change; reticence in public policy decision-making process as a result; and the quantification of the economic and social benefits of reducing GHG emissions is generally lacking [57,58]. So while derivative financial instruments and other mechanisms developed to “fill the gap” between the true cost and sustainability can aid the shift toward a green economy, if they are poorly designed, they can have the reverse effect of creating more problems than they solve [85]. To develop effective approaches to manage increased reliance, sustainability, and productivity, an understanding of the complexity of biodiversity, ecological functioning, and service provision is required [26,74,89], with the benefits accruing within the environmental sphere through a public–private partnership.

While monetization of services and goods is one approach, others have been suggested. For example, an Ecological Sustainability Index (ESI), which is comparable to the ecological footprint or the material flow accounting (MFA) used in economics: these indices seek to measure the sustainability of human use of the environment [75]. A complex index, the ESI, attempts to overcome the issues associated with converting all measures to a uniform numéraire, by creating several hierarchical layers grouping the component variables, rather than using a simple sum, that form indicators, grouped in different categories that capture different elements of environmental impact [75].

Four main mechanisms have been developed over the last decade to initiate the recovery and conservation of ecoservices: (1) regulation and penalty, (2) cap and trade, (3) direct payments, and (4) self-regulation [85]. Each has flexibility in application, implementation, compliance, and distribution among industries, communities, countries, and ecoservice provisions, but will not be discussed in detail here. Suffice is to say that the mechanisms exist and are used with varying degrees of success, depending on the level of industry, public and political support for their introduction, and the degree to which the benefits of such schemes can be realized at variable temporal and spatial scales. However, as with other process of accountability, the determination of value is subjective, and the application and assessment of impact can be a limiting factor, either through a lack of understanding or minimal data availability.

6.4 Ecohydrology: Monitoring and Assessment

Ecohydrology, as a science, can provide essential elements (and data) to assist other sciences and disciplines to create environmental assessment frameworks, compliance targets and indicators, policy directives, governance, and regulatory frameworks, and assist with stakeholder dialogues. Through a process of monitoring, analysis, and discovery, the ecohydrologist can provide parameters to develop

- Evidenced-based system for management and policy development
- Targeted management strategies
- Integrated platform to ensure science basis for decision making

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* https://www.theice.com/ccx.jhtml
† http://carbontradexchange.com/

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• Models to assess the potential impacts of investment decisions prior to implementation
• Models to assess social and environmental impacts
• A broader basis for an evaluation framework that is more inclusive

In this way, land and water management decisions can be made and evaluated at variable scales and landscapes from on-farm, to catchment and river basin, with each scalar expansion bringing with it added levels of complexity (Figure 6.5).

Some approaches to overcome this complexity have already been discussed, from economic (REC, PES, MFA), to the environmental (ESI, REDD) and the Millennium Ecosystem Assessment principles, all of which have merit in their own right, but essentially are not holistic and inclusive independently. Alternatives for measuring sustainability and use have been suggested, such as ecological and water footprints, via virtual accounting processes [75,89], or broader climate change models to determine cause and effect scenarios, all of which have limitations, in process understanding, data availability, real-time monitoring, and on-ground applications, and in some cases, policy and regulatory vacuums [85,89,107,141].

However, as with most models and accounting principles, there are limitations, and these systems are no different. An ecological footprint is a strong sustainability measure that focuses on natural resources and the environment, whereas the assessment of savings or accounting is based on economics, with measures of health required to integrate them [75]. While having limitations, a footprint (either ecological or water based) can be calculated at any scale and be applied across cities, regions, and countries [132] and provides a simple flag as an indicator of a country’s consumption patterns. This model adopted by its proponents attempts to bring more rigor to the calculation of ecological footprints by using the environmental impact of production systems that required to deliver its products irrespective of where that production occurs [75]. How this may be applied to assess the sustainability of industry practices or a country’s consumption and productive output is questionable [141].

At the core of these methods is the necessary link to nature and natural systems, which is often overlooked in the current societal and economic models and governance structures [125]. Without understanding these links and the impact of anthropogenic activities either in the short term or thorough cumulative impacts, it is often difficult to determine the true cost and sustainability of such activities as promoted by governments, industry, and market economies. The future focus and that of the engineer is on the green economy and natural solutions that can often be more cost effective and durable than other capital engineered solutions for delivering specific services or policy objectives [125].
A number of cornerstone processes need to be in place to assist in the transition to a more ecohydrologically sensitive green economy, which include

1. Minimizing losses and avoiding inappropriate trade-offs
2. Investing in environmental infrastructure
3. Active management of environmental risks
4. Proactive investment in natural capital
5. Good governance
6. Identification of direct and indirect benefits to various economic sectors and industries
7. Further ecoefficiency for relative decoupling
8. Absolute decoupling of the economy from resource use and its negative impacts [125]

The capacity and ability to implement these fundamentals are dependent on the context of the national and international economies, global environmental considerations (i.e., climate change), conservation frameworks, and the delivery of local and regional benefits that have realizable on-ground returns.

6.4.1 Ecohydrology and Knowledge-Based Systems

As this pressure on the world’s water resources increases, it has generated new and increasingly interconnected challenges, resulting in the introduction of new disciplines, new techniques, new language, and new thinking [23,99]. Ecology, economics, and other social sciences have all progressively added to the historic hydrology and engineering base. To continue this evolution in the wake of new challenges, the adoption of “imported” terms from other sciences becomes a precursor to transdisciplinary learning and collaboration [98]. This is where ecohydrology, in the broadest sense of the term, can play a significant role in developing water and ecosystem management tools as proposed by Zalewski [143], Harper et al. [70], McClain et al. [91], and others.

This has led to the use of concepts and terminologies that were originally defined for a specific disciplinary context, being commonly used in a broad and diverse range of disciplines. According to Neto [98], “….this gave rise to a certain conceptual confusion and the construction of a mixed terminology.” For example, the broad use of economic efficiency terminology that has been introduced into the water management sphere, breaching contextual constraints such that “…the term ‘supply’ and ‘demand’ of water or the ‘water market,’ restricting the assertion to a service provision and interpreting water as a mere ‘commodity’ subject to natural monopoly…. “ [99]. More recently, sociology, anthropology, and social psychology have also become part of solution to the challenges of sustainable water management [98], thus they form part of the revised ecohydrology agenda, supporting the drive toward an expanded theoretical and practical application within this field.

In the last decade, there has been a transition from seeking solutions within individual scientific disciplines to multidisciplinary, interdisciplinary solutions, and latterly transdisciplinary thinking and approaches [98]. Multidisciplinarity, in its strictest sense, does not require the researcher to transition to another discipline [110]; it requires that a group of researchers in a range of disciplines use traditional theories and methods to integrate the findings from these disciplines into a single understanding. However, a transdisciplinary approach focuses on developing a common conceptual framework that delivers a coherent integral process that allows for the cross-pollination of ideas, policy development, and implementation strategies [10,79].

Part of the processes driving this shift has been the tendency toward the globalization of both problems and solutions, driven in part by climatic and economic factors that have the capacity to impact on water and food resources. This globalization has also increasingly enabled the extension of localized solutions and practical experience to a much larger audience, providing opportunities to build on existing knowledge frameworks to solve interlinked and complex problems [10,98]. History provides a stark realization of the consequences of water-use decisions, made with limited science or awareness of the
risks to the environment, society, and the water source itself (e.g., Murray Darling Basin, Australia [8]; Lake Taihu, Jiangsu, China [108]). Communities are now better trained, connected, and equipped to monitor government and industry decisions, and there is an expectation that new developments will not only deliver acceptable environmental impacts, but also generate social and economic benefits [8,23,98]. These actors are placing increasing pressure on decision-makers, engineers, governments, and developers to evaluate the broader view of localized to global-scale impacts and deal with the interrelationship complexities and dynamics as the shared need emerges. To deal with these complex water management issues, a more adaptive and flexible policy approach is required, and when coupled with online technologies, it will deliver interactive learning and best practice to the wider community, stakeholders, and industry partners [103].

There is a growing need for transdisciplinary approaches, such as that proffered for ecohydrology, to develop beyond water and ecology science into a more holistic visionary framework that is able to incorporate nonformal knowledge and effective participatory processes. This framework is aimed at achieving multilevel learning processes that address the hierarchical structure of governments, markets, and networks and provides for both top-down and bottom-up actions for the identification of problems and solutions [98,102]. However, there is tension and competition between specializations within different disciplines, and without specialization, it is difficult to obtain formal and academic recognition. The 2010 Capacity Building Workshop on Water Education in Paris identified the need to build tertiary or vocational-level learning opportunities, which includes participants with different backgrounds in order to facilitate cooperation and exchange of views [98], thus providing broader opportunities for engineers and hydrologists to expand their knowledge base and become more interactive with other disciplines.

However, both personal and institutional barriers can limit the development of these partnerships. Particular issues exist around a willingness to operate outside disciplinary comfort zones and their professional norms and associated the reward and value systems. Scientific knowledge must compete with both personal and institutional values, with issues of moral judgments and social equity involved in the consensus-building processes that occur within decision-making forums [75,83,124]. This integrated approach, when coupled with the evaluation and decision support framework outlined previously, should enable communication between specialists addressing specific problems, as well as other expert practitioners, providing new skills and knowledge competencies promoting a paradigm shift that delivers a new “water practitioner” or ecohydrologist profile [102], thereby creating the freedom and flexibility needed to tackle the increasingly interrelated and complex water challenges the world is now facing.

Pahl-Wostl [103] suggested adopting management practice theory to develop an adaptive evaluation framework using triple-loop learning theory (Figure 6.6) to refine the influence of governing variables that underpin assumptions and values. This approach follows on from double-loop learning [6], which assesses the “cause and effect” relationships within a value-normative framework, and enables the user to test the underlying theoretical assumptions employed within a management or evaluation context [102,103]. By running through a sequence of actions, key criteria, reflections, and transitions delivered from the actionable outcomes, it is possible to provide a theoretical framework: One in which all participants can agree on actions without having to go through the longer-term practical application and evaluation cycles (i.e., trial and error) necessary to deliver agreed outcomes.

A further step from Argyris and Schöns conceptualization, to learn by simply reflecting critically upon the theory-in-action, Finger and Asún [50] suggest that it is now possible to readjust the theory through double-loop learning (Figure 6.6) to avoid experiencing the entire learning circle. Smith [117] suggested that this process will often entail capturing the maximum participation of stakeholders, minimizing the risks of participation, starting at an agreed baseline, and designing methodologies that value rationality and honesty. Pahl-Wostl [103] argues further that in using triple-loop learning that provides avenue to move away from the formative norms, to an informal adaptive process, it is possible to drive innovation in water management, policy development, and water governance.
6.5 Applying Ecohydrology Concepts

The services generated by ecosystems are many and varied; increasingly as we are forced to move to a green economy, understanding the functionality, fragility, and resilience of these systems is important in determining appropriate measures for monitoring, exploitation, and service extraction. To do this requires these services to be organized in a coherent framework [19]. The causal interactionary nature of these services requires a robust framework that considers multiple scalar processes and spatiotemporal considerations as cumulative impacts may manifest locally (e.g., salinization) or globally (e.g., carbon accumulation); therefore, classification of what constitutes a benign or degrading activity is proving to be manifestly difficult with current classification systems offering only arbitrary evaluations. The next section examines approaches taken to monitoring and evaluating ecosystems, through better governance frameworks, technological innovation, and assessment tools.

6.5.1 Ecohydrology and Ecoservices as an Evaluation Tool

The Millennium Ecosystem Assessment [93] has suggested that by dividing services into four categories, interactive services and relationships can be more easily defined. The first of these categories is provisioning services that provide food, freshwater, timber, and fiber for direct human use and is a significant part of the current economy. The second category and much less widely appreciated is the regulating services that maintain the global environment and localized habitats such that it is biophysically possible
for people to live and prosper (e.g., pollination of crops, climate stabilization) [111]. The third category is based around cultural services, those that provide intellectual and spiritual inspiration and aesthetic values. The last category groups the supporting services that underpin ecosystem processes that generate the previously described ecoservices [19,93]. To increase the tractability of the ecosystem services concept, there have been an increasing number of attempts to quantify services through some process of ecosystem accounting; however, the limitations of these efforts become clear once their benefits defined at the local or service delivery scale are removed, to support a more diverse range of products, products in which the immediate ecosystem support, processes, or provisions are not readily self-evident [19]. The Millenium Assistant (MA’s) system can be used to emphasize that supporting services are fundamentally intermediate, and not an end product in themselves, which are essential to managing and maintaining the delivery of ecosystem end products [20,93].

Therefore, a system of accounting is required that enables the tracking of base products, support services, transition services, and that which ultimately links the end users with all the services provided and recognizes the true cost of the utilization of that service. To date, we have not developed or created such an accounting system, nor do we currently have the capabilities in place to trace and track all levels of services, let alone place a value (either monetized or service) that will enable the global community to be accountable for the full range of ecosystem services, support service processes, and degradation costs.

As a basis for the foundation of an accounting service, Brauman et al. [20] refined the term of hydrological services, through the division of these services into five broad categories:

1. Extractive water supply services
2. In-stream water (supply) services (both quantity and quality)
3. Water damage mitigation
4. Provision of water-related cultural services
5. Water-associated supporting services [20]

In this way, services can be defined more readily (and visibly), impacts on extraction and management can be quantified, and the beneficiaries identified. By assessing the chain of processes through which hydrological services are delivered, and evaluating the impacts of these activities on the service sustainability, and thus identifying the beneficiaries, appropriate actions can be undertaken. These may include assigning value, calculating the long-term cumulative impacts, determining the costs and benefits of services, developing appropriate regulation and governance structures, or even terminating the activities if they are deemed to be inappropriate.

However, to measure and assess the activities and the longer-term impacts, an effective and efficient monitoring and evaluation framework is also required. Measurement of change, if associated with medium to long-term impacts or cumulative influences, may require a wide range of monitoring techniques that are able to collect data on both rapid and incremental changes in the ecosystem performance. Measuring small incremental changes may be enough to detect the influence of change across the system network before they have a significant impact allowing for adjustments in both practice and target values [42].

In reality, these measurements and conditions are difficult to amass for ecosystem services, as the relevant systems tend toward a high degree of interdependency, where seemingly small changes in one sector can result in significant changes in the overall system [42,85]. The amount of uncertainty in the knowledge of ecological processes points toward either a small-step approach or cessation of activities if the outcome is unsure to avoid irreversible consequences. In addition, there is conundrum on where to place the value of service relative to current versus future costs and benefits [73,85].

There are contending views as to the effectiveness of the commoditization as an instrument of conservation that range from full support of this tool, which provides a pragmatic and transitory valuation with marketable solutions as core strategies, to a completely opposite view in which the market has no place in this process [65]. However, there is some consensus that economic valuation...
could lead to the commodification of ecosystem services with potentially counterproductive effects in the longer term for biodiversity conservation and the equity of access to ecosystem services and net benefits [65]. Some social discounting is inevitable if future generations are likely to benefit and have greater access to sustainable ecoservices, a situation that if current practices continue is unlikely to prevail [85]. This debate is beyond the scope of this discussion, but has been highlighted to demonstrate that while intentions can be innocent, the outcomes can be as unintended as the consequences of uninformed actions.

6.5.2 Ecohydrology as a Management Framework

As in other case studies, Newman et al. [100] suggest that improvements in the understanding of the linkages between hydrological, biogeochemical, and ecological processes are required to effectively foster integrated, interdisciplinary approaches to developing better resource management frameworks. By they environmental, social, economic, or political in nature, new methodologies and ways of thinking about complex interdisciplinary approaches will improve the impact forecasting capacity [100]. They state that ecohydrology recognizes that vegetation, water, and nutrients are intimately coupled and that changes in one bring about changes in the others. Furthermore, Newman et al. [100] argue that while individual sciences and disciplines have carried out varied and wide-ranging studies on plant, soils, nutrient transport, and uses, an in-depth complete understanding of the interdependencies and interaction of these three components is yet to emerge.

By applying an ecohydrological approach that merges the concepts and tools from numerous disciplines (i.e., geology, biogeochemistry, plant physiology, soil science, and atmospheric science), advancements in unraveling the complex relationships in the vegetation–water–nutrient nexus that dictate fluxes and transport in the critical soil–root zone can be achieved [100].

By adopting this “merger” perspective, a broadening of the individual disciplines of hydrology and ecology is more likely to produce a general or “universal” understanding about ecohydrological functionality. While arguing this case, in which closer ties between hydrological and ecological disciplines will deliver more unified understanding, this broadening also opens the door to other possibilities that stand outside the circle of the sciences, but are of equal importance if desired sustainability and production goals are to be achieved. Environmental transformational and agronomic adaptation is not new; however, the pace at which it proceeds at global and localized scales has reduced the time that allows for adoption and/or adaptation [36]. A number of examples follow, of different approaches taken in which ecohydrology, and perhaps the broader interpretation of this transdisciplinary science, could be adopted and adapted to deliver better environmental and engineered outcomes.

6.5.2.1 Ecohydrology of Water-Limited Environments

Water-limited environments* [68,105] occupy approximately 50% of the land surface and support some of the fastest growing populations, with nearly two billion people living in these regions [35,100]. Scarcity and/or variability in the distributions of available nutrient and water resources ensure that these environments are highly responsive to changes in land cover–land use and water capture or redistribution [36,77]. Given their importance, in terms of human needs and the competition between environmental considerations, the impacts of increasing demands on water and other natural resources create significant social problems and scientific challenges [100]. There are numerous examples of broad-scale environmental changes that have occurred over vast areas, as previously discussed, that have brought about significant changes in water-limited environments including desertification, woody plant encroachment, groundwater depletion, salinization, and soil erosion [43,81,92].

* Defined as water limited due to annual precipitation (P) being typically less than annual potential evapotranspiration (Ep), such that the ratio of P to Ep ranges from about 0.03 to 0.75, and because extreme temporal variability results in extended periods with little to no precipitation.
To address the future needs of these water-limited environments, Newman et al. [100] describe the significant challenges ahead for the ecohydrologist, and their capacity to influence and manage the changes that are upon us at this time. These scientific challenges are stated as follows:

1. Partitioning of evaporation and transpiration
2. Water and nutrient interactions
3. Vegetation and streamflow
4. Vegetation and groundwater recharge
5. Hydrological change and vegetation
6. Landscape interactions in the paleodominated and human-dominated ages [100]

By incorporating these challenges into a research framework, improved understanding can be delivered by addressing issues associated with scale and complexity (Figure 6.5), thresholds and balance, and feedback and interactive loops (Figure 6.6). These processes drive the biotic and landscape response to anthropogenic intervention within the ecosystem delivered by the expanding requirements of human population and limited or unevenly distributed resources [81,100]. This is particularly the case in semiarid (or dryland) environments that are fragile and prone to collapse under external pressures.

6.5.2.2 Salinization in the Dryland Agricultural Areas of Western Australia

Broadacre land clearing for agriculture, resulting in secondary salinization, is widespread in Australia and exists in other countries as a result of clearing and poor irrigation practices. In Western Australia, successive governments promoted agricultural development in the “wheatbelt” or dryland areas of the state, with the last great land-clearing program, “a million acres a year” started in the 1960s and completed in the 1970s [31]. In all, about 15.7 million hectares of perennial, deep-rooted forests and open woodlands were cleared, removing an estimated 15 billion trees and vast areas of mallee scrub and heath. By 2001, when clearing had effectively ceased, over 19 Mha of land had been converted to annual crops and pastures, thus paving the way and unknowingly creating the right conditions to develop one of the worst examples of dryland salinity in the world [12].

The extent of secondary salinity development has been particularly severe and widespread in the dryland agricultural areas of southwest Western Australia [72], with more than 1.1 Mha impacted and a further 4.4 Mha at risk [58]. The main cause of the salinity problems in the southwest was largely the result of rising groundwater due to the extensive clearing of native vegetation and its replacement by short rooted, annual cropping systems [72,114]. This created “leaky” landscapes, with increased water (i.e., rainfall) drained below the root zone into the water table, thus mobilizing the significant salt store within the regolith. Despite lower than average rainfall over much of the wheatbelt since 2000, there is continued salinization expansion in all regions, especially following episodic floods, such as occurred in 1999–2000, 2001, and 2006 [58]. The irony of this situation is that in a dryland environment, poor management of excess water (i.e., rainfall) in the landscape has produced to one of the most widespread degradation issues in Australia.

In response to national legislation on the natural environment, which tied state funding to natural resources policy, the Western Australian State Government, between 1996 and 2003 released a number of policy documents that were targeted at providing a policy framework for the improved management of the state’s natural resources. These included the Western Australian Salinity Action Plan [2], State Salinity Strategy [3], State Water Strategy [65], and State Sustainability Strategy [66], which were significant in integrating the government’s approach to natural resource management for a decade between 1996 and 2006. The formative basis of these strategies was that the

1. Fundamental understanding of the environment existed
2. Scientific and economic farming systems and management strategies were available

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3. New or revised land and water management practices will be developed
4. Decision support tools would follow that would enhance land managers’ (farmers) capacity to deal with change within their industry

During this decade, research science, in the main, concentrated on developing engineering and bioremediative management strategies and farming systems to provide a multipronged approach to tackling the environmental and economic challenges facing rural communities. However, the social capacity of these communities was given limited consideration. This has led to a patchwork delivery and adoption system that has had varied success and did not achieve the stated outcomes of the state's strategies at the level of adoption and participation required, given the scale and impacts of land degradation in the southwest of the state [34].

Part of the problem was associated with the level of funding support to transition farmers and industry from current land management practice to a more sustainable approach. Hydrology, biodiversity conservation, catchment water management, and soil conservation were discussed as providing potential avenues for change [31]. As a whole, neither the ecosystems of the southwest, nor the ecосervices they provided were discussed, in a holistic sense. A major focus of the community was on drainage to manage land degradation, and how this may be funded, implemented, and sustained over decades required to remediate the degradation cause by secondary salinity [24,37,82]. Limited thought was given to the scale and integrative issues, or the complexity of issues surrounding land ownership, access rights, common law, and regulation in place at the time (Figure 6.7).

The outcome of this brief evaluation of the adoption of the state’s natural resources management strategies, relative to the wheatbelt (or dryland agricultural) areas of southwestern Australia, highlights issues of scale and integration as shown in Figure 6.7. While the state's focus was on the water, salinity management, and agricultural production issues, the crisis of implementation and adoption was considered to be external to the natural sciences and thus crossed disciplinary boundaries. This is an important conclusion and supports the notion that while ecohydrology is in itself a new “science,” it is now poised to link key sciences and may need to look outside this science to develop networks that are more inclusive of other stakeholders, which in turn may ultimately determine the effectiveness of on-ground activities.

**FIGURE 6.7** Increasing complexity of implementing water management through drainage on a farm within a catchment. Evaluations of services delivered and services disrupted become increasingly complex from farm to catchment scales.
6.5.2.3 Humid Zone Ecohydrology

Humid lands are a prime example of a water-controlled environment where the exchange and transfer dynamics are notably different from those of arid and semiarid (dryland) ecosystems previously discussed. Soil moisture, its availability and replenishment frequency, is a key factor in maintaining the health of terrestrial ecosystems [112]. Soils are instrumental in creating and maintaining feedback loops between the Earth’s surface and the atmosphere, and its composition, flux transfer capacity (i.e., water and nutrients), is a key determinant in the health and distribution of vegetation cover and/or agricultural productivity. The dynamics of soil water in humid areas, and in particular wetlands, present challenges in relation to understanding the performance of the soil profile (and underlying regolith), including linking the stochastic fluctuations of both the water table and the soil moisture in the unsaturated zone [112].

These fluctuations are in themselves dependent on the climate, soil, and vegetation of the region being studied [131]. Therefore, to build on our understanding of the inherent dynamics of humid land ecosystems will necessitate the construction of a process-based quantitative framework. This contextual model will be used to evaluate the water table and soil moisture dynamics relative to the random nature of localized rainfall patterns, the vegetation (i.e., root profile, water tolerance, root uptake strategies, plant water relations), and the soil physical properties (e.g., storage capacity, hydraulic properties) [112]. In addition, the potential to generate overland flow (either from infiltration or saturation excess runoff) and ponded conditions caused by raised water tables, or perched systems—owing to near-saturated surface conditions—further complicates the classification of water redistribution processes within humid land landscapes [112]. Furthermore, understanding the influence of various localized factors such as topography, vegetation patterns, and soil heterogeneities on the lateral redistribution of soil water is problematic in deriving a simplistic process-based quantitative framework [18,131]. Also, critically important to understanding the ecohydrology of regions with shallow water tables and humid lands is divining the distribution probabilities of soil moisture content for soil layers at different depths in the unsaturated zones, for inclusion in this framework [112]. Rodriguez-Iturbe et al. [111] suggest that this approach will unravel the complex ecohydrology of humid areas, so as to provide a platform for the development of revised scientifically based management practices that are required for the adaptation of food production systems facing a changing climate. Targeted best management practices based on a refined understanding of humid regions are of paramount importance, given they are some of the most productive ecosystems and critical to the continued function of the planet [93].

Not only are there significant ecohydrology challenges within the sphere of humid regions, but it is also incumbent upon us to look to other fields of endeavor for research assistance and support, which can link to the characteristics of soil, climate, and vegetation to provide for a strong platform to underpin adaptive management strategies and policy decisions. As part of understanding the interconnectedness and impact causality of this research, Rodriguez-Iturbe et al. [111] suggest that a broadening of the research network should occur to establish links with related fields, including

1. Environmental fluid mechanics
   a. For the effect of wetland vegetation on surface and subsurface flow (e.g., [90,113])
   b. Sediment deposition/erosion (e.g., [97])
   c. The mixing/transport of dissolved contaminants or nutrients (e.g., [112,138])
2. Humid land restoration, to develop quantitative ecohydrological tools for restoration projects (e.g., [54,96,134])
3. Landscape architecture and urban ecology, to investigate how in urban humid lands the interactions between hydrological processes and ecosystem function are modified by the built environment (e.g., [43,130])
4. Environmental health, to relate ecohydrological environmental conditions to human health (e.g., [119])
While no silver bullet solution is offered in this discussion, nor is it comprehensive, it does highlight the specific challenges related to humid regions in which excess water is a common phenomenon.

6.5.2.4 Ecohydrology and Biodiversity

One approach taken to applying an ecohydrological model to assess a humid ecosystem [61] is that adopted to evaluate the performance of the Serengeti National Park (SNP), in Tanzania. The ecohydrological model is a simplified triple trophic model that assesses the movement of water within the system based on rainfall inputs, river flows, and population dynamics [60]. The model assesses the numbers and migrations of animals (both herbivores and carnivores) within the SNP, in monthly time steps, relative to water availability, grass production, and climatic factors [61]. The model predicts the future population densities of herbivores and carnivores within the SNP over a 50 year period (until 2060) based on known animal behavior, vegetation patterns, and historical climate data.

The water-use scenarios are based on flows from the Mara River, namely, (1) to evaluate performance relative to the implementation of remediation measures in the upper reaches of the river in Kenya, maintaining perennial flows in the Mara River (based on preclearing data prior to 1972); and (2) to evaluate the impact of continued deforestation of the Mau forest and overuse of Mara River water in Kenya (i.e., business as usual) [60]. The model is sufficiently representative to demonstrate that the changes in the hydrological processes during the previous 50 years have occurred as the direct result of land-use change (i.e., deforestation and irrigation in Kenya). These changes are accelerating particularly over the last decade and now threaten the survival of the ecosystem [60]. The authors stress that it will require significant effort on the part of the authorities of both the countries (Kenya and Tanzania) to find ecohydrology-based solutions to prevent the collapse of the Serengeti ecosystem [60].

While this model is relatively simplistic in process capture (and the authors caution against its potential flaws), it was able to identify divergent trends and potential threats to the continued ecosystem functionality of the SNP. This approach also highlights a salient point and one of the major themes of this chapter. That is, while the science has established that there are significant threats, and potential disruption of the ecosystems in the SNP, the capacity to deliver changes across borders and between countries currently lies outside the realm of the ecohydrologist and engineer. Increasingly, there will be a need for these professionals to link with and broaden their understanding of the geopolitical and economic circumstances that have a tendency to override the science and drive decision-making processes.

6.5.3 Ecohydrology Applications and Lessons Learned

As has been demonstrated [31,34,104], a shift in the agricultural industry approach to dryland production systems, so as to include a water management focus that addresses the industries’ productivity, profitability, and environmental concerns, is likely to result in more sustainable long-term outcomes. The biophysical, social, and economic complexities all increase at the various spatiotemporal scales, as does the need for information to be able to address these issues [34] at each scalar expansion (Figure 6.7). For landholders to effectively manage their landscapes across these scales, their need for improved, timely performance and system health information is crucial.

The recognition that the broader community, through government, is investing in a partnership with the local communities to protect the natural environment within an agricultural catchment is an important concept. Previous negotiations with landholders indicated that a willingness to proceed with on-ground works is generated where there are financial incentives for implementation and a good understanding of the on-farm and catchment scale benefits. New approaches to implementing water management and engineering solutions involve community capital and empowerment as well as technical advice [34]. The challenge for the ecohydrologist and the environmental engineer in this case is the development of broadly inclusive agricultural systems that provide information on the impacts of these
activities on the complex ecological systems they disturb: a system that provides an understanding of the trade-offs and benefits to landholders, and deals with complex scale issues—at local, regional, and global scales—that lead to the adoption of sustainable agricultural practices.

Jackson et al. [81], as with others [69,91,100,140], have also embraced this concept that in order to develop an integrated ecohydrological perspective, there is a need to build a framework that fosters proactive collaboration of ecologists and hydrologists. However, the author supports the case that this integrative approach should be further augmented to include a wider group of sciences and disciplines to create greater opportunities for success. The ideology is commensurate with the notion of basin scale applications and monitoring that would enable an explicit focus on ecohydrological principles, but also provide opportunities for the involvement of a wider network of stakeholders.

### 6.6 Ecohydrology: Future Directions and Applications

A key part of understanding the ecohydrological effects of human actions is based around landscape connectivity, understanding and observing ecohydrological connections that link surface and groundwater flow and flux exchange capacities [81]. While no panacea is offered in this discussion, nor is it comprehensive, it does highlight the specific challenges. Some would consider the world’s ecosystems as capital assets [42] as they are the basis for continued life on this planet. How are they to be managed into the future? There is an incessant call for growth, in all aspects of society, on the premise that this will improve the life expectancy and life styles of the majority. However, this must be set as backdrop against the cost of this “growth” relative to the limitations of the capital assets to continue to provide the raw materials and services necessary to maintain and deliver the aspirations and goals of the world’s population.

If sustainably managed, ecosystems are able to yield a flow of vital services, including the production of goods (i.e., water, food, fiber, and timber); life support processes (e.g., soil formation, pollination, water treatment, climate regulation, and genetics); and life-fulfilling conditions (i.e., aesthetics and spiritual fulfillment) [42,92]. Ecosystems, however, as capital assets are poorly understood, rarely monitored, and are often in rapid degenerative decline, with extensive loss of service capability [95]. This shift in service provision is generally undocumented or unreported until the ecosystem collapses. The recent Millennium Ecosystem Assessment [92] report indicated that of the “Approximately 60% of the ecosystems services evaluated…are being degraded or used unsustainably” and the “….human use of all ecosystem services is growing rapidly….”

The relationship between these services is such that declines in production function also reveal critical points and interdependencies in the supply of a combination of services, which may also be in decline, and reflect subtle variabilities in the time scales over which the ecoservices and ecosystems are amenable to repair [40,42]. Invariably, these scales and interrelationships only reveal themselves as they become overexploited and dysfunctional and, often, typically respond nonlinearly to perturbation [19]. For example, the development of secondary salinity in Western Australia largely went unnoticed for decades, due to the yearly incremental changes in landscape hydrology and subsoil salinity mobilization following widespread vegetation clearing [36]. However, as discussed previously, following widespread flooding and redistribution of localized runoff [22,29,36,58] over decades, a tipping point was reached resulting in significant proportions (1.1 Mha) of the agricultural landscape became salt affected with a further 1.7–4.4 Mha at risk [59]. Reparations to manage this impact are costly, long term, and may prove to be irreversible [36]. Furthermore, ecosystems are formed through interactions of local conditions creating distinctive and individualistic relationships, such that restorative actions initiated in one landscape or regional scale may not apply elsewhere [42]. Therefore, the potential to develop a universal single application solution is rare, and remedial and conservative actions often require localized “tweaking” to deliver the desired outcomes [22,32].
Remediation of ecosystems, landscapes, and reengineering built environments (e.g., CUD*) through rethinking and assessing the performance of the system and thereby extracting true value from the system (Figure 6.1). Thus, while providing services that can be supported for long term, the system is not significantly degraded at the same time, beyond set parameters. By analyzing the cause and effect (i.e., double-loop learning) and applying revised approaches to the way in which activities are designed, orchestrated, and implemented, there exists the potential to create more efficient and productive living environments that have limited negative impacts. These systems, by necessity and design, will strengthen and create sustainable ecoservices.

Through the use of local and global scalable approaches, ecosystems can be protected or restored to more effectively manage natural disasters such as floods, to enhance soil fertility and improve productivity, to treat and recycle waste water, and to provide healthy rivers, wetlands, and habitat that will offer both productive and aesthetic services [74]. Changes in management approaches and system design bring not only environmental benefits, but are being viewed as an increasingly viable, financially sound alternative. Therefore delivering theory into practice will necessitate locally based information. This is the future role for the ecohydrologist or environmental engineering, that is, being able to determine the synergies within an altered “natural” landscape or urban environment that will provide the necessary levers to deliver the most balanced and sustainable outcome in a given locality.

6.6.1 Ecohydrology and Climate Change

The increasing challenges encountered to satisfy the global water demand are well documented (e.g., [51–53,129,136]). Shifting demographics and increasing consumption associated with rising per capita incomes are key drivers of increased demand [129]. As discussed, the tendency of human populations to gather near coastal regions or water bodies, coupled with population dynamics such as growth, gender, and age distribution, generates unmet or exclusive demands on freshwater resources [79]. This often results in loss of the pristine nature of the river system (e.g., Tigris and Euphrates Rivers, Iraq) or complete failure (e.g., Aral Sea, Kazakhstan and Uzbekistan) through increased water demand and pollution. Projected climate variability, resulting in changes to rainfall patterns and distribution, threatens the viability of food production systems, already stressed under the burgeoning demands of population growth and increasing affluence [51].

As agriculture develops and land and water use intensifies, the impact of agriculture on natural ecosystems will become more apparent, damaging the integrity of these ecosystems, undermining the food-producing systems that they support. Effective adaptation to the impacts of climate change on water availability and food security requires an integral knowledge of agronomic science, water management, hydrology, and ecology, intertwined with the resulting environmental interactions and trade-offs [79]. Water, energy, and food are inextricably linked and underpin the basic requirements for life, long-term development, and the current global trade and productivity models [35]. Limited access to these three fundamentals for life is compounded by growing concerns about their future availability and sustainability in the face of climate change, population expansion, and resource limitations [53].

An increasingly urbanized planet will exert significant pressure on the level and complexity of natural resource trade-offs required, trade-offs that at the same time must act to minimize ecosystem degradation [35]. A new approach, thinking in a Nexus perspective [78], is at the core to redefining our understanding of the interrelationships between the water, energy, and food security and is a fundamental tenet to realizing the green economy [125]. This paradigm shift is vital to achieving the sustainability development goals in an environment of global climate and economic change [136]. Changes in water distribution, quality, and availability associated with short- to medium-term regional climate variability will also create challenges for future water, energy, and food security [35]. To assure the

broader community that water and land managers are utilizing natural resources sustainably (and are being independently assessed), there is a requirement for both an adequate and flexible eco-accreditation framework supported by a robust real-time monitoring and reporting system [31]. This is where the enhanced role of the engineer, the hydrologist, or the ecohydrologist fits into the equations and will need to deliver better designed, more effective, and sustainable food production systems, water resource management strategies, and harmonious built environments.

6.6.2 Integrated Systems, Monitoring Networks, and Global Linkages

Part of the promise of modernism was that technology could provide services more efficiently and more reliably than natural systems [74]. However, although it may be possible to augment or replace some ecosystem services—often at great cost, on a limited scale, or in constrained locations—the reliance of technology on functioning ecosystems often goes unrecognized. The challenge now facing us to improve or maintain water quality and access is a growing global concern, typified by the creation of the European Commission WFD [46] and the U.S. Clean Water Act [130], among others. A transformation in thinking and approach is necessary with the adoption of new management and development opportunities, which are enabled by innovative technology [35]. By recognizing their reliance on natural systems, people have long attempted to divorce themselves from the vagaries of this dependence.

6.6.2.1 Monitoring Networks

Place-based or catchment-based research is an effective way of promoting collaboration and focusing efforts on the integration of reductionist and holistic approaches [100]. An ideal starting point would be an effective scalable monitoring network, which links the micro- to the mesoscales and provides for an understanding of water fluxes and water quality variations from the plant-root level through to the basin scale. Within this framework, and of global concern, is the increasing storage of agricultural chemicals in soils and various surface and subsurface water bodies arising from the overapplication of fertilizers, herbicides, and pesticides. Chemical species such as nitrates and chlorides impact on crop growth and adversely on the quality of water supply for both communities and commercial activities [33,39,109]. This could be achieved through new technologies that link targeted molecular sensor monitoring with wireless networks that can deliver real-time responses within catchments and regions, and potentially globally, through satellite monitoring technologies.

Wider monitored areas are required, particularly in semiarid regions, and as suggested by Newman et al. [100], such areas are (1) geographically extensive and contain a significant and growing proportion of the human population, (2) extremely sensitive to ecohydrological processes, and (3) composed of well-defined and broad elevational gradients, with numerous, closely spaced ecotonal and hydrological transition zones ideal for comparative studies. To undertake the challenge of explaining the large spatial and temporal variability observed in patterns of soil moisture across multiple space–time scales, understanding the interactive soil–vegetation–atmospheric fluxes and exchanges is critical [15,87]. Access to this information is fundamental to understanding the impacts of changed vegetative covers or in designing intervention or recovery strategies that may need to be implemented or required to influence the rate of change, at multiple scales [142]. External factors like atmospheric forcing, topography, soil properties, and vegetation, which interact in a complex, nonlinear way (e.g., [67]), present measurement and quantification challenges in determining (or predicting) soil moisture spatial variability [87,131].

In addition to the necessity for evaluating ecological and soil–landscape changes as they come under increasing pressures, there is a need to manage water resources and water quality. The main drivers of poor water quality are economics, poor water management, agricultural practices, and urban development [147]. Given that over 90% of the world’s population lives in countries that share river basins, of which 40% lives in river and lake basins that comprise two or more countries [138], access to water, water quality, and water allocation become increasingly problematic from the headwaters, to the discharge point [33]. This becomes more complex within river basins, as there are multiple monitoring and compliance
requirements that are often undertaken across borders, under differing governance structures and administrative capabilities [33]. Water-quality monitoring (WQM) is currently undertaken through small-scale and single-application sampling and testing with limited techniques available and expensive highly technical instrumentation and selective decision support tools [39]. The amount and quality of data available clearly limit the amount of extractable knowledge gained and thereby inherently limit the capabilities of the scientist, modeler, or land manager to deliver appropriate information on which to base actionable decision [80]. A framework with key attributes for real-time, spatial–temporal, and multilevel catchment-level monitoring is proposed [147]. Therefore, there is a case for evaluating the multilevel impacts that various stakeholders have in a catchment on water resources. This would allow the implementation of a more inclusive and effective monitoring and management framework. This framework is underpinned by a real-time integrated and targeted monitoring system that allows for the assessment of both catchment function and modifications to those functions or services by the stakeholders (i.e., land managers). This linkage and similarities between individual sensing requirements indicate that there is need for an autonomous vegetation–soil–water-quality monitoring framework based on targeted wireless sensor technologies [147].

The suggested new modeling frameworks will need to be validated and tested against field data. To this end, improved field measurement and data collection networks are required to observe variations in ecosystem performance. In addition to in-field measurements, satellite observations provide spatially distributed data of surface soil moisture and water depth that could be used to investigate ecohydrological processes in spatially extended systems [29]. Using remote sensing technologies will provide an intercomparison analysis of average surface conditions from remote-sensed measurements and ground-based measurements, land surface models can be utilized to determine variability in soil moisture distribution patterns. Thus they can provide an indication of relative soil moisture conditions to improve runoff predictions and analyze land surface–atmosphere interactions for regional climate predictions in data-limited areas [28]. These data sets can be utilized to improve predictive models of land–atmosphere interactions, rainfall–runoff processes, and groundwater recharge processes [27] and thus be used to assess changes in function, management, land cover, and land use.

Coupling remote technologies with ground-based monitoring networks creates a system that encourages both independent measures and verification tools for remotely sensed data. A survey of ground-based monitoring techniques suggests that wireless sensor networks are tools that, despite their limitations, are attractive for real-time spatial–temporal data collection for soil and water monitoring applications [39]. These tools have a huge potential for dense data collection for monitoring agricultural activities. For effective implementation of this system, key attributes can already be determined, which include multiscale catchment monitoring, spatiotemporal data collection, long life, and real-time systems. Other aspects of technology for consideration include the development of appropriate targeted networks, including variable frequency range, variable sampling, well-defined sensor interface, lifetime, ease of deployment and configuration for hydrologists, and a network model for broad environment monitoring. These requirements are not well catered for by using off-the-shelf components [39].

### 6.6.2.2 Indicators and Metrics

To progress this field of research and to ensure the best managed outcomes, placing a greater emphasis on field data, long-term monitoring, scalable data collection, targeted and well-designed performance indicators (KPIs), and means of verification (MOVs), integration of varied data sets from multiple disciplines is required. While there is broad discussion on the need for improved monitoring technologies, there is also a sustained effort required to develop appropriate targets and indicators of change within catchments. Therefore, while effort goes into the technologies required, additional research is required to derive indicators of sustainability that clearly identify and monitor shifts in ecosystem performance. At best, current practice informs us whether we are moving in the wrong direction or that our current activities are not sustainable [75]. More often than not, these indicators simply draw our attention to the existence of problems, but do little to identify their origins and have limited scope in solving these problems [75]. Therefore, the construction and development of appropriate indicators, monitoring networks,
and reporting frameworks are required to assess ecosystem performance and deliver sustainable outcomes at multiple levels. But in order to do this, ecohydrology, as a discipline, by necessity must look to collaborate with a wider transdisciplinary network.

Thus, through the combination of the varied monitoring and tools for individual areas of a catchment, within a river basin or within regions, a greater understanding of geo-bio-physical trends and the quantification of the contributing factors are within our grasp. This can be achieved through new technologies combined with a network of like-minded institutions, industry partners, and governments to deliver real-time global observations of the impacts of anthropogenic activities, climate change, and localized ecosystem variability. Here, then, presents the opportunity for the ecohydrologist and engineers in determining what type of sensors are required and how these may be implanted within the plant soil continuum and linked to the wider network of sensors from the plot to the catchment scale.

6.7 Summary and Conclusions

The review of ecohydrology concepts presented here is by no means comprehensive, but does highlight the changing nature of issues surrounding water–soil–vegetation ecosystem management and the water and food security issues in that area associated with the services provided by these systems. The integrative requirement of sciences to deliver a broader focus to understanding interrelationships within ecosystems and the need to bring in both policy and governance as tools to assess and monitor ecosystem performance relative to the demands placed on it has been discussed. The use of technologies to monitor the local to global responses on impacts to ecosystems, in this time of rapid change and increased demands, is viewed as imperative. Appropriate measures, metrics, and indicators are required to be developed and categorized, without which short-, medium-, and long-term goals, policies, and directions cannot be set. By broadening the nature of ecohydrology, it provides numerous opportunities for the researcher, to develop and test new skills and applications that will deliver benefits into the global community.

This review has also highlighted the changing roles of industry and economics and the need to underpin the current economic models with a greening ecological framework. There is a continued requirement to provide significant support from a wide variety of researchers, sponsors, NGOs, and governments to build the necessary evaluation frameworks, integrative networks, global monitoring systems, and subsequently responsive and responsible governance and regulation. As has been discussed through this chapter, the scope and breadth of ecohydrology are still emerging, and while there is clear evidence of interdisciplinary collaboration, it has not yet consolidated into new ways of approaching the science. There has been limited progress over the last 15 years in integrating the methodological strengths of the respective parent disciplines (i.e., ecology and hydrology), with a dominance of observational correlation studies, which are rarely coupled with empirical measurements and almost never coupled with experimental studies [84]. The existing research is still dominated by one-way interactions (i.e., hydrological impact on biota or biota impact on a hydrological process), and there exists the potential for the broadening of the scope of this discipline through the coupling models with more controlled manipulative field experiments [115].

The review has highlighted, first, the need for stronger research in arid and semiarid ecosystems, where water is scarce and a tight coupling exists between hydrology and ecology. However, these challenges are not dissimilar to those experienced by other regions on the planet. Second, a requirement to develop predictive frameworks for understanding the consequences of vegetation change, with landscape connectivity, through recharge and discharge dynamics, with global climate. Third, a proposal is presented to further widen the role of the ecohydrologist in creating more integrated networks of a transdisciplinary nature that will foster improved linkages with other areas important to the delivery of sustainable ecosystems and the services that they provide. Fourth, there is an identified need to define ecoservices in a way that is broadly understood by the engineers, communities, governments, and
industry partners and allow this understanding to be introduced into management frameworks that promote resilience and sustainability in the use of the planet’s natural capital.

If the types of political, scientific, and sustainability strategies discussed herein are to be successful, then mechanisms for the provision of adequate and targeted funding and the identification of cost-benefit accruals to the individual, community, and environmental returns are required. In addition, the impacts of physical and soft engineering interventions at short-, medium-, and long-term time periods, and the communities’ capacity to accept and generate change, require substantiation. There is a marked shift toward the development of evidentiary-based systems in which the science of ecohydrology can be positioned as a major player in ensuring our future.

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