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Ecohydrology and hydroecology: A 'new paradigm'?

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It is clear from recent literature, including two commentaries in *HPToday* (Bond, 2003; Pringle, 2003), special issues of journals (e.g. Gurnell *et al*., 2000; Zalewski, 2000; Kundzewicz, 2002; Baird *et al*., 2004), a new journal (Zalewski and Harper, 2001), several books (e.g. Baird and Wilby, 1999; Eagleson, 2002; Rodriguez-Iturbe, 2003) and national and international conference themes (e.g. Acreman, 2001), that ecohydrology (eco-hydrology) and hydroecology (hydro-ecology) have made a mark on the global environmental agenda. However, despite increasing attention and claims of the emergence of a 'new' discipline(s) (e.g. Zalewski and Robarts, 2003), opinions still vary as to what the disciplinary focus should be (e.g. Bonell, 2002). In particular, a number of important questions require clarification: (1) What are hydroecology and ecohydrology and are these terms clearly defined and understood? (2) Do hydroecology and ecohydrology represent a paradigm shift or repackaging of well-established research strands imbedded within hydrology or ecology? We address these questions by reviewing the scientific literature and categorizing bibliographic search data. Our aim is to provide a critical perspective, particularly with respect to identifying the theoretical core of hydroecology and ecohydrology and the disciplines' interdisciplinary (or multidisciplinary) nature.

What Is in a Name?

The terms 'hydroecology' and 'ecohydrology' (including the sub-discipline of ecohydraulics) both imply research at the interface between the hydrological and biological (ecological) sciences. Before exploring the host of definitions on offer, it is worthwhile examining the terms' etymologies. The prefix 'eco' ('hydro') in 'ecohydrology' indicates it is a modifier of the word 'hydrology' ('ecology') and, thus, the discipline should be more about hydrology than ecology (and vice versa) (Kundzewic, 2002). However, in practice this rubric has not been applied, as many ecologists refer to ecohydrology (e.g. Zalewski, 2000) and hydrologists refer to hydroecology (e.g. Dunbar and Acreman, 2001). It is also important to note that the French term *hydroecologie* is not the same, since it translates as 'aquatic ecology' in English (i.e. the study of freshwater, brackish and marine ecosystems). The use of *hydroecologie* in francophone publications explains many of the mistaken references to hydroecology in the early 1990s.

The simplest definitions of ecohydrology and hydroecology consider either: (1) the scientific overlap between the fields of hydrology

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and ecology or (2) the impact of hydrology on ecosystems or *vice versa* (Kundzewicz, 2002; Zalewski, 2002). Neither basic definition specifies the remits or aims of the disciplines. The definitions explored herein derive from previous debates on the terms' usage (Bond, 2003; Kundzewicz, 2002; Nuttle, 2002). As a preface to our discussion, we believe that each definition is valid in its original context, but when extracted and (mis)applied elsewhere may cause great confusion. Notably, it is the caveats and boundaries that are applied to the various definitions, which are not usually explained in subsequent reuse, that provide most insight into the underlying meaning of the terms and the subjects' remits. We will examine each term in turn, starting with ecohydrology.

The first clear definition appeared in a special issue of *Vegetatio* and relates to wetlands. It states ecohydrology is 'an application driven disciplin [sic] and aims at a better understanding of hydrological factors determining the natural development of wet ecosystems, especially in regard of their functional value for natural protection and restoration' (Wassen and Grootjans, 1996: 1). Baird and Wilby (1999: 5), in an edited volume on ecohydrology that 'focuses on plant–water relations in terrestrial and aquatic ecosystems', recognize the problems associated with the unidirectional nature and narrow subject field of Wassen and Grootjans' (1996) definition. Hence, Baird and Wilby (1999) broaden the environmental context to include ecohydrological interactions in ephemeral dryland, forest, stream, river and lake systems, although they acknowledge that this still does not consider marine ecosystems or the role of hydrology as a determinant of animal (rather than plant) populations. However, faunal studies are increasing in hydroecological research (e.g. Kemp *et al*., 2000; Wood *et al*., 2001; Pringle, 2003; Sadler *et al*., 2004).

A frequently cited definition of ecohydrology was developed within the framework of the UNESCO International Hydrological Programme IHP-V (Zalewski *et al*., 1997). In a special issue of *Ecological Engineering*, Zalewski (2000: 1) proposes ecohydrology to be 'the study of the functional interrelations between hydrology and biota at the catchment scale'. Potentially, this definition has wide applicability, as it recognizes the two-way interaction between hydrology and ecology. However, this definition has been adopted mainly within the context of water resource management and biological conservation, particularly in terms of the need to assess ecosystem responses to natural and anthropogenically induced water stress (Zalewski, 2002; Zalewski and Robarts, 2003). This definition seems to emphasize the establishment of functional links rather than fundamental process understanding.

The definitions of hydroecology appear to be a little more prescriptive. Dunbar and Acreman (2001: 2–3) define applied hydroecology as 'the linking of knowledge from hydrological, hydraulic, geomorphological and biological/ecological sciences to predict the response of freshwater biota and ecosystems to variation of abiotic factors over a range of spatial and temporal scales'. They concede that papers published (in the same edited conference volume in which their article appears) do not cover the full breath of hydroecology because of the absence of research upon soil and vegetation (cf. Baird and Wilby, 1999), and nutrient fluxes and resource management (cf. Zalewski *et al*., 1997). It would seem that Dunbar and Acreman (2001) consider ecohydrology and hydroecology as largely the same entity. Perhaps, this is where the greatest confusion lies, as both terms could, or should, define the same interdisciplinary science (Kundzewicz, 2002).

Proliferation of Terms: A Brief History and Bibliographic Search Data

From the review of definitions, the underlying thesis that hydroecology and ecohydrology denote a cross-disciplinary research approach would appear to hold true. However, a closer analysis of the adoption of the terms hydroecology and ecohydrology (as mapped out in the literature) and bibliographic search data raise the question as to whether, or not, these terms represent a truly holistic, interdisciplinary (as opposed to multidisciplinary) science.

Research at the hydrology–ecology interface has a long tradition, beginning with seminal work on vegetation and hydrology (e.g. Hack and Goodlett, 1960; Penman, 1963; Eagleson, 1978).

This research was followed by 'ecohydrological' or 'hydroecological' studies of shallow groundwater systems (Pedroli, 1990), wetlands (Wassen and Grootjans, 1996), natural and impacted rivers (e.g. Armitage, 1977; Ward and Stanford, 1979; Petts, 1984), and whole watersheds (e.g. Hynes, 1970; Vannote *et al*., 1980; Junk *et al*., 1989). A logical outcome of this historical background and ever-growing body of literature is the 'new' ecohydrological or hydroecological 'paradigm' currently being embraced (e.g. Baird and Wilby, 1999; Bond, 2003; Rodriguez-Iturbe, 2000; Zaleweski, 2000). Parallel development of the discipline(s) has occurred in hydrology and ecology (Gurnell *et al*., 2000). While many hydrologists appear to be actively engaged with the 'new paradigm', it has been suggested that biologists are less aware of, or are unconsciously involved in, the ecohydrology and hydroecology 'revolution' (e.g. Bond, 2003). This may reflect the fact that hydrological and water resource journals make little or no impact upon the vast biological literature (Nuttle, 2002) and/or that the 'new paradigm' has been overshadowed by other debates within ecology. However, it is as (or perhaps more) likely that ecologists consider the abiotic environment as an integral part of the ecological system (e.g. Ward *et al*., 2002; Brown *et al*., 2003) and perceive little, or no, value in explicitly distinguishing themselves as ecohydrologists or hydroecologists.

A bibliographic survey of the ISI Web of Knowledge (http://wos.mimas.ac.uk) Science Citation Index database was undertaken using the following words in a topic search: ecohydrology, eco-hydrology, hydroecology and hydro-ecology. This search looked for each term in the title, abstract and keyword lists of approximately 18·5 million publications (i.e. articles, letters and book reviews) in ISI-rated journals and conference proceedings since 1981. As of 1 March 2004, the results showed 87 entries have used one, and in two instances more than one, of these terms. The frequency of use, in descending order, was: ecohydrology = 52, hydroecology = 18, eco-hydrology = 10, and hydro-ecology = 7. Thus, ecohydrology (plus eco-hydrology = 62) is by far the more commonly used term (cf. hydroecology and hydro-ecology = 25). It is clear that some papers with hydroecological or ecohydrological subject matter do not use the above words and, thus, they are overlooked by this search. For example, of the 54 papers in four hydroecology or ecohydrology special issues of international journals (Gurnell *et al*., 2000; Zalewski, 2000; Kundzewicz, 2002; Baird *et al*., 2004) only 11 employ any of the above words. As a result, bibliographic analysis of topic words is likely to provide an underestimate of the true extent of hydroecological or ecohydrological research, but not the adoption of the term(s). Indeed, Bond (2003), Bonell (2002) and Kundzewicz (2002) have also commented there is a large body of hidden literature that fails to mention the terms explicitly but could be deemed hydroecology or ecohydrology by content. The lack of use of the above terms by authors doing hydroecology or ecohydrology (in terms of subject matter) could be interpreted as either: (1) a lack of knowledge or recognition of the 'new paradigm' or (2) a conscious decision not to jump on the bandwagon or get involved with a potentially passing scientific fad.

Notwithstanding the limitations of the bibliographic analyses, it is clear that the use of such terms has increased markedly since the early 1990s, reaching a peak of 19 papers in 2002 and 17 publications in 2003 (Figure 1). Articles are distributed across 35 journals with *Hydrological Processes* publishing the greatest number of papers (14). Analysis of journals by subject classification (based upon standard library cataloguing systems; i.e. US Congress Stack and Dewey Decimal) revealed most papers have appeared in three areas: (1) geosciences, 32 articles (hydrology, earth surface processes, etc.); (2) water resources and engineering, 30 articles; (3) ecology and other biosciences, 20 articles. The remaining five papers were in journals from other subject areas (e.g. environmental planning and economics). Thus, the vast majority of papers appear in physical sciences (71%) rather than biological (23%) publications.

Analysis of papers' contents was conducted whereby each article was assigned to one of the following seven categories based upon the dominant subject matter: (1) ecology–flora; (2) ecology–fauna; (3) ecology–flora and fauna; (4) hydrology–water resource management; (5)

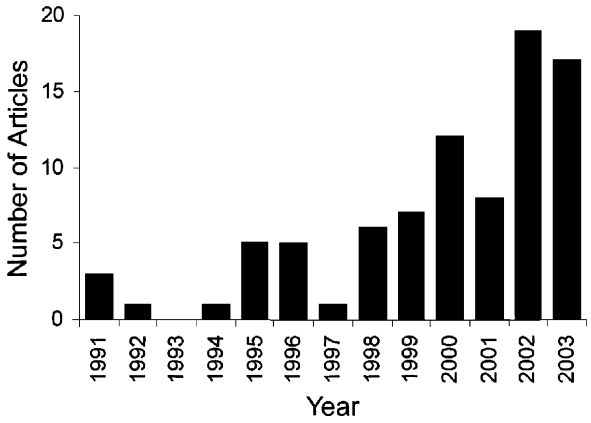

Figure 1. Number of articles using the terms ecohydrology, eco-hydrology, hydroecology and hydro-ecology since 1991

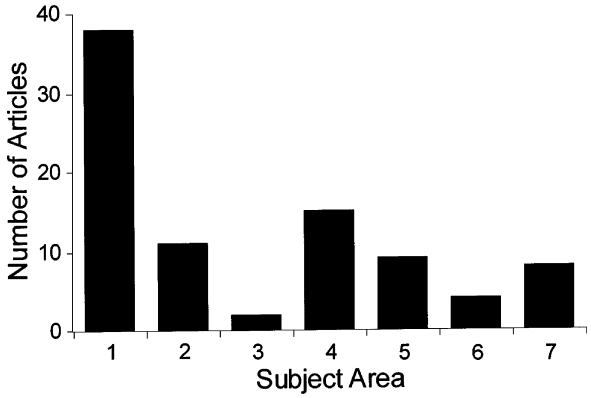

Figure 2. Number of hydroecological or ecohydrological articles (since 1991) classified by dominant subject matter: (1) ecology–flora; (2) ecology–fauna; (3) ecology–flora and fauna; (4) hydrology–water resource management; (5) hydrology–ecosystem response; (6) hydrology–water resource management and ecosystem response; (7) discussion papers

hydrology–ecosystem response; (6) hydrology–water resource management and ecosystem response; and (7) discussion papers (Figure 2). Classes 1–3 (4–6) have an emphasis on more ecological (hydrological) aspects. The majority of papers focus upon plant–soil–water interactions (ecology–flora = 38 articles) with hydrology–water resources management the next most common subject area (15 articles). Overall, ecological articles account for 59% of publications although these mainly appear in physical sciences journals (see above). Hydrological papers are fewer (32%, or 28 articles in total) with most focusing upon hydrology–water resource management (see also Table I). Notably, these water resource management articles often infer ecological implications but contain limited, or no, supporting biological data. Nine papers identify hydrology–ecosystem response empirically, and four articles jointly consider water resource management and ecosystem response. It is interesting to observe seven discussion papers debate the nature and philosophy of ecohydrology or hydroecology. The approach in the papers is reasonably balanced between studies that consider patterns, processes, modelling and management; but meso- and macro-scale studies are far more common than micro-scale research (Table I).

The final set of analysis examined the postal addresses of the corresponding author to determine the academic department or research institutes and, hence, discipline affinity. As may be expected, the results indicate that research is being conducted mainly in university departments of Geography and Environmental Sciences (35 articles), and Biosciences and Ecology (27 articles). Although Geography and Environmental Science departments (employing both hydrologists and ecologists) yield slightly more papers, these figures

Table I. Number of hydroecological and ecohydrological articles (since 1991) classified by dominant (a) approach to and (b) scale of research (micro: particle–patch; meso: patch–reach; macro: reach–catchment)

	(a) Approach					(b) Scale		
	Pattern	Process	Model	Management	Discussion	Micro	Meso	Macro
Ecohydrology	21	15	9	10	7	4	27	31
Hydroecology	5	3	6	10	1	1	15	9
Total (N = 87)	26	18	15	20	8	5	42	40

clearly demonstrate that biologists and ecologists (working in Biosciences and Ecology departments) are well aware of hydroecology and ecohydrology and they are using these terms (cf. Bond, 2003). The remaining articles originate from university departments of Engineering and Water Resources (10 articles), cross-disciplinary governmental and non-governmental research institutes, and independent researchers (15 articles).

A 'New Paradigm'?

Ecohydrology and hydroecology have been described as a 'new paradigm' (Zalewski and Robarts, 2003: 1) and an 'emerging discipline' Bond, 2003: 2087) at the interface of hydrological and ecological sciences. Zalewski (2002: 829) takes this point even further by stating that ecohydrology is the 'third phase in the development of ecology from a descriptive natural history (e.g. Linne), through an understanding of processes, to control and manipulation of ecological processes for enhancement of resource quality'. Similarly, other authors suggest a significant shift in scientific thinking associated with the integration of hydrology and ecology, but they doubt that the scientific approach is entirely new (e.g. Bonell, 2002; Nuttle, 2002).

At the core of the 'ecohydrology paradigm' outlined by Zalewski (2002; Zalewski and Robarts, 2003) is the need for sustainable (coupled) water resource and ecosystem management. However, the ability of ecohydrology and hydroecology to emphasize the interdependence of hydrological and ecological processes while yielding an overarching paradigm for sustainable water resource management has been fundamentally questioned. For example, Nuttle (2002: 805) believes ecohydrology cannot provide this dual role and, therefore, defines it as 'the sub-discipline shared by the ecological and hydrological sciences that is concerned with the effects of hydrological processes on the distribution, structure, and function of ecosystems, and the biotic processes on elements of the water cycle'. This definition, as a shared subdiscipline, may sit more easily with many inherently sceptical or cautious scientists, as it respects traditional subject boundaries, but it offers nothing 'new' or 'revolutionary'.

It is clear from our literature review and bibliographic analysis that a definition identifying a theoretical core is needed before hydroecology and ecohydrology becomes an established paradigm or discipline. A definition that includes the discipline's aim and subject scope would serve as a focal point to help unite the research community. In this regard, a single definition that applies equally to hydroecology and ecohydrology is key. At present, there is no single accepted definition of either term (reviewed above), never mind a joint definition. Instead of providing another scientific sound-bite, we suggest a list of definition elements may be more instructive. Thus, a definition of hydroecology (hereafter used as a synonym for ecohydrology) should include explicitly: (1) the bidirectional nature of hydrological–ecological interactions and importance of feedback mechanisms; (2) the requirement for fundamental process understanding, rather than simply establishment of functional (statistical) links without a probable chain of causality; (3) the subject scope to encompass (a) the full range of (natural and human-impacted) water-dependent habitats/environments and (b) flora, fauna and whole ecosystems; (4) the need to consider process interactions operating at a range of spatial and temporal scales (including palaeohydrological and palaeoecological viewpoints; e.g. Brown, 2002; Parr *et al*., 2003); (5) the interdisciplinary nature of the research philosophy (cf. the multidisciplinary approach used by the vast majority of studies). We recognize the potential danger that definitions can become either too restrictive or nebulous to be effective and/or applicable. Like hydroecology, other 'new' scientific paradigms have begun life as 'hot topics', but they have faded away due to a problem of identity (definition). If hydroecology is to avoid a similar fate, we must also ensure it is an identifiable and constructive discipline, not a deconstructed version of existing paradigms or academic disciplines.

In our opinion, and contrary to previous authors, it is not simply the integration of hydrology and ecology *per se* (i.e. subject matter) that will herald and sustain the 'new paradigm' of hydroecology, but the way in which integrative science is conducted. For hydroecology to move forward, it requires to be

a truly interdisciplinary science (i.e. combining the academic disciplines of hydrology and ecology, which are usually considered distinct; cf. Morillo *et al*., 2003). At present, however, hydroecological and ecohydrological research appears to be operating in a multidisciplinary mode (i.e. making use of parts of the traditional disciplines of hydrology and ecology but without integration). The use of the term hydroecology by hydrologists and ecohydrology by biologists indicates a gap rather than overlap between disciplines. Further evidence of this multidisciplinary approach is provided by results from the bibliographic search, which illustrate few integrative studies in terms of subject matter and/or authors list (i.e. research teams are predominantly composed of groups from either Geography and Environmental Science or from Biosciences and Ecology departments, not both). Thus, ecologists and biologists appear to be looking at research questions from one perspective and hydrologists (mainly geographers and engineers) from another. Scientists may be seeking to address the same issue or solve the same problem without converging on the most perceptive or robust hydroecological answer(s) due to a lack of theoretical underpinning in the 'other' discipline (perhaps because they are asking inappropriate questions within the 'other' discipline).

If a true paradigm shift is to occur and hydroecology is to flourish, then ecologist and hydrologists need to bridge the gap between traditional subject boundaries to build real interdisciplinary teams and so reap benefit from the synergies of working at the cutting edge of research in both hydrology and ecology. If this major reorientation of approach from multi- to inter-disciplinary does not transpire, then ecologist and hydrologists will continue to approach hydroecological research from opposite directions and the 'new paradigm' or 'emerging discipline' will not develop further, leaving hydrologists reinventing the ecological wheel, and *vice versa*.

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