18 An Interdisciplinary and Hierarchical Approach to the Study and Management of River Ecosystems

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INTRODUCTION

Rivers are complex ecosystems (Thoms & Sheldon, 2000a) influenced by prior states, multi-causal effects, and the states and dynamics of external systems (Walters & Korman, 1999). Rivers comprise at least three interacting subsystems (geomorphological, hydrological and ecological), whose structure and function have traditionally been studied by separate disciplines, each with their own paradigms and perspectives. With increasing pressures on the environment, there is a strong trend to manage rivers as ecosystems, and this requires a holistic, interdisciplinary approach. Many disciplines are often brought together to solve environmental problems in river systems, including hydrology, geomorphology and ecology. Integration of different disciplines is fraught with challenges that can potentially reduce the effectiveness of interdisciplinary approaches to environmental problems. Pickett *et al.* (1994) identified three issues regarding interdisciplinary research:

– gaps in understanding appear at the interface between disciplines;
– disciplines focus on specific scales or levels or organization; and,
– as sub-disciplines become rich in detail they develop their own view points, assumptions, definitions, lexicons and methods.

Dominant paradigms of individual disciplines impede their integration and the development of a unified understanding of river ecosystems. Successful interdisciplinary science and problem solving requires the joining of two or more areas of understanding into a single conceptual-empirical structure (Pickett *et al.*, 1994). Frameworks are useful tools for achieving this. Established in areas of engineering, conceptual frameworks help define the bounds for the selection and solution of problems; indicate the role of empirical assumptions; carry the structural assumptions; show how facts, hypotheses, models and expectations are linked; and, indicate the scope to which a generalization or model applies (Pickett *et al.*, 1994). Interdisciplinary river science lacks such an integrative framework. Existing frameworks, e.g. Leopold *et al.*'s (1964) explanation of fluvial processes, Hynes's (1975) "The stream and its valley", the River Continuum Concept of Vannote *et al.* (1980) and Pringle *et al.*'s (1988) patch dynamics perspective, generally approach a problem from a single disciplinary perspective and do not broadly serve the multi-dimensional decision-making environment of interdisciplinary river science. Individually, they have value, but collectively they do not provide a basis for geomorphologists, hydrologists and ecologists to integrate their thinking, concepts and data collection.

This chapter develops a framework for the interdisciplinary study of river ecosystems and considers its use in determining environmental water allocations for a large Australian lowland river system. The framework is hierarchical, integrative, holistic and process-based, thereby allowing the incorporation of paradigms from different disciplines for the prediction of process-pattern relationships at appropriate scales. The lack of an appropriate framework that enables different disciplines to collaborate in an interdisciplinary setting is an impediment to the full realization of the benefits of such collaboration (Petts, 2000).

PHILOSOPHY OF APPROACH

Rivers are natural hierarchical ecosystems that can be resolved into different levels of organization or holons (Werner, 1999). A level or holon is a discrete unit of the level above and an agglomeration of discrete units from the level below. Separate levels can be distinguished by frequencies or rates that differ by one or more orders of magnitude (O'Neill & King, 1998). Subsystems with similar frequencies or rates occupy the same level within a hierarchical system. Higher levels within a hierarchical system have slower rates or frequencies and therefore react more slowly than lower levels. Levels of organization are not scales. The former is essentially a relative ordering of systems and lacks units of measure. It is inappropriate to use the terms level and scale interchangeably, as is commonly done (O'Neill & King, 1998). A level of organization is not a scale but can be characterized by scale (O'Neill *et al.*, 1986). Scale refers to physical and temporal dimensions of observed phenomena and entities. It is recorded as a quantity and involves measurement units, which are used to characterize and distinguish between objects or the frequency of processes. Scale is used to assign or identify dimensions and units of measurement and to answer questions, such as: "how big is a catchment, river or ecosystem?". This can be stated only with a scale; hence scale is the physical dimension of an entity. Scale also refers to the scale of observation; the spatial and temporal dimension at which phenomena are observed. There are two aspects to scale: grain and extent. Grain refers to the smallest spatial or temporal interval in an observation set (O'Neil & King, 1998) or the smallest scale an organism responds to pattern. Extent is the total area or length of time over which observations of a grain are made or the largest pattern an organism may respond to—its home range.

A characteristic feature of hierarchical systems is that higher levels occur at large-scales and have slow rates of behaviour while the lower levels occur at small scales and react more quickly. As such, hierarchies are considered to be "nearly decomposable" because each level of organization responds at a characteristic spatial and temporal scale (O'Neill & King, 1998). In addition to being nearly decomposable, hierarchical systems also have emergent properties. Emergent properties are the properties of higher levels that can not be deduced from the functioning of their parts (Allen & Starr, 1982) and arise because it is only the averaged, filtered or smoothed properties of a lower level that input to higher levels of the hierarchy (O'Neill *et al.*, 1986). With an increase in the number of intervening levels separating levels of interest, there is a corresponding decrease in the influence of the rapid behaviour of a lower level on any level that is above it in the hierarchy (O'Neill *et al.*, 1986; Kotliar & Wiens, 1990). Lower levels in a hierarchically organized system are constrained by conditions imposed by successively higher levels. Lower levels of organization can also influence the structure and functioning of those at higher levels, and this is dependent upon the nature of the boundary between individual levels in the hierarchy. Boundaries based on gradients in rates are said to show loose coupling between successive levels in a hierarchy (O'Neill *et al.*, 1986). The rate of activity within a level and that between successive levels influences the dynamics of the next higher level in the system. Thus, the structure and function of a lower level can influence the structure and function of the next higher level.

River scientists, independent of their discipline, commonly organize problems in time and space. However, individual disciplines contain accepted paradigms that drive the style and scale at which they generally view the structure and function of river systems. Fluvial geomorphology, for example, organizes river systems in a hierarchical manner. Geomorphological factors sit within a hierarchy of influence, where larger-scale factors set the conditions within which smaller-scale factors form. As a result, river systems can be divided into nested levels that encompass the relationships between a stream and its catchment at a range of spatial and temporal scales. The approach of Petts & Amoros (1996) is typical. At the top of the hierarchy, catchments persist at larger spatial scales and longer time scales (Table 18.1). This pattern continues through the hierarchy of river system, functional process zone, reach, functional channel set and functional unit levels until at the bottom of the hierarchy, mesohabitats persist at small temporal and spatial scales (Table 18.1). Thus, the division of a catchment into component hierarchical levels can provide a practical representation of the complex interrelationships that exist between physical and geomorphological factors across different spatial and temporal scales.

In hydrology, five levels of hydrological behaviour have been identified as being important for river ecosystem functioning (Thoms & Sheldon, 2000b). Different levels in the hydrological hierarchy are commonly ascribed a scale, albeit temporal, and these

Table 18.1 *A geomorphological characterization scheme for river systems (modified from Petts & Amoros, 1996).*

Scale	Spatial extent (km)	Temporal extent (years)	Description
Basin	10^5	10^7–10^6	Area of the primary drainage basin
River system	10^4	10^6–10^5	The river channel and flood plain from its source to its mouth or a defined distance downstream
Functional process zone	10^3–10^2	10^4–10^3	Lengths of the river system that have similar discharge and sediment regimes; can be defined from major breaks in slope and from style of river channel or flood plain
River reach	10^2–10^1	10^2–10^1	Repeated lengths of river channel within a process zone that have similar channel style
Functional channel set	10^0	10^0	Units associated with specific landforms such as major cutoffs, aggrading floodplains, main channels
Functional unit	10^{-1}	10^{-1}	Characterized by a typical aquatic community that is indicative of the habitat conditions present at a site
Mesohabitat	10^{-2}–10^{-3}	10^{-1}–10^{-2}	Areas sensitive to variations in control variables that may change from year to year reflecting the sequence of discharge and sediment loads; e.g. sand bars, gravel patches, scour holes

can be:

- the flow regime (long term, statistical generalization of flow behaviour or climate; macro-scale influences that extend over 100s of years and are relevant to continental landmasses, catchments and river channels);
- flow history (the sequence of floods or droughts; meso-scale influences between 1 to 100 years that extend to river channels, zones and channel cross sections);
- the flood pulse (an individual flood event; micro-scale influences that generally extend less than one year and are often related to channel cross sections, bedforms and boundary sediment composition);
- channel hydraulics (velocity and turbulent fluctuations in three dimensions, bed and shear stresses; nano-scale influences of minutes and seconds that may influence bedforms, boundary sediment composition);
- fluid mechanics (surface pressures; pica-scale influences of boundary layers).

In freshwater ecology there are also distinct levels of biological organization. Typically these correspond to individuals, populations, communities and ecosystems (Table 18.2). While these are not scales (Petersen & Parker, 1998), they operate in characteristic spatial and temporal domains and are used to stratify components within biological systems. For example, physiology and behaviour are generally studied at the level of the individual; species richness and diversity are studied at the community level; and energy and nutrient fluxes are studied at the ecosystem level (Table 18.2).

Table 18.2 *Levels in the ecological hierarchy (levels are given from smallest to largest). After Thoms & Parsons, 2002.*

Level of hierarchy	Attributes of the hierarchy
Individuals	Physiology, behaviour
Populations	Rates of births and deaths
Communities	Species, composition, diversity, richness
Ecosystems	Energy and nutrient fluxes

Viewing river systems from an interdisciplinary perspective requires links to be established between disciplines. Pickett *et al.* (1994) argue that an interdisciplinary philosophy of science should be scale-sensitive and move away from the conventional reductionist falsification approach that limits understanding of complex systems such as rivers. This would demand a scale-based approach that integrates description, causal explanation, testing and prediction (Pickett *et al.*, 1994). Hierarchy is the common thread running through hydrology, fluvial geomorphology and freshwater ecology and is therefore a fundamental tenet of an integrated river science. However, identification of the appropriate scales or levels of organization that link similar attributes across disciplines is rarely attempted because of entrenched views within individual disciplines.

A framework for the interdisciplinary study of river ecosystems should be hierarchical, integrative, holistic and process-based. The overarching goal of the framework is to match a problem with a river system process, so that the appropriate causal explanations can be identified at the correct spatial and temporal scales. In turn, this allows consideration of paradigms from different disciplines that may be descriptive, explanatory or experimental, but which ultimately lead to multiscale prediction of pattern–process relationships. The primary components of this framework are:

- There should be an emphasis on defining the scale-dependant study domain (bounded universe in which the dialogue between conceptual construct and reality is conducted).
- Ecological and geomorphological complexity can only be deconstructed by research at multiple scales. Multiscale studies provide a mechanism for embedding small scale understanding within the context of larger-scale processes.
- Studies at different scales are amenable to different approaches. The larger the scale the more difficult it is to incorporate experimental replication and controls so that generalization (pattern seeking) and causal explanation are more appropriate techniques for understanding system processes.
- The classic emphasis on falsifiability is too restrictive for ecology and geomorphology because the prerequisites for its use, universality and simple causality, seldom apply in natural systems where organisms and their abiotic environment are characterized by multiple causality.

Previous studies incorporating hierarchy theory, view rivers as single hierarchical structures. River ecosystems have multiple hierarchical structures—hydrological, geomorphological and ecological hierarchies. Identifying appropriate levels of organization and therefore scales between different hierarchies in complex systems has rarely been attempted because of entrenched paradigms within the individual disciplines. River ecosystems cannot be arbitrarily defined in space and time as is commonly done by individual disciplines. Rather, they must be defined relative to the level of the problem being addressed, and defining and isolating the relevant level in a hierarchy is a critical step in setting up any problem (O'Neill *et al.*, 1986). The different hierarchies present in river ecosystems, as defined by the different disciplines of geomorphology, hydrology and ecology, also have different levels of organization and associated scales. In any hierarchy with a change in observational scale, you may eventually move across a discontinuity in scale, thereby changing levels of organization, grain and extent. This may reduce the power of explanation of cause and effect. This can also occur if you move between different hierarchies because levels of organization and scale may be incompatible between the different hierarchies. Linking levels of organization in different hierarchies can be achieved by matching scales. River ecosystems are scale-sensitive, multiple hierarchies. For each level of a particular hierarchy, there will be appropriate matching variables, both within the primary hierarchy and the other hierarchies in the river ecosystem.

Problem solving is typically reduced to simplistic top-down or bottom-up approaches, thereby limiting and fragmenting solutions, especially when dealing with multiple hierarchical systems (Walters & Korman, 1999). The approach of individual disciplines in an interdisciplinary setting is where you understand your own individual system and then add extra relationships peculiar to your study or issue at hand. To overcome this, Walters & Korman (1999) proposed a "working outward" model for interdisciplinary issues which involves the identification of key variables, their level within a hierarchy followed defining its spatial and temporal scale. Identifying the appropriate scale enables the cross linking between hierarchies. This approach does not constrain solutions within a linear framework; instead it allows key variables, their respective levels and scale to be linked across hierarchies.

Linkage between the three hierarchies is accomplished through the identification of appropriate response scales. Thus, the use of multiple scales of measurement as a framework for the study of river ecosystem phenomena allows identification of scale dependent patterns, and facilitates further investigation of the processes that may determine these patterns (Levin, 1992; Fischer, 1994). Knowledge of the characteristic levels of organization and scales at which patterns and processes operate can then be considered to represent the levels of organization that are present in a river ecosystem hierarchy.

INTERDISCIPLINARY APPROACH TO RIVER ECOSYSTEMS: EXAMPLE OF ENVIRONMENTAL FLOWS IN THE MACINTYRE RIVER, AUSTRALIA

Allocating water to sustain natural ecosystems, restore rivers degraded by over abstraction and protect biodiversity has become a key issue in river management. One of the goals of environmental flows is to allocate water to maintain riverine habitats (e.g. PHABSIM, Gore & Nestler, 1988; Tennant (Montana) Method, Tennant, 1976). However, the definition of habitat varies within hydrology, fluvial geomorphology and ecology. Regardless of discipline, there are two overarching components to habitat. First, habitat should be defined with reference to the species being considered; and second, habitat must be defined in terms of physical and biological properties. As such, habitat is interdisciplinary, rather than discipline specific. Habitat also sits within a hierarchical context, where biotic and abiotic processes that shape habitats occur at multiple spatial and temporal scales. Thus, maintenance of habitat as an endpoint in environmental flow approaches is meaningless without reference to an ecological entity and the hierarchical organization of river systems.

Environmental flow management is frequently concerned with the question: "How much water do we need to allocate to protect and conserve river function?" Outside of an interdisciplinary framework, this question is likely to have three answers, because hydrologists, geomorphologists and ecologists view river systems from the experience of their own disciplines. For example, from a geomorphological perspective, water allocations are required to maintain the structure and function of natural physical features of the river channel (Gippel & Stewardson, 1998). From a biological perspective, water allocations are required to maintain individuals, populations, communities and ecosystem processes. Hence, environmental water allocations generated outside of an interdisciplinary approach may never fully protect and conserve river function, because they do not consider all components of river system, and are not cognizant of multiscale linkages among disciplines.

Using the concept of hierarchy within the context of environmental water allocations, top-down constraints must be recognized. Dollar *et al*. (2005) suggest that employing a conservation ecology analogy, a top-down approach would recognize the character of the hydrological landscape, at different scales. Here the management objective would be to maintain the diversity or heterogeneity of this landscape. Managing landscape diversity or heterogeneity is an essential component in conserving system resilience (Pickett *et al*., 2003) and in the context of environmental flows, the resilience of riverine ecosystems.

Currently in Australia, and elsewhere, environmental flow strategies view rivers as uniform and fail to consider spatial and temporal complexity within a river system. A recent study by Thoms *et al*. (2005) demonstrated a complex spatial pattern of hydrological character in a large Australian dryland river system. The study of the

Macintyre River, Australia, identified six distinct hydrological zones along the river, using multivariate statistics. Full details of the methods employed are given in Thoms *et al.* (2005) and Thoms & Parsons (2003). These hydrological zones represent "patches" within the hydrological landscape mosaic of the Macintyre River system and they correspond to the main geomorphological zones of the Macintyre River (Thoms *et al.*, 2005). This hydrological study also notes that the dominant time scale of each differed between the river zones. The hydrological character of the headwater zones in the Macintyre River was characterized by short-term variables corresponding to individual floods, whereas longer time scale variables, characteristic of event sequencing, better represented those zones lower in catchment. Thus the spatial and temporal complexity identified at this larger scale requires environmental water allocations to be managed at scales that capture the appropriate patterns of hydrological character in the system in question.

The spatial and temporal complexity of hydrological character within the Macintyre River is an example of a heterogeneous hydrological landscape. Recognition of hydrological mosaics has several implications for environmental flow strategies. The time scale of flow variables associated with the spatial arrangement of the different hydrological patches needs to be recognized so that management intervention can be placed at the appropriate spatial and time scale. Different targets of flow restoration need to be set for individual hydrological zones whereby the attributes of flow must be manipulated, restored or conserved in accordance with the different time scales of hydrological influence. Maintaining the hydrological integrity of individual zones would allow maintenance of the diversity of the broader mosaic of the hydrological landscape within a catchment. Environmental water allocations are effected through manipulation of the hydrological regime. At what scale should these hydrological manipulations be made to predict physical and biological responses? At a particle scale, flow hydraulics influences the character of the riverbed substratum (Lancaster & Belyea, 1997) and if macro-invertebrates are the diagnostic fauna, the corresponding level of biological organization may be that of an individual organism. At a larger scale, the frequency of a flow partly determines the morphology of river zones (e.g. macro-reaches) and the corresponding level of biological organization is that of a macro-invertebrate community.

In many rivers macro-invertebrate communities, collected at the local scale, are used as primary biological indicators in environmental flow assessments. These community-level attributes, however, may be inappropriate because of the inherent spatial and temporal complexity in hydrological and geomorphological character. For example, given the dominance of short-term pulse scale hydrological variables in the headwater zones of the Macintyre River, it would be more appropriate to monitor populations of individual organisms at small patches within a reach (Fig. 18.1). In those zones located further downstream, characterized hydrologically by events over longer time scales, community level attributes could be monitored. Thus biological indicators used to monitor environmental flows must match the appropriate scales of physical and hydrological processes that occur in the river system. Incorporation of this multidimensional spatial and temporal approach into existing environmental flow strategies will advance the application of the natural flow paradigm and by association, may improve ecosystem responses to managed flows (Thoms & Parsons, 2003).

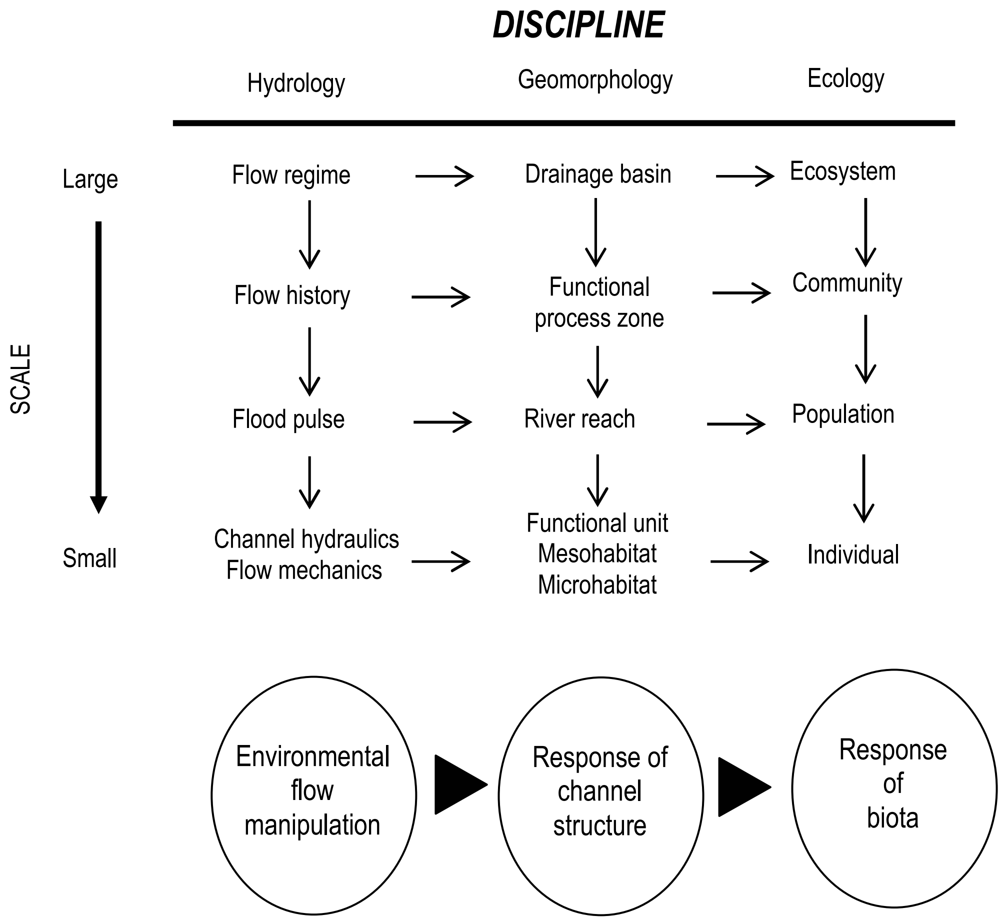

Fig. 18.1 *Multiscale relationships between hydrology, fluvial geomorphology and ecology. Environmental flow strategies need to monitor geomorphological and ecological responses to hydrological manipulation at the appropriate scale, and need to conduct hydrological manipulations at the appropriate scale to produce a geomorphological or ecological benefit (modified from Thoms & Parsons, 2002).*

The framework places the collective use of top-down and bottom-up methods in a multi-dimensional context and facilitates an adaptive management approach for the setting and management of environmental water allocations (Fig. 18.1). The management and conservation of diversity in the hydrological landscape is a higher-level objective within which methods like IFIM and the Building Block Methodology could be used to assess flow needs in specific patches of the mosaic. Dollar *et al.* (2005) note that determining important biophysical flows then has a context; important biophysical flows, whether they be for a single species at a site or a range of organisms within multiple river patches, become the focus for hypothesis-based monitoring. Monitoring through testing hypotheses about the functions of certain flows and the implications of changing these flows in river ecosystems overcomes the much-critiqued approach of monitoring for the sake of monitoring.

CONCLUSIONS

An evident trend in river research over the last 10 years has been the increased integration of hydrology, geomorphology and freshwater ecology with an emphasis on the importance of interconnections between the different components of a river system. This has improved our understanding of rivers and the quality of advice given to river managers—supporting the maxim that sound science underpins good management (Cullen, 1990). This trend has led to the development of a new area of science: river science (Pickett & Rogers, 1997). Although in its infancy it is an exciting area to be in, with the cross fertilization of ideas, concepts and paradigms on the structure and function of river systems. While these interactions may be stimulating they may also represent barriers to the development of river science.

Recognition of the scale-dependant associations between hydrological, geomorphological and biological features is important area in river science. For example, hydrological features will have a variable influence on the physical structure and biological communities in the river system. Indeed some hydrological features may have an important role in certain reaches whilst having little or no influence in other reaches. Identification of the key scales of interactions throughout a river system is essential for effective management. At present, many management strategies do not address the question: What part of the river system can or needs to be managed? In addition, these strategies do not provide scientific knowledge at the appropriate scale for management.

The interface between science, in this case hydrology, geomorphology and freshwater ecology and policy management is turbulent, but potentially an exciting one. Effective communication of knowledge to the water industry can only improve with the development of a common framework and set of concepts which river scientists can operate from.

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