6 Intersection of Hydrology and Other Disciplines

KATE HEAL, CATERINA VALEO, TAIKAN OKI & SUSAN HUBBARD

In Chapter 1 the uniqueness of hydrology was identified as its interdisciplinary nature because resolving problems associated with the hydrological cycle involves integrating expertise from many disciplines ranging from the atmospheric sciences, engineering, and biology, to landscape architecture and the social sciences. In this chapter, selected examples are presented that describe the interaction between hydrology and other disciplines when addressing some of the scientific questions facing hydrology and water resources management.

6.1 GLOBAL CHANGE AND HYDROLOGICAL CYCLES

The global hydrological cycle dictates moisture exchange, mass and heat transport, and control of biogeochemical cycles; thus, it is an integral component of the Earth System. The widespread recognition of global environmental problems has resulted in a paradigm shift for research in the natural sciences and a new era in the geosciences. Because of the entwined vulnerability of the hydrological cycle and human activity, hydrological research should not only deal with the science of water cycling in the Earth System, but also examine the cycle's impact on society and in turn, the anthropogenic impact on the hydrological cycle.

Anthropogenic impacts on the hydrological cycle are possible from a variety of activities. Land use/land cover transformations, such as topographical modification, compression of soil layers, urbanization, and the cultivation of different species of plants (agricultural activities), impact the hydrological cycle by altering boundary conditions. Water withdrawals, whether for irrigation, municipal use or industrial use, modify water cycles both quantitatively and qualitatively. These anthropogenic impacts on surface/subsurface water cycles may have indirect effects on atmospheric circulation and regional climate; for example, deforestation may have caused long-term decreases in precipitation that is generated by local boundary conditions as opposed to large-scale circulation (such as the Asian Monsoon) (Kanae *et al.*, 2001).

Figure 6.1 schematically illustrates the impacts of increasing population and economic activities, associated with a consumptive life style, on hydrological cycles and water withdrawals, and the resulting changes in water stress (Oki, 2006). Water withdrawals are increased directly by the increase in population and water usage per capita, and indirectly through the increase in food production. Both food production and industrialization also change land use. Increased industrial activities and land use changes are increasing the emission of greenhouse gases and are therefore altering

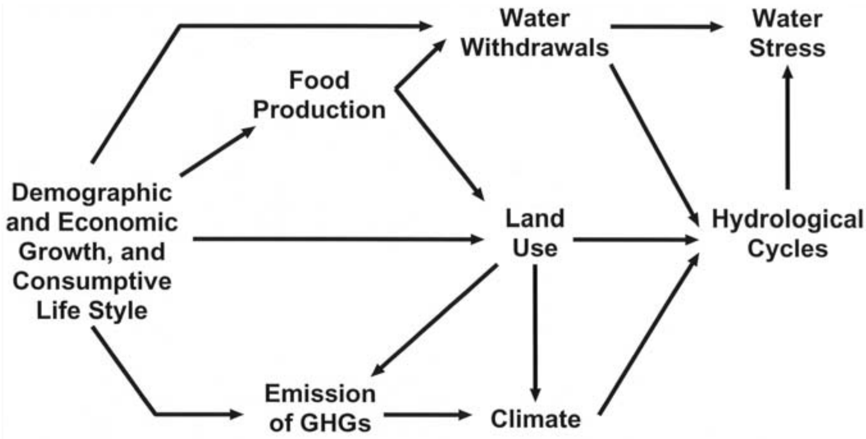

Fig. 6.1 *Diagram illustrating how demographics and economic growth affect the hydrological cycle through land use changes, water withdrawals and changes in climate related to food production and the emission of greenhouse gases (GHGs).*

the climate. Any change in both the supply side (hydrological cycle) and the demand side (water withdrawals) will incur adaptation in water resources management. Climate change also results in more intense and intermittent precipitation leading to more frequent occurrence of floods (Milly *et al.*, 2002) and droughts (Manabe *et al.*, 2004). From this perspective, climate change presents multiple pressures on water resources.

Urbanization is one of the more dramatic and significant types of land cover transformations possible in a basin. Urban areas are also the locus for many other activities with hydrological impacts, such as municipal water use. The rapid increase in urbanization in the second half of the 20th century is expected to continue in the coming decades, given the predicted rapid expansion of urban populations, particularly in developing countries. Urban systems require special attention from hydrologists because the radical modification of terrestrial, atmospheric and human processes means that the standard basin hydrological cycle has to be redrawn.

6.2 WATER AND URBAN SYSTEMS

Since the 1940s, the study of water in urban systems has developed into a significant sub-discipline within hydrology. All aspects of the basin hydrological cycle may be modified in urban systems. The altered urban microclimate affects the amount, type, timing and frequency of precipitation. Changes in the nature of the land surface (often a reduction in vegetation cover and increase in relatively impermeable surfaces) alter interception, infiltration and runoff rates. To meet the water demands of urban populations, water may be transferred from other basins and large volumes of wastewater are generated that require disposal without compromising urban resources.

Hydrologists have had to develop and adopt new tools, models and theories to study urban systems because much of the existing knowledge within the discipline was based on “natural” systems. For example, because runoff from urban basins is much flashier than from natural basins, precipitation must be characterized on the scale of minutes, as opposed to hours or days, resulting in various problems for data collection, archiving, management and modelling that are unique to urban hydrology. Hydrologists have also had to form new working partnerships with other disciplines because of the specific demands and constraints of these systems. As already discussed in Section 3.3.6, urban populations have very specific, yet conflicting demands for water resources: provision of a clean, plentiful water supply, but also wastewater disposal, with the two water streams remaining separate for public health reasons. Freedom from flooding is also required. Furthermore, the cultural and social aspects of water resources cannot be overlooked in urban environments: water resources need to be fully integrated within the spatial constraints of urban areas where people live, work and socialize.

One way in which the conflicting demands on water in urban systems are slowly being resolved is through *water sensitive urban design* (WSUD), which emerged as a concept in urban water resource management during the early 1990s. WSUD aims to minimize the impact of urbanization on the basin hydrological cycle by better integrating land and water planning in urban development. Key objectives of WSUD are: managing the water balance, maintaining and (where possible) enhancing water quality, encouraging water conservation (e.g. by promoting the re-use of storm water and effluent and minimizing the import and use of water supplies), maintaining water-related environmental and recreational values and adding value while minimizing

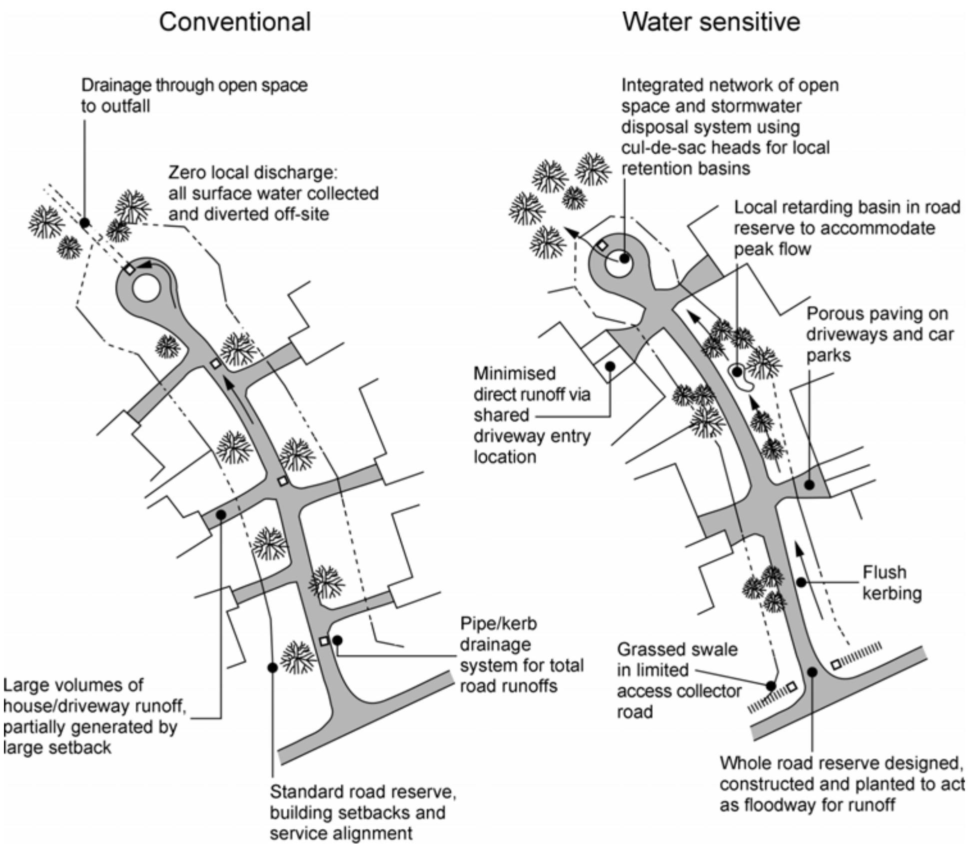

Fig. 6.2 *Comparison of a conventional and a water sensitive design for an urban residential cul-de-sac (after Melbourne Water, 2005).*

development costs (often through minimizing the drainage infrastructure cost). WSUD can be applied at any scale from single buildings to whole districts or settlements. Considerable practical experience in WSUD has developed in Australia, see for example CRCCH (2001), and an example of WSUD applied to a residential street is shown in Fig. 6.2.

To further develop solutions to urban water issues, such as WSUD and others, that will be valued and sustained by urban communities, hydrologists need to work with social scientists, landscape architects and ecologists, as well as engineers, planners and public health scientists. Some specific examples of the interaction between hydrology and other disciplines in the resolution of urban water issues are now presented.

6.2.1 Urban water supply

Traditionally, demands for urban water supplies were mostly satisfied by importing water from outside the urban area. But in order to meet the increasing demands of expanding urban populations, increasing attention is being paid to maximizing the use of water resources available within the urban area. This change in attitude is particularly apparent in cities in arid climates, but is also of wider concern with the possible increase in variability of water resources due to climate change. While management of water demands is an important component in utilizing water resources efficiently in urban areas, hydrologists are working with engineers, public health scientists and social scientists to quantify water resource availability within urban systems. This includes providing estimates of precipitation availability for rainwater harvesting and characterization of aquifer recharge processes and rates in the management of groundwater resources.

The use of rainwater tanks is one method of reducing dependence on piped water supply and is increasingly promoted in arid climates such as Australia (enHealth, 2004). Currently only 7% of households in state capital cities in Australia have rainwater tanks, but it is estimated that in the city of Adelaide (mean annual rainfall about 500 mm), collection of runoff from a medium-sized roof of 150 m^2 area in a small 1 m^3 tank could provide 24% of the total household annual water requirements. Use of rainwater for drinking water supply still requires attention to water quality (e.g. microbial contamination from the storage tank), but the public health risks of using rainwater for hot water, bathing, laundry, toilet flushing and garden watering are low.

In addition to utilizing rainwater, part of the water resource demands in urban areas may be met through water recycling. Storm water runoff, bathroom and laundry effluents (grey water), domestic wastewater (black water) and municipal wastewater can be used in numerous ways, ranging from drinking water and groundwater recharge to toilet flushing and irrigation of gardens, public spaces and agriculture, after treatment appropriate to the end-use. In California, wastewater re-use has been practised since the 1920s. In 2000, 600 million m^3 of municipal wastewater was recycled after treatment, primarily for agricultural (48%) and landscape irrigation (20%), but also for groundwater recharge (15%) and industrial purposes (5%). For more detailed discussion and examples of water recycling, see Department of Water Resources (2003) and Radcliffe (2004).

While the technical feasibility of using water recycling to meet increasing urban water demands has been widely demonstrated, community and public acceptance is essential for the successful implementation of such schemes, particularly for provision of domestic water supplies, due to public health concerns. To achieve this, hydrologists need to work more closely with engineers, health scientists and social scientists.

6.2.2 Urban wastewater disposal

With rising populations and the increasing pressure on water resource availability, the approaches adopted for wastewater disposal have moved away from traditional engineering methods practised in developed countries that dispose of waste in centralized facilities requiring extensive sewerage networks, large volumes of water, copious energy and high levels of maintenance. This is particularly the case in urban areas in developing countries where alternative methods of wastewater treatment with lower construction and maintenance costs have been adopted since the 1970s, including waste stabilization ponds, land treatment (application to soils) and constructed wetlands. In addition to human health protection, such schemes often also aim to utilize the liquid and nutrient resources from wastewater for agricultural irrigation.

The benefits of using wastewater with no or minimal treatment for agricultural irrigation in urban and peri-urban areas are now beginning to be recognized. Wastewater agriculture provides food supplies to urban populations, reduces fertilizer purchase costs to the farmer, and is a more cost-effective method of wastewater treatment than centralized wastewater treatment works. Studies in several Asian and African cities showed that over 50% of the urban vegetable supply originated from wastewater agriculture (IWMI, 2003). In the Guanajuato River Basin, Mexico, it was estimated that treating wastewater before re-use would cause farmers' net annual incomes to decrease by US$135 per hectare because of fertilizer purchases required to replace the nutrients contained in untreated wastewater (IWMI, 2003). In contrast, provision of a large centralized wastewater treatment plant in Guanajuato City would cost US$2.6 million to construct and incur annual maintenance costs of US$200 000 (IWMI, 2003). However there is also a need to minimize the risks of wastewater use in agriculture. Measures found to be effective in minimizing the human health risks to wastewater farmers and food consumers and reducing the potential for soil and groundwater contamination include: wearing shoes in irrigated fields to reduce the incidence of hookworm, regular deworming campaigns for farmers and their families, educating farmers and consumers in simple hygiene measures and using alternative irrigation methods such as bed and furrow that reduce direct contact between crops and wastewater (IWMI, 2003).

6.2.3 Urban storm water management

Another important area of urban water management is the management of storm water runoff. Traditional urban drainage design was based on combined sewerage systems in which both domestic and industrial sewerage and storm water runoff were conveyed to treatment works with capacity to treat only a portion of total sewerage flow (often set at six times the dry weather flow). This meant that, at high flows, raw sewage was discharged in combined sewer overflows directly to the receiving watercourse, although the theory was that dilution would occur by the less contaminated storm water runoff. To reduce the public health and ecological side-effects of combined sewerage systems, separately-sewered systems were constructed from the 1950s onwards. In these, all sewerage was treated but surface storm runoff was piped directly to the receiving watercourse without treatment. It was then recognized that storm runoff is itself contaminated with pollutants, such as potentially toxic metals, hydrocarbons, pesticides and sediment, which are deposited on impervious urban surfaces and washed off during rainfall events, causing degradation of water resources and aquatic ecology downstream.

The most effective way of combating diffuse pollution arising from urban storm runoff is to reduce the volume and contamination of runoff at source, for instance by good housekeeping measures for oil and pesticide storage, raising public awareness, and campaigning for manufacturers to reduce the potentially toxic metal content of products like vehicle brake fluids. Such measures will take time to become effective so Best Management Practices (BMPs), sometimes known as Sustainable Urban Drainage Systems (SuDS), "a sequence of management practices and control structures designed to drain surface water in a more sustainable fashion than some conventional techniques" (Martin *et al.*, 2000), are increasingly being implemented in urban areas, particularly in new developments. SuDS control structures are fully described in numerous publications, such as Martin *et al.* (2000), and should be implemented as part of a surface water management train, ranging from source control of runoff (e.g. using porous surfaces and rainwater tanks) to regional treatment in ponds. SuDS provide water quantity, water quality and amenity functions in the "sustainable urban drainage triangle". Aquatic contaminants are removed by SuDS through processes of filtration, settlement of particulates, plant uptake and precipitation, while increased infiltration and detention times of storm runoff reduces the modification of river flow regimes by urbanization. SuDS such as wetlands and ponds improve the amenity for urban communities and provide a diversity of ecological habitats. Additionally, SuDS have economic benefits as they have been shown to have lower capital and maintenance costs than conventional urban drainage systems and their presence can increase the value of adjacent properties.

With the increasingly holistic approach to urban drainage that is demonstrated by the above examples, hydrologists, with their experience of interdisciplinary work, have a greater role to play. Today urban wastewater disposal is viewed as part of the flows of water and contaminants in urban systems that also interfaces with social, cultural and environmental aspects, instead of the "out-of-sight, out-of-mind" attitude of the past. The tools and theories of hydrology are increasingly applicable within such new conceptions of urban systems. Examples include the study of sedimentation and water quality treatment in SuDS, infiltration and recharge of different urban surfaces, and modelling the interaction of different wastewater streams in urban basins.

6.2.4 Modelling urban systems

Ten years ago, O'Loughlin *et al.* (1996) examined the state of rainfall–runoff modelling in urban hydrology. They outlined the theory of urban rainfall–runoff processes, modelling practices and the use of computer models at the time of publication. Their main conclusions regarding the state of knowledge in modelling the hydrology of urban systems at that time included: (a) the interaction of climate, topography, geology, soils and vegetation has an important influence on the hydrological impacts of urban development; (b) low intensity storms have the greatest impact in urban areas because impervious areas will always produce runoff, whereas in rural areas, water losses by evapotranspiration are relatively large in small storms; (c) the response from an impervious surface should be more predictable than from a pervious surface, and, in theory, the reliability of rainfall–runoff model results should increase with the percentage of impervious area; (d) urban rainfall–runoff models are primarily composed of a loss part and a routing part; (e) current limitations to urban rainfall–runoff models include inaccurate data and insufficient quantities of data; (f) different models are developed independently at different scales, but are often combined into one large unit, creating incompatibility problems within the model.

The authors' recommendations for future research to improve modelling of the hydrology of urban systems (O'Loughlin *et al.*, 1996) included: (a) greater consideration of scale, e.g. taking into account the appropriate levels of detail and the relationships between various scales when combining models for urban and rural areas or modelling a basin with some degree of urbanization at many scales; (b) incorporating the spatial variability of rainfall; (c) using a continuous mode for modelling in urban areas; and (d) integrating Geographic Information Systems (GIS) with urban models.

Since that paper, these recommendations have been addressed to only varying degrees of satisfaction. A plethora of urban hydrological models exist, each designed to achieve a variety of possible objectives, but two are widely used in North America because of their range of capabilities and flexibility (Viessman & Lewis, 2003): the US Environmental Protection Agency's Storm Water Management Model (SWMM), and the Hydrologic Simulation Program–Fortran (HSPF). The latter was originally devised to evaluate basin-scale water quality impacts including those from non-point sources. SWMM was developed to assist the urban drainage system design process and there are numerous user-friendly versions that are integrated with pseudo-GIS software or ESRI GIS products. Both models operate in continuous mode and include relatively sophisticated techniques for determining runoff from pervious areas, incorporate activity such as diversions and flow controls, and include water quality simulation (Viessman & Lewis, 2003). Incorporating accurate estimates of the spatial (and temporal) variability of rainfall is only limited by the raingauge network available (often as a function of funds) although this may be successfully augmented by radar-derived precipitation data and related satellite information.

However, the one recommendation that perhaps has yet to be realized is the issue of scale when attempting to "integrate" rural and urban modelling into a holistic model applicable to basins of mixed land use. The primary modelling objective of an integrated urban and rural model is to predict the combined runoff generated; however, the scale of the processes leading to runoff from different land covers is radically different for urban *vs* rural areas. The differences in both temporal and spatial scales occur due to the generally higher heterogeneity observed in the urban landscape, for example, the occurrence of small-scale asphalt structures near strips of pervious grass cover, as well as the faster runoff response times to precipitation input. The weakest feature of most, if not all urban hydrological models, is generally considered to be the runoff generating mechanism (Raimbault, 2001). This is due to the fact that infiltration of rainwater in the urban area is neglected in most models. While there is less infiltration than in rural areas, urban structures (whether intentionally or unintentionally, controlled or uncontrolled) and pervious vegetated areas within urban areas provide infiltration flow pathways and thereby affect the total volume of net rainwater entering the basin (Raimbault, 2001). Infiltration in urban areas is highly variable both spatially and temporally (Raimbault, 2001), and therefore, it is not surprising that an area of weakness common to urban and rural hydrology is characterizing and modelling infiltration and subsurface flow pathways. Because infiltration occurs through constructed surfaces and natural areas within the urban region, the spatial scales leading to runoff generation will be different. Modelling urban regions accurately therefore requires great attention to the spatial detail in the heterogeneity of the urban form, and the variability of precipitation over very short time periods.

Because urban drainage design depends heavily on regional climate, urban hydrological modelling is climate specific. The humid tropics have unique issues primarily stemming from the fact that humid tropical countries also tend to be developing countries. Particular problems that affect the design and modelling of sustainable urban drainage systems in this type of climate include: (a) lack of information, guidelines, regulations, enforcement; (b) lack of funds and poor management; (c) adoption of inappropriate practices from developed countries; (d) a general lack of awareness and education as to the benefits of alternative drainage systems; (e) lack of hydrological data; and (f) lack of public participation. In addition, because change is occurring rapidly in these areas of the world, constant updating of data is required and this is difficult to resource (Maksimovic & Tucci, 2000).

Urban drainage in arid and semi-arid climates is also unique as one of the greatest problems for sustainable urban drainage design in these climates is soil erosion. The soil type, the tendency for reduced vegetation, and the general characteristics of rainfall (infrequent high intensity events) lead to large erosion problems and adverse effects on infrastructure. Design in these countries is often suboptimal because of the misapplication of methods from humid regions. Furthermore, sophisticated hydrological monitoring and storm water quality sampling programmes are required in arid regions because of the random nature of storm water runoff and short duration and rapid rise of hydrographs and hyetographs (Nouh, 2000).

Urban drainage in cold climates has traditionally been characterized by limited research and attention, although the situation is changing as an entire conference was recently devoted to urban drainage and highway runoff in cold climates (Viklander *et al.*, 2003). Again, there has been a misuse of methods intended for more temperate climatic conditions. There is also a need for appropriate urban hydrological measurements during the winter and careful calibration of models to simulate winter conditions (Saegrov *et al.*, 2000).

6.2.5 Freedom from flooding

Flooding is expected to impinge increasingly on people and their livelihoods over the next few decades as a result of increasing populations. This is particularly true in river flood plains and coastal areas that often offer the most favourable locations for economic activity, and are susceptible to rising sea-levels and increased severity of rainfall events predicted as a consequence of global warming. Urban systems are particularly at risk of flooding and its attendant costs, both directly on economic activity and indirectly through adverse social and health impacts. This is due to the fact that many cities are located in flood prone locations and urbanization normally results in a more frequent occurrence of high river flows. Again, with the increasingly holistic conception of urban drainage, approaches to addressing urban flooding have moved from reduced reliance on controlled fully-engineered flood defences to more stringent planning controls, use of SuDS, and improving public knowledge of flood risk and awareness.

Source control measures to reduce flooding should be selected based on their ability to meet regulatory requirements, effectiveness in removing pollutants, public acceptance of the practice, ease of implementation, and institutional constraints and costs (Marsalek, 2001). Hydrology has and will continue to be a key discipline for developing solutions to flooding. Areas in which hydrologists can contribute in the future include: increased understanding of the link between land use and flooding, prediction of the effects of climate change on flooding, improved flood hydrograph forecasting incorporating real-time hydrological data, provision of more flow data of greater accuracy as a basis for flood modelling and analysis of flood probability, and increased primary data acquisition (telemetered raingauges, soil moisture and water level monitors) for basin planning purposes (Institution of Civil Engineers, 2001).

6.2.6 Urban water in integrated basin management

Adoption of an integrated basin management plan means that urban planners recognize that their planning and management must consider a larger region than the immediate area experiencing a problem (Zeman & Spatka, 2001). As indicated earlier, urban drainage solutions require a holistic approach, which is also essential for "integrated basin management". The impetus behind effective integrated basin management working within the relevant socio-economic constraints is an interdependent relationship between atmospheric inputs, urban drainage, water supply, groundwater resources, wastewater management and receiving waters (Marsalek *et al.*, 2001). The aim of integrated basin management is "to achieve the sustainable, coordinated management of water resources within a region, with objectives of controlling and conserving water, minimizing adverse effects, and achieving specified and agreed water management and social objectives" (Marsalek *et al.*, 2001).

Successful implementation of an integrated basin management plan involves developing a plan of action that begins with the definition of the problem, objectives and goals (Marsalek *et al.*, 2001). They go on: "*With respect to integrated management, there is a need to promote a broader multi-disciplinary approach to integrated catchment management, where the environment to be managed is a complex entity of interacting ecosystems that operate within a landscape. Integrated water management accounts for system complexity and interconnectivity of its elements. It is holistic in its approach, which is characterized by involving local and regional authorities, employers, environmentalists and decision makers, politicians, as well as the people affected. It is cross-sectorial by its nature, and transcends societal structures, divisions and institutions*".

Achieving sustainable and successful integrated management of basins that includes urban water requires strong informatic support as almost all water supply systems lack reliable information and data. Obtaining high quality data to support water distribution system analysis, flood and water quality analysis, treatment process modelling, and other activities related to urban water systems is essential (Butler & Maksimovic, 2001; Matsui *et al.*, 2001). However Marsalek *et al.* (2001) suggest that the greatest challenge encountered in the implementation of integrated basin management is the creation of cross-sectorial cooperation and relationships because the restoration of urban waters will require the cooperation of the entire society. Improved communication at all levels is necessary, including between departments of the same municipality (Roche *et al.*, 2001), as well as between engineers and stakeholders (Lundqvist *et al.*, 2001) and with the public (Affeltranger, 2001).

6.3 WATER AND AGRICULTURE

As discussed in Sections 2.4.3 and 3.3.4, agriculture is the dominant user of the world's water resources, accounting for about 70% of the annual withdrawal of renewable freshwater. With the important linkages between water, agriculture, land use and food production, hydrologists have, and always will, continue to work closely with crop scientists, soil scientists, agronomists, agricultural engineers, meteorologists, physiologists and animal scientists. In addition to interacting with numerous different disciplines, hydrologists also need to influence water use decision-making in agriculture, which occurs at all scales. Agriculture is influenced by international and national economic policy because it is the mainstay of the economy in many developed countries. At the same time, agriculture comprises individual family livelihoods and water use in agriculture is affected by millions of individual land-use and management decisions throughout the world. Collectively these decisions may impact on all aspects of the basin hydrological system, from groundwater recharge to green water use to water quality and ecosystem health.

The interaction of agriculture with other components of the basin hydrological system is increasingly recognized within agriculture and water resources management and policy making. The promotion of the blue-green water concept in water resource management, which particularly highlights the contribution of rainfed agriculture to water resource availability, has already been discussed in Section 2.9.2. A further example of this shift in opinion is changing perspectives on water use efficiency and water productivity in agriculture. Classical irrigation efficiency is defined as the crop water requirement (actual evapotranspiration minus effective precipitation) divided by the water withdrawn or diverted from a specific surface or groundwater source. Under this definition, irrigation systems with high water losses due to evapotranspiration but also from seepage, percolation and runoff were uniformly regarded as "inefficient" and in need of upgrading, even though the water losses may have been of benefit to other water users in the basin through maintenance of downstream flows and groundwater recharge. It is perhaps more useful to evaluate water productivity instead of water use efficiency. Water productivity can be assessed at several scales, from crop water productivity (the ratio of the product, in weight or monetary value, to the amount of water depleted) to basin water productivity, which takes into account multiple uses of water depleted, including environmental water requirements (Seckler *et al.*, 2003). As a result of this new perspective on basin water productivity, supposed "improvements" in the efficiency of irrigation water schemes will not make as many new resources of water available as previously estimated.

Examples of regional-scale policy influences on the relationship between agriculture and water resources include the following in the European Community: the Nitrates Directive (EC, 1991), which aims to minimize nitrate contamination of groundwaters; the Water Framework Directive (EC, 2000) which requires all threats, including agriculture, to the ecological quality of basin waters to be identified and treated; and the reform of the Common Agricultural Policy in which farm payments are no longer linked with production but instead with maintaining land in good agricultural and environmental condition (EC, 2003). Although current policy making aims to improve water resources, it is important to consider the interaction between agricultural land use and management and water, soil and atmospheric resources. "Pollution swapping" has been observed, in which land management measures (such as buffer strips), implemented to reduce diffuse water pollution caused by nitrate leaching from agriculture, have increased emissions of nitrous oxides (a greenhouse gas) (Dosskey, 2002). In Canada, large areas of wetlands have been drained for agricultural purposes, yet recent recognition of their importance in providing wildlife habitat, improved water quality, attenuation of floods and augmenting low flows, as well as groundwater recharge (Watt, 2001) has resulted in increased cooperation between the agricultural community and conservation authorities to ensure that wetlands are protected or restored.

The above wide-ranging examples demonstrate the continued need for interaction between hydrologists and other disciplines relevant to agriculture, including social scientists and public health scientists. Urban source control measures and BMPs have a longer history than agricultural source control measures (that mitigate water quantity and quality). As a result there are a greater number of obstacles to implementing agricultural source control measures compared to urban ones, including: less well-defined terminology for agricultural measures; fewer levels of government imposing regulations on rural areas where agricultural activities are most prevalent; and the different water quality issues encountered in agricultural runoff (Watt, 2001). Defining and understanding the ability of agricultural source measures to mitigate hydrological effects, water pollution (faecal indicator organisms, nutrients, pesticides), farm wastes, soil erosion and habitat concerns requires involvement from a wide variety of scientific disciplines and stakeholders but, in particular, hydrological knowledge is critical. Since agriculture is the main consumer of renewable water resources and is also the main provider of food for the expanding human population, the input of hydrologists is imperative.

6.4 ECOHYDROLOGY/HYDROECOLOGY

Of the examples of interdisciplinary work between hydrology and other disciplines discussed in this chapter, the relationship between ecology and hydrology is probably the youngest. Following work on vegetation and hydrology interlinkages in the 1960s, some of the early collaborations between ecologists and hydrologists started in the 1970s driven by a specific need to develop methods to define the environmental flow requirements of fish in order to manage river flows below dams. Arising from this was the Instream Flow Incremental Methodology (IFIM) and in particular the Physical HABitat SIMulation system (PHABSIM) developed by the US Fish and Wildlife Service (Bovee, 1982). PHABSIM combines a hydraulic model that is calibrated to a river reach using field measurements of water depths, velocities and flows, with habitat suitability information for the target species/life stage to produce a Weighted Usable Area (WUA) of river channel for a specific flow. The relative merits of different flows can therefore be assessed for the target species/life stage to inform river management.

From this very narrowly-defined beginning, different conceptualizations of ecohydrology/hydroecology developed in the 1990s, including a broad definition of ecohydrology as “a new paradigm for the sustainable use of aquatic resources” (Zalewski *et al.*, 1997). This arose from the recognition that freshwater ecosystems provide a range of goods and services on which crude economic values can be placed (see Section 3.2.1). The consequent interdependence of environmental aspects of freshwater resources and sustainable development formed the central theme of the IUCN Report (2000), *Vision for Water and Nature*. Ecohydrology thus became an

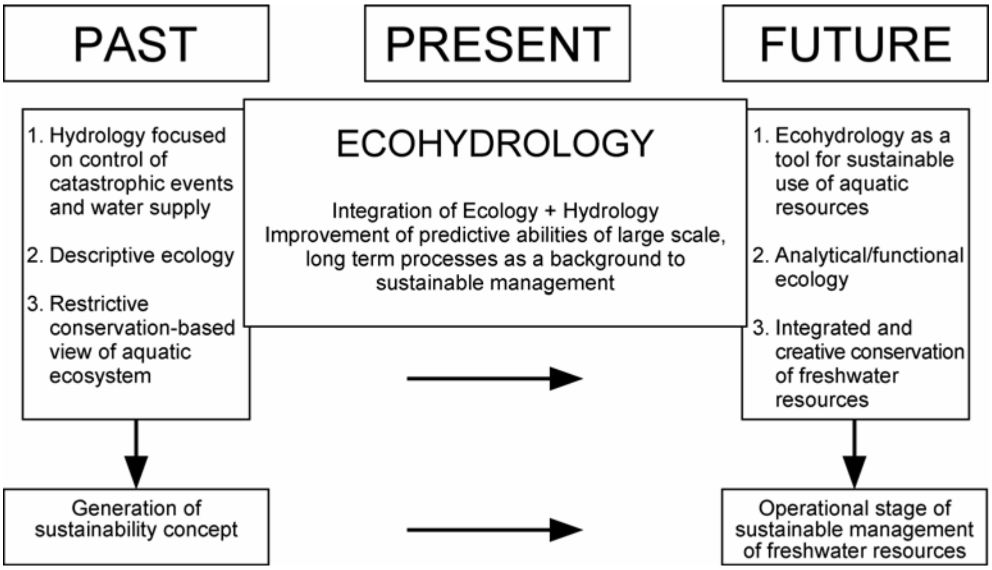

Fig. 6.3 *The development of ecohydrology into a new tool for the sustainable management of freshwater resources (after Zalewski et al., 1997).*

essential component of basin management, described by Falkenmark & Folke (2002) as "socio-ecohydrological basin management". Figure 6.3 traces the evolution of ecohydrology into a tool for water resource management.

The nature and development of all aspects of ecohydrology/hydroecology is evaluated in detail by Hannah *et al.* (2004). From literature reviews and bibliographic data analysis, Hannah *et al.* (2004) suggest that ecohydrology/hydroecology is not (yet) a new paradigm or discipline, principally because research in this field is still conducted in a multidisciplinary rather than an interdisciplinary fashion. Ecohydrology/hydroecology is defined in different ways, with different emphases within ecology and hydrology, and few studies are conducted by teams with members from both disciplines. Instead of proposing yet another definition of ecohydrology/hydroecology, Hannah *et al.* (2004) identify elements that an appropriate definition should contain. These include: "(a) the bidirectional nature of hydrological–ecological interactions and the importance of feedback; (b) the requirement for fundamental process understanding; (c) all water-dependent environments … and flora, fauna and whole ecosystems; (d) process interactions operating at a range of spatial and temporal scales … ; and (e) … the interdisciplinary … research philosophy".

In socio-ecohydrological basin management, emphasis moved from protection of species to protection of ecosystem processes, the community of organisms required to develop the food web of primary producers, consumers and decomposers that mediate energy flows and cycling of elements, and that together sustain ecosystem functions and services (Falkenmark & Folke, 2002). Increasingly, basin management has adopted ecological concepts, such as resilience: the capacity of the ecosystem to absorb change without loss of stability. The incorporation of ecology into basin management has resulted in large changes in water policy making and management in which greater emphasis is placed on ecosystems and the surface–subsurface water interactions of the whole basin area. In turn this has placed new demands on ecohydrology to meet the needs of the rapidly evolving policy arena.

A good example of the new approach to policy is the EU Water Framework Directive (WFD) (EC, 2000) that sets the target for all surface, groundwater and coastal waters in the EU member countries to achieve “good ecological status” by 2015 through the process of participatory integrated basin management. The Directive sets out a timetable and general procedures for achieving this ambitious aim. Member states are required to define river basin districts and, for water bodies within these, to identify: their current status (compared to baseline reference conditions), pressures on them and, if required, the measures to raise them to good ecological status. All this information will be contained within river basin management plans that will be reviewed every six years.

The recent and relatively rapid adoption by policy makers of ecohydrology as a means of managing basins means that scientific understanding currently lags behind policy in a number of areas. Ecohydrology-based policies tend to contain general principles and guidance, but implementation and enforcement normally requires precise definitions and quantification that often are inadequate descriptions of the dynamics and functioning of ecosystems. Adam (2001) elaborates on these points in his discussion of policy and knowledge concerning wetlands. Different definitions of what constitutes a wetland are used in different policies and in different parts of the world, often as a result of local geography and language. It could be argued that it is preferable to accept a diversity of ecohydrology-based policies, appropriate to local conditions, although concerns might be expressed about the effects of differing policies on the economy and trade between countries. Adam (2001) suggests that it is preferable to “*explain to the public the spatial and temporal complexity of the natural world than to engage in pseudoscientific exercises of imposing artificial limits on natural continua*” (in this case wetland boundaries).

A prerequisite for ecohydrology-based basin management is appropriate measures of ecosystem health in order to assess the status of water bodies and monitor changes over time, often in response to remedial measures. However, it is problematic to find quantitative indicators of aquatic ecosystem health since it is influenced by ecological interactions, habitat, water quality and the timing of water availability (flow regime, flooding). Many ecologists are uncomfortable with providing such quantitative indicators from the current knowledge base and feel that a field evaluation of a water body by a trained ecologist often provides a better assessment of the pressures, current status and remedial action required than the application of quantitative measures devised to meet a specific policy. One example of a holistic biological water quality indicator is RIVPACS (River InVertebrate Prediction And Classification Scheme), developed in the UK, in which the observed macroinvertebrate diversity at a site is compared with the expected diversity, derived from surveys of unimpacted sites in rivers of similar physical and chemical characteristics. An example of the RIVPACS approach is given in Table 6.1 for the Moors River, southern England. The results of the RIVPACS analysis showed that the river is stressed since only 30 (or 57%) of the 53 taxa predicted to be present from 11 environmental variables were actually observed. In the World Water Assessment Programme report of 2003 it is suggested that measures of biodiversity have the potential to provide the most cost-effective integrated indicator of overall ecosystem condition. Biodiversity underpins many of

Table 6.1 Comparison of observed and expected taxa in the Moors River, southern England. Species level prediction was obtained from RIVPACS I based on 11 environmental variables and taken to the 50% probability level (adapted from Wright *et al.*, 1993).

Taxonomic group	No. taxa observed after 3 sampling seasons (O)	No. taxa expected with 50% probability of capture (E)	O/E
Gastropoda	2	2.48	0.81
Bivalvia	1	1.51	0.66
Oligochaeta	4	6.88	0.58
Hirudinea	3	3.00	1.00
Hydracarina	0	0.98	0
Crustacea	2	1.77	1.13
Ephemeroptera	4	7.90	0.51
Plecoptera	0	2.02	0
Coleoptera	2	3.48	0.57
Megaloptera	0	0.55	0
Trichoptera	1	8.81	0.11
Diptera	11	13.42	0.82
TOTALS	30	52.80	0.57

the services provided by freshwater ecosystems and responds to numerous environmental factors.

A further gap between science and policy in ecohydrology is the identification of baseline reference conditions in order to assess the current status of water bodies and develop targets for remediation. This has been one of the key scientific challenges in implementing the EU WFD because of the lack of pristine sites remaining in the EU. Consequently palaeoenvironmental and modelling studies may have to be used to define reference conditions, but these raise questions about the Directive's aims. What baseline do we want to return water bodies to, e.g. pre-Neolithic or pre-industrial conditions (and is it practicable)?

It is also difficult for ecohydrology to provide prescriptions and targets for the restoration and rehabilitation of freshwater ecosystems. Restoration of an ecological system is returning the system to its former or original state whereas rehabilitation is a broad term that refers "to any attempt to restore elements of structure or function to an ecological system, without necessarily attempting complete restoration to any specified prior condition" (MacMahon, 1997). The lack of a complete understanding of ecosystem functioning and dynamics means that currently management of freshwater ecosystems must be viewed as an experiment. Thus the success or failure of any management action should be assessed through properly designed studies that compare ecosystem health before and after intervention so that we can learn from experience. Related to this is a need to synthesize the rapidly increasing experience of basin managers to develop a firmer base for future management (Adam, 2001). Greater interaction between hydrologists, ecologists, biologists, engineers, social scientists and conservation managers is therefore required.

The role of hydrologists and ecologists in contributing to the development and implementation of ecohydrology-based policies in the future is to provide a firmer basis for management. Syntheses of existing data are unlikely to yield valid generalizations about ecohydrology functioning due to the variation between sites and in study methodologies. More basic research is therefore required to understand the effect of surface and subsurface hydrology on both individual aquatic species, entire aquatic communities and ecosystem processes. Coupled with this is a need to develop improved methods to assess the interaction between aquatic plants, animals and the surface water environment in the physical, chemical and biological conditions of field environments. There is also a specific role for hydrologists in developing methods to estimate the "natural" flow or water level regime of water bodies (e.g. Richter *et al.*, 1996). These activities are required worldwide, but particularly in developing countries where it is often politically difficult to accord ecosystem protection a high priority, but which are the areas where aquatic ecosystems are likely to be most impacted in the future. Most of the research on indicators of ecosystem health has been conducted in developed countries and there is a critical need to develop similar measures appropriate for tropical aquatic ecosystems in order to support basin management in developing countries. In all these endeavours, interdisciplinary working between hydrologists and ecologists as equals is essential for improved understanding of the aquatic environment and thereby advising on its sustainable management.

At the same time scientists must take care not to overinterpret the evidence and promote apparent ecohydrological theory prematurely which could discredit the need for basin management (termed the "brownlash" by Ehrlich & Ehrlich (1997)). Adam (2001) illustrates this point for salt marshes with the example of the "outwelling" hypothesis, proposed in the 1960s on the basis of research conducted in US salt marshes, which states that almost half of salt marsh production is washed by the tides into estuaries, thereby supporting an abundance of animals. Consequently the hypothesis was used as the basis to define the minimum sizes of salt marsh required for conservation. However, the data to evaluate the outwelling hypothesis were not available until the 1980s, by which time the hypothesis had already been widely used to underpin salt marsh conservation policy, including for very different types of marshes, such as mangroves in Australia (Adam, 2001).

At a more fundamental level, some aspects of ecology are being embraced by hydrologists to assist in developing "a new unified theory of hydrology at the basin scale". The need for and approaches towards such a theory are reviewed by Sivapalan (2006). In this review, new interactions between hydrologists and ecologists are identified, particularly with regard to vegetation–water relations. Sivapalan (2006) highlights the relevance of functional vegetation ecology to hydrology as a route towards discovering rules or organizing principles at the basin scale. An early attempt to define such a set of rules was the ecological optimality hypothesis (which includes vegetation, climate, soil and hydrological terms) proposed by Eagleson (1982) to describe the state of vegetation in a natural undisturbed ecosystem. Instead of being viewed merely as an input to hydrological models, basin vegetation should be regarded as indicative of the feedback between hydrological patterns and processes.

From the above examples it is evident that there will be increased interaction between the disciplines of hydrology and ecology in the future at all levels and scales, from studies of hillslopes and individual river reaches, to basin theory and management. For the full benefits of this interaction to be realized in terms of developing new scientific research and theory and improving basin management, it is vital that both hydrologists and ecologists approach joint projects in an open frame of mind, unencumbered by the often one-sided views of ecohydrology/hydroecology that have been an impediment in the subject area so far in its short history.

6.5 WATER AND ENERGY

Population growth will result in both increased energy and water consumption. Water use and energy production are linked: water is needed for energy production (such as hydropower and for cooling purposes in thermal electrical power stations), and electricity is needed for water conveyance, storage, and treatment (such as desalination). Electricity requirements of developing countries, such as Brazil, China, India and Turkey, are predicted to increase by 6–10% per year, but some of these countries are also expected to experience water shortages in the near future. In spite of the reliance of large-scale energy production on water, hydrologists have only recently begun to critically consider water issues in the light of energy needs. Assessment is needed to identify where, and to what magnitude, water resources may not be able to meet energy demands over seasonal to decadal time scales. Such hydrological estimates are required to identify critical regions and to guide policy geared toward circumventing or reconciling conflicts between water allocation and energy development. Hydrologists need to work more closely with engineers, technologists, economists and energy forecasters and policy makers in providing accurate assessments of energy production and availability that take account of water resource availability.

6.6 CONCLUSIONS AND FORWARD LOOK

The selected examples discussed above of the interaction between hydrology and other disciplines demonstrate the current breadth of interaction between hydrologists and other scientists. It is anticipated that interdisciplinary work between hydrology and other disciplines will increase in the coming decades as it is increasingly required by research funders for the resolution of water-related issues and to advance hydrological science. In particular it is anticipated that hydrology will increasingly interact with disciplines with which it has had limited contact in the past, such as the social sciences. At the moment, however, the full benefits of interdisciplinary work are often not realized: interdisciplinary working tends to occur more in theory than in practice. Many so-called “interdisciplinary” projects are in fact “multidisciplinary”: a research team is assembled with representatives from different disciplines but the actual research is compartmentalized and conducted in isolation in each discipline so that no advancement occurs through interaction between disciplines.

There is no straightforward formula for achieving true interdisciplinarity. It requires considerable inputs of time and effort from the scientists of all the disciplines involved and also changes in funding patterns. Interdisciplinarity can only really be achieved if all participants recognize the benefits of interdisciplinary work, have informed respect for the contribution of disciplines other than their own, and recognize the weaknesses of their own discipline. Scientists must challenge the view, expressed by some, that only second rate science arises from interdisciplinary research because each discipline needs to simplify its contribution to enable understanding to be reached with the other disciplines. One of the challenges for scientists working in an interdisciplinary environment is that different disciplines are at different stages of development. For instance, advanced tracer and fingerprinting techniques are available for soil erosion research, but tools and models are arguably more poorly-developed for ecohydrology. Hydrologists have to dare to “think out of the box” and appreciate that other disciplines, especially the social sciences, also have a valid contribution to make to water resources management. Within individual projects communication at all stages, beginning with project inception, is essential for achieving interdisciplinary work and new outcomes. It has also been proposed that the development of indicators can assist in improving communication between disciplines. More generic measures that can be taken by the hydrological community to increase true interdisciplinary work include incorporating skills in cooperation in the training of all scientists, including hydrologists.

Changes in the nature and pattern of funding are also required to foster interdisciplinary research and realize its benefits. Currently many sources of funding are often available only to single disciplines. Furthermore, interdisciplinary research does not appear instantaneously but usually arises from continued communication between scientists from different disciplines. Creation of an appropriate environment to stimulate such communication can be difficult when different organizations, and even the departments within an organization, are competing with each other for resources. Increasing funding is available for interdisciplinary network activities with the aim of establishing dialogues between scientists from different disciplines from which interdisciplinary research will be generated. The Swedish Water House is an example of this type of initiative. It aims to support international water policy development in the areas of sustainable basin management and integrated water resources management through the stimulation of networking and communication between academic institutions, consultants, governmental and non-governmental organizations and other stakeholders. Another example is the Canadian Water Network which emphasizes the importance of addressing the socio-economic aspects of water management in conjunction with a scientific approach and only funds interdisciplinary research. While funding should not be completely diverted from “pure” hydrological research, funders need to recognize that, to be successful, interdisciplinary research often requires longer timeframes than traditional tightly constrained single-discipline projects. The experience of participants in interdisciplinary research projects is often that the initial one or two years are spent becoming familiar with the language and conceptual frameworks of the other disciplines. By the time interdisciplinary work starts to be achieved the project funding is finished and the gains from interdisciplinary research are not fully realized.

Some hydrologists may be concerned that increased interdisciplinary work will undermine the integrity of hydrology as a discipline and create difficulties in recruiting and training the hydrologists of the future. We argue here that it is the interdisciplinary nature of hydrology, coupled with the core subject material of the hydrological cycle that are the defining characteristics of the discipline; the diversity within hydrology should be regarded as a strength rather than a weakness.