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Groundwater dominated rivers

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Abstract:

This paper explores the significance of groundwater dominance in the surface water system through a combination of review and an exposition of the general hydrology, ecology and geomorphology of rivers draining the main UK aquifers. Groundwater dominance is shown to vary according to the nature of the aquifer lithology, the mechanism of groundwater:surface water interaction and the scale at which one examines this interaction. Using data derived from a range of studies including the UK Environment Agency River Habitat Survey and the UK Institute of Freshwater Ecology RIVPACS invertebrate database it is shown that the nature of the aquifer and mode of influent discharge strongly control the hydrological and ecological characteristics of the environment but that a specific groundwater ecology or hydrogeomorphology is masked by the overriding controls exerted by aquifer geology and catchment topography. Despite this, it is clear that river systems dominated by groundwater flows have specific hydrological characteristics and management issues that require holistic, multidisciplinary approaches that recognise the significance of groundwater and the nature of the interaction with the surface water environment. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS groundwater dominance; hydrogeomorphology; ecology; water quality

GROUNDWATER AND SURFACE WATER RESEARCH

The physical characteristics of groundwater and surface water have been considered to be distinctive, although more recent studies have described surface water as a 'perched groundwater aquifer' (Shand *et al.*, 1995) in recognition of the isotopic history of both components. The broad distinctions however, are generally considered to be a stable flow and thermal regime and a stable chemical regime that reflects the underlying aquifer geology. Groundwater research has until recently been dominated by two areas of scientific enquiry, hydrogeology and hydrology, the former concentrating on the quality and quantity of subterranean transmission of water as a resource, the latter concentrating on the maintenance of low flows and the stability of the flow regime (Younger, 1995). A similar research model exists in the study of geomorphology and groundwater, which has traditionally been dominated by morphogenetic studies of karst landscapes, that focus attention on the role of chemical degradation of the land surface and the features associated with cavity flows within the vadose zone (Brown, 1996). In applied hydrology, the role of groundwater in sustaining low flows has provided the focus for much recent research which has identified the clear link between low flow regime and the nature of the soils and lithology in the upstream catchment (Gustard *et al.*, 1992). Ecological studies of groundwater rivers have also tended to be dominated by research in carbonate (chalk) groundwater systems (Berrie, 1992).

Recently, the aquifer–river 'boundary' has begun to blur as the scientific community recognises the importance of river–aquifer interactions. This has been driven by recognition of the impact that groundwater abstractions have made on the low flow regime of some rivers (NRA, 1993) and the increasing

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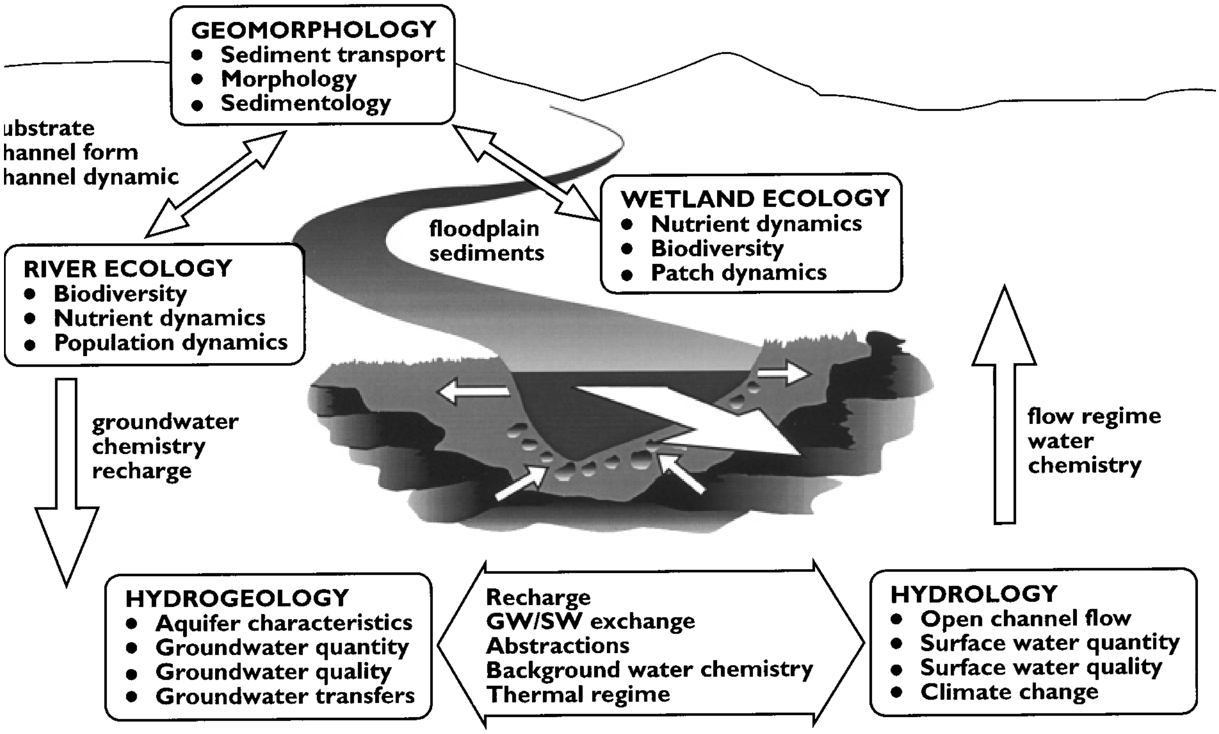


Figure 1. Interaction between eco-hydrological components and areas of science in groundwater dominated rivers

realisation of the role that groundwater plays in the heterogeneity of floodplain and river ecology (Petts and Amoros, 1995). More specifically much ecological research has focused attention on the characteristic ecology associated with groundwater dominated rivers draining the chalk and limestone aquifers (Mackey *et al*., 1982). However, comparatively little research has been conducted on rivers with different groundwater regimes. Recent emphasis on the role of groundwater in river:floodplain interactions have begun to establish the importance of 'groundwater ecology' as a branch of the science in its own right (Petts and Amoros, 1996).

Although groundwater has been identified as important to many aspects of the river process, few studies have attempted to systematically identify a groundwater–surface water signal in the hydrology, water chemistry, ecology and geomorphology of the river system, although as Figure 1 illustrates, the degree of interaction that is possible suggests that this area merits further research. At one level, the literature reveals clear evidence of hydrological, ecological and geomorphological factors that may be used to identify groundwater dominance in river systems. Instream biota can be sensitive to the source of intragravel water and several indicator species have been suggested as diagnostic of a groundwater dominated source (Creuze des Chatelliers and Regrobellet, 1990; Fortner and White, 1988). In terms of water quality, thermal properties are most frequently used to diagnose groundwater sources with the main characteristics being a more stable thermal regime reflecting the stability of groundwater temperature (Crisp *et al*., 1982). Studies of the geomorphology of groundwater dominated rivers tend to be dominated by the analysis of karst terrains formed in carbonate rocks. However, significant direct and indirect effects of groundwater on fluvial forms and processes may be observed in other river types (Keller *et al*., 1990). Some of these effects relate primarily to rivers with carbonate water chemistry, but more generic effects can be observed in most rivers (e.g. reduced bank stability).

Despite the evidence of a groundwater dominated effect, it is revealing to note that many of the studies of groundwater fed rivers have been conducted on similar aquifer rock types, or reflect local scale groundwater influence. Definition of groundwater dominated rivers is therefore likely to be both aquifer type and scale dependent.

GROUNDWATER DOMINATED RIVER HYDROLOGY

Rivers derive their streamflow from various sources — overland flow, flow through soil and flow through aquifers. A reasonable question arises from this statement; — does the relative preponderance of different sources have a significant effect on the physical and ecological character of a river? More particularly, do rivers with a significant groundwater contribution have a distinct character? Intuitively the answer to this question is yes, for example chalk streams 'appear' different to other rivers, and rivers draining heavily fissured limestone have peculiar properties. The purpose of this paper is to make a first attempt to quantitatively characterise groundwater-dominated rivers. This paper focuses on groundwater as a contribution to streamflow and discusses the implications of groundwater dominance in the context of four areas:

- the instream hydrological regime
- the morphology and sedimentology of the river channel
- the quality of the water
- the instream ecology.

GROUNDWATER DOMINANCE AND THE HYDROLOGICAL REGIME

Groundwater interacts with streamflow at different scales (Figure 2). Groundwater contributes to streamflow, and can be derived from streamflow. Groundwater regimes in floodplains affect floodplain processes and ecology. Any definition of groundwater dominance must relate to the nature of the interaction between groundwater and surface water components of the hydrological system. There are two main aspects of this process, flow of groundwater to the channel (influent discharge) and flow from the channel to the aquifer (effluent discharge). The former is common in temperate environments whilst the latter occurs widely in arid environments.

The groundwater component of a river is derived from continuous and intermittent flows from aquifers that drain to the river under varying degrees of hydraulic connection. Burt (1996) recognises that a continuum of rainfall–runoff response (defined by speed of response to precipitation) exists for catchments from cavernous (Karst) limestone to porous chalk catchments. Conceptually both ends of this continuum include a degree of groundwater dominance, although the nature of the groundwater flows and their residence time in the aquifer are markedly different. Table I modified from Wright (1980) illustrates the diversity of groundwater:surface water interactions that might locally contribute to groundwater dominated flow regimes in the river network. With the application of radioisotope studies it is becoming clear that even during flood flows, much of the stream flow is dominated by water sources with water quality signatures characterised by the shallow aquifer or soil chemistry (Shand *et al.*, 1995).

In larger river basins many of these sources may be present simultaneously, providing further diversity of groundwater flows within the channel network. The notion that stability of flow, thermal and chemical regime might define groundwater dominated rivers is clearly only valid for some types of groundwater dominated rivers. Thus at one end of the groundwater:surface water river type might be found hot water spring/geyser fed rivers characterised by high temperatures and unstable flow regime whilst at the other may be the stable flow regimes and seasonal cold water characteristics of temperate chalk rivers. However, in many of the cases cited in Table I the measurable effect is spatially limited. In the case of hot water spring systems, the thermal regime may be equilibrated with ambient conditions within much less than a kilometre. The presence of an impermeable overlying drift or land cover can significantly affect hydrological characteristics (van Lanen *et al.*, 1996) whilst variations in the structure of the aquifer can occur in four dimensions

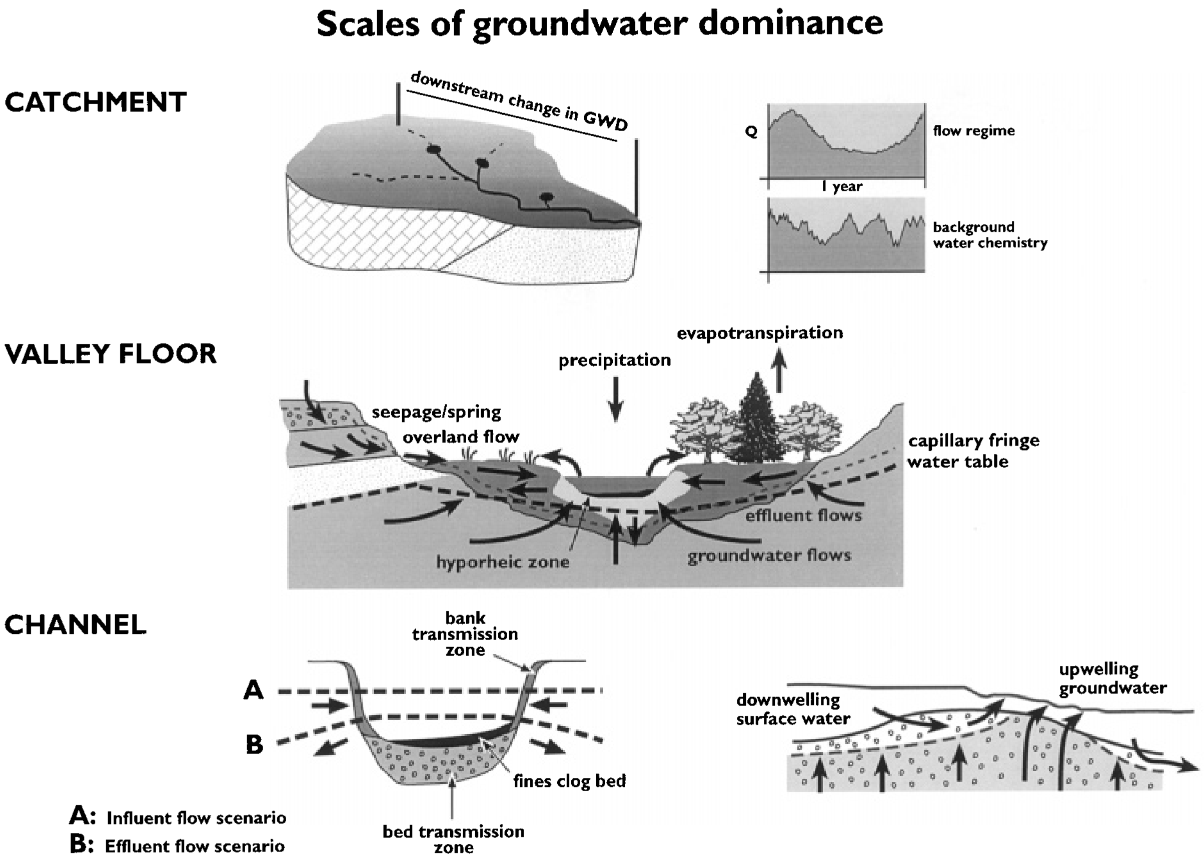


Figure 2. Scales of groundwater dominance in river systems

(although temporal changes are generally related to antecedent hydrology). Riparian vegetation can under low summer flows, intercept groundwater flows to the channel, resulting in a loss of baseflow contribution and potentially reduced low flows (van Wonderen and Wynes, 1995). Thus the nature of groundwater dominance is difficult to determine regionally, and must be defined either from detailed knowledge of local

Table I. Aquifer:surface water interactions (modified from Wright 1980)

Aquifer Class	Aquifer Type	Recharge mechanism
Unconfined	Intermittent	Groundwater (interflow)
		Temporary perched water in mountain rock
		Raised bogs
		Intermittent Springs & geysers
		Meltwater from frozen groundwater
		Return water or bank storage
	Continuous	Phreatic groundwater
		Aquifer overlying permafrost
		Interflows between aquifers
		Flow beneath permafrost
		Waterlogged soils
		Springs
Confined (Artesian)	Open Flow	Confined water flow direct to channel from springs/geysers
	Close Flow	Confined water moving into overlying aquifer

soil and hydrogeology, or from actual river flows. The downstream changes in groundwater dominance must also be considered in the same way, since the relative importance of influent and effluent flows can change in space and time depending on flow regime, floodplain stratigraphy, or hydrogeological characteristics (Gustard, 1996).

Groundwater dominance is broadly represented by stability of the flow regime. This can be characterised by high values of Baseflow Index (BFI), Q95 expressed as percentage of Mean Annual Flow (Permeable Catchments $>30\%$, Impermeable $<15\%$, and a low Coefficient of Variation (CoV) for the ratio of monthly mean flow:mean monthly flow. The United Kingdom Institute of Hydrology Baseflow Index is assumed to be an index of the relative proportions of baseflow (from groundwater) and direct runoff. The BFI can be thought of as measuring the proportion of the rivers runoff that is derived from stored sources. A series of separation rules are applied to the daily stream flow record from which the BFI is calculated as the ratio of the flow under the separated hydrograph to the flow under the total hydrograph. Details of this procedure are to be found in Gustard *et al.* (1992). The higher the BFI the greater the contribution of baseflow to stream flow and the less day to day variability in flows (Gustard, 1996). Similarly, the Q95 expressed as a percentage of Mean Annual Flow, is recognised as a measure of baseflow contribution within the UK and Europe (Gustard, 1996). The value of BFI, Q95 and CoV are strongly influenced by lithology and drift geology as well as by land cover, in particular the presence of significant urban surfaces in the catchment. Whiting and Stamm (1995) comment on the stability of the hydrological regime associated with spring-fed channels. They observe that spring-fed channels typically equal or exceed bankfull flows for 30% of the time, compared with 5% or lower for runoff-dominated rivers and the 100 year flood discharge is estimated as only 2·1 times greater than bankfull discharge. Dunne and Leopold (1978) also observe that stability of the flow regime is a feature of groundwater-dominated rivers. In their study, the average annual discharge was found to range between 3–10% of bankfull discharge in rainfall-dominated rivers, 10–25% in snowmelt-dominated rivers and 14% on average in spring-fed rivers.

Whereas discharge from an aquifer largely depends on the hydraulic properties of the medium, recharge is controlled by precipitation, evaporation and temperature. In temperate areas, where annual precipitation is generally much greater than potential evaporation, recharge is mainly through precipitation. Groundwater flows are generally towards rivers and combine with direct runoff to form total river flows, the relative proportions of which vary according to the seasonality of precipitation, potential evapotranspiration and temperature. Changes in groundwater levels depend upon the characteristics and state of the unsaturated aquifer and overlying soil. This depends on the degree of saturation, effective porosity, permeability and depth to water table. These factors govern the water table response to precipitation and may vary seasonally. In humid temperate environments, autumn and winter rainfall contribute to the recharge of groundwater, and water tables peak around January to February depending on hydrogeology. In regions where precipitation falls as snow, recharge occurs during the snowmelt and maximum water table levels are reached between March and May. In arid environments, groundwater recharge occurs from the river to the aquifer during the rainy season. In this case river flows are dominated by periodic surface runoff with long periods without streamflow due to high evaporation resulting in lowering of the water table below the level of the stream bed. Groundwater flow is therefore away from the channel. In temperate environments recharge mechanisms may be further subdivided into headwater catchments where infiltration from ground surface dominates and larger catchments where influent seepage from water bodies and the stream become more important (Burt, 1996). In catchments that generate runoff from subsurface (soil) flows without a significant aquifer, runoff regimes tend to be more seasonally variable than groundwater dominated rivers.

A further hydrological factor that may reflect groundwater dominance is the presence of significant river network diminution (Gregory *et al.*, 1980; Maddock *et al.*, 1996). Controls on network diminution are exemplified by Anderson and Burt's (1980) study of drought on lias clays and oolitic limestones. Clay streams showed less reduction in network than those on limestones, except where springs fed limestone streams where flows continued throughout a drought period. The scale and seasonality of network diminution may also reflect groundwater dominance in the catchment.

Despite the diversity of groundwater:surface water interactions presented above, groundwater dominance can be identified at a range of scales (Figure 2). At the catchment scale, groundwater dominance is reflected in the stability of flow regimes and water chemistry associated with aquifers with high specific yields and water tables that provide significant perennial flows. At the valley floor scale, groundwater may contribute significantly to the mosaic of hydrological conditions both within the valley floor alluvium and to the surface water network. The passage of groundwater through the valley floor may be strongly influenced by longitudinal gradients and the presence of alluvial basins and bedrock outcrops, whilst lateral transmission will reflect the relationship between channel and water table elevation and the stratigraphy of the valley floor sediments (Grischek *et al*., 1996; Brown, 1996; Bradly and Petts, 1995). Particular interest in groundwater at the valley floor scale has been driven by the significance of the river:aquifer interactions, and particularly by the recognition of the importance of the hyporheic zone as a refugia and habitat for benthic organisms (Stanford and Ward, 1988). Within the channel, upwelling groundwater may be utilised by fish species for refugia (cool pools) or as areas of preferential spawning habitat.

GROUNDWATER DOMINANCE AND WATER QUALITY

Hydrological pathways strongly influence the physical and chemical characteristics of stream flow, and may be useful indicators of groundwater dominance. The quality of stream water may be usefully divided into chemical characteristics and physical characteristics including suspended solids concentration, colour, temperature, dissolved oxygen and conductivity.

The form and concentration of dissolved materials in stream water depends on its history of contact with other geochemicals in the atmosphere, ground surface, soil profile, groundwater and other surface water bodies. Within groundwater aquifers, the water chemistry will vary according to the characteristics of the recharge water, the solubility of the minerals encountered along the flow path, the order in which they are encountered and the reaction rates relative to groundwater velocity (McCuthcheon *et al*., 1994). The strong control exerted on water chemistry by the geochemistry of the underlying rock precludes the use of specific ionic concentrations as a general discriminator of groundwater dominated-rivers. Rather the water chemistry changes as the groundwater passes downstream and becomes mixed with stream water derived from upstream or groundwater sources of different water chemistry. Therefore, although groundwater chemistry is generally similar over a given aquifer, significant changes can be expected both between aquifers and within the river network. Furthermore, the quality of water will be subject to temporal variations as the dominance of hydrological pathways (each with a different contact time) and as seasonal patterns of hydrology, temperature and biotic activity change over the year. There is also considerable spatial heterogeneity of influent and effluent discharge from river channels to the groundwater store, providing further cause to expect wide spatial variation in water quality within a river network.

Water chemistry and the related determinands of conductivity and total dissolved load are therefore most likely to be diagnostic of groundwater dominance closest to the point of entry to the channel, and will be characterised by relatively high concentrations of aquifer geochemicals and stability of thermal regime (Smith, 1981). A more general characteristic of groundwater-dominated streams may be the stability of certain water quality determinands (each specific to the individual catchment geology) over time. For example Walling and Webb (1992) describe the low amplitude nature of the seasonal thermal variations in groundwater fed streams and Berrie (1992) records low coefficients of variation in chemical determinands for chalk streams. However, these are again strongly influenced by local geographical factors including human activity in the catchment and the nature of land use and land cover. Further blurring of the groundwater dominance water quality signal will be the presence of sewage treatment discharges and interbasin water transfers coupled with the changing water quality of groundwater resulting from human activity. Despite the heterogeneity that results from the processes and impacts discussed above, groundwater dominated rivers in many lithologies are characterised by relatively stable thermal regimes, low sediment concentrations and high water clarity (Smith, 1981; Berrie, 1992; Schumm *et al.*, 1995; Whiting and Stamm, 1995; Walling and Webb, 1992).

GROUNDWATER DOMINANCE AND RIVER CHANNEL GEOMORPHOLOGY AND SEDIMENTOLOGY

Table II documents some of the main geomorphological effects that groundwater dominance of the hydrological regime may express in the river network. In addition to these largely humid-temperate examples, may be added the extensive literature on Karst river terrains that relate to the intermittent nature of the conduit systems of rivers and the solutional features created by channel and subsurface chemical and mechanical erosion (Ford and Williams, 1989). As Table II indicates, geomorphological effects may be direct or indirect. Direct effects relate to the fluctuations in the groundwater table and the nature of the flow pathways into and out of the river channel. Indirect effects relate to the chemical status of the resultant stream water, and the controls on sediment transport exerted by the stability of the hydrological regime. Groundwater processes can strongly control the development of the drainage network of the surface river system, often through the process of spring-sapping (Higgins and Coates, 1990; Schumm *et al.*, 1995). Drainage density has been shown to be inversely related to baseflow discharge, reflecting the reduction in the role of surficial runoff processes in the development of the river network as groundwater dominance increases. Schumm *et al.* (1995) review the literature and report the following large-scale geomorphic features of spring-fed river basins:

- light-bulb shaped drainage basins
- low drainage density
- dendritic drainage pattern
- theatre or cirque-like valley heads
- steep valley walls and flat valley floors
- relatively constant valley width
- structural control of drainage network
- long main valleys and short tributary valleys
- high tributary junction angle (55–65)
- hanging valley tributaries.

Table II. Effects of surface water:groundwater interaction on the geomorphology of river systems

Direct affects on geomorphology
• *Low drainage density* and (in some cases) significant ephemeral/intermittent drainage • *Flow resistance decreased* in gaining reaches and increased in loosing reaches • *Unit stream power increased in gaining reaches* as water surface slope increased (as did sediment transport capacity and competence) • Positive upwards force on particles can *increase stream competence* • Formation of mud-seals caused by infiltration can *reduce competence* • *Bank erosion enhanced* where seepage flows occur • Fluctuations of groundwater lead to *temporal changes in network characteristics*
Indirect affects on channel geomorphology
• *Reduced bank stability caused by water table fluctuations* arising from de-watering of channel for prolonged periods or aggradation increasing water tables • *Tufa development* in $CaCo_3$ rich upwelling flows can concrete bed and provide a low density, inorganic bedload

These features seem to be independent of aquifer lithology other than the presence of concentrated (spring) groundwater discharge. The process of spring-head sapping is strongly controlled by the permeability and structure the aquifer lithology and the elevation of the groundwater table.

Stability of the hydrological regime may be expected to exert controls on the relationship between discharge variables and the scale and form of the river cross section. For example, Harvey (1969) studied three lowland streams with variable lithology that indicated that channel dimensions in groundwater dominated chalk streams were scaled to much more infrequent events than those with less stable hydrological regimes. Keller *et al.* (1990) report a possible process for this disparity in the form of groundwater seepage controls on river bank erosion which may lead to much wider channels relative to a standard recurrence interval flow. Whiting and Stamm (1995) however, report similar recurrence interval correlations between groundwater-dominated and runoff-dominated river cross-section morphometry in spring-fed streams draining volcanic geology. The same authors identify a correlation between stable groundwater-dominated hydrological regimes and a range of geomorphological and sedimentological features, including high width:depth ratio (average 33), lack of channel bars, low rates of fine sediment transport leading to a lack of fines covering the river bed, long residence times of large organic debris within the channel, and typically low values of bed shear stress. Long periods of bankfull or near bankfull flows result in relatively waterlogged floodplain soils that are reflected in low densities of arboreal species along the river corridor and mainly organic floodplain deposits.

GROUNDWATER DOMINANCE AND INSTREAM ECOLOGY

The ecology of rivers is influenced by discharge variability and quantity, channel morphology and the underlying geology. Superimposed on these factors are climatic variables, riparian characteristics (forest or grassland), and biotic interactions. Together these elements interact to create conditions suitable for particular biotic assemblages. For example a steep sloped, soft water stream in a north temperate zone will support totally different communities to those found in a lowland hardwater stream. The relative proportions of surface to groundwater inputs will also have a considerable influence on the biotic communities of rivers. In general the increased stability of flow associated with high groundwater inputs from the aquifer results in relatively high flows of clear cool water throughout the year. Such conditions, which are most clearly met in chalk streams and rivers, are particularly favourable for the development of dense beds of macrophytes and a rich and abundant faunal community. These groundwater dominated sections or ‘typical chalk-streams’ frequently represent only a proportion of the whole river. Most streams of this type flow through mixed geologies for at least part of their length but retain characteristics of the groundwater dominated physical environment such as dampened discharge fluctuations, a gravel dominated substratum and relatively high alkalinity. Such conditions will favour particular communities but local hydraulic and raparian features may outweigh or modify the influence of the groundwater on the ecology of the river.

GROUNDWATER-DOMINATED RIVERS IN THE UK

The role of groundwater in the surface flow regime of rivers is exemplified by the surface water characteristics of the UK. There are three main aquifers in UK, chalk, limestone and Permo-Triassic sandstones (Figure 3). All are recharged during winter and sustain river flows throughout the summer. Nevertheless, hydrological regimes vary. In chalk catchments, most of the runoff is derived from groundwater flow, whilst rivers with significant limestone geology may sustain relatively rapid runoff response to precipitation due to the presence of significant conduit drainage systems within the aquifer. The general characteristics of these aquifers together with their broad surface hydrology are given in Table III. Table III illustrates how the aquifer lithology/hydrogeology contributes to the surface hydrology through the Q95 and BFI values. In contrast to these aquifer rocks, values for the range of BFI for impervious soft clay and metamorphic rocks are typically 0·18–0·32 and 0·31–0·65 respectively. Values for Q95 are $<10\%$ and $<25\%$ for clays and impermeable

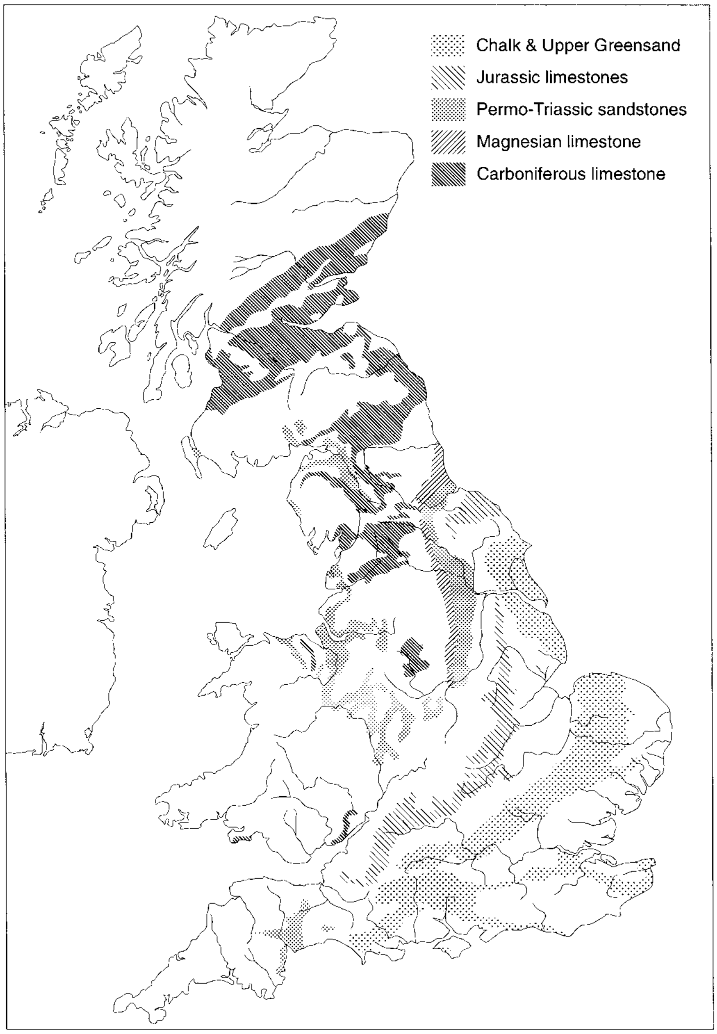


Figure 3. Distribution of main UK aquifer rocks

metamorphic rocks. Measures of the ratio between mean flow and mean annual flood strongly reflect aquifer hydrogeology. Figure 4 distinguishes between streams with increasing groundwater dominance as defined by BFI and the ratio of Mean Flow:Mean Annual Flood. Gauging stations have been selected on the grounds of geological homogeneity and rural landcover. The effect of urbanisation and capping of the aquifer rocks by impervious drift geology moves the groundwater dominated channels towards lower BFI and higher Mean:MAF ratios. The catchments shown in this Figure also have a range of altitudes and geographical distribution that influence stream hydrology. It is instructive that even with these factors within the dataset, groundwater dominated channels are still possible to distinguish.

Table III shows that broadly the main aquifers do have a significant effect on the surface hydrology of rivers. Baseflow Index values, though variable, are generally much higher than other less permeable catchments, and this is also reflected in high percentage of the mean annual flow recorded for the Q95. Hard limestones such as the carboniferous series, have a much wider range of BFI and a lower Q95 compared to the other aquifer lithologies reflecting the significant contribution from the vadose flows associated with massive fracture and conduits in this rock formation. In contrast, rivers rising on chalk are characterised by a

Table III. General hydrogeology and surface water hydrology of main UK aquifers

Aquifer Lithology	Aquifer Characteristics			Surface Hydrology				
	Water Table fluctuation (m) (mean (range))		Principle Flow Type	Q95 (% of mean flow)	Baseflow Index (mean (range))		MAF/Mean (mean (range))	
Chalk	11·2	(5·6–25·8)	Fracture	40·8	0·83	(0·53–0·99)	5·7	(1·8–22·6)
Soft limestones	3·2	(0·5–8·2)	Fracture	31·9–49	0·69	(0·50–0·94)	10·3	(2·5–26·2)
Permo-Triassic sandstone	1·1	(0·3–3·4)	Fracture/ Intergranular	6·5–65·7	0·68	(0·52–0·93)	14·7	(3·4–61·0)
Hard limestone	16·9	(4·2–32·4)	Fracture	15–25	0·42	(0·30–0·96)	21·9	(10·3–37·6)
Impermeable Lithologies								
Soft clays	N/A		Mixed	<10	0·38	(0·14–0·73)	28·8	(7·1–125·0)
Metamorphics	N/A		Fracture	<25	0·49	(0·23–0·67)	21·0	(5·9–74·6)

MAF = Mean Annual Flood for period of record, Mean = mean flow for period of record.

narrow range of high BFI and a high value for Q95 and might be considered to be dominated by groundwater flows.

Given that hydrological definitions can be used to broadly discriminate types of groundwater dominance and that these are largely related to aquifer type, it is possible to utilise existing datasets from these rivers to assess if a groundwater dominance effect can be observed in the ecology and geomorphology. Two datasets have been used; the first is the 1996 River Habitat Survey, and the second is the RIVPACS invertebrate dataset for the UK.

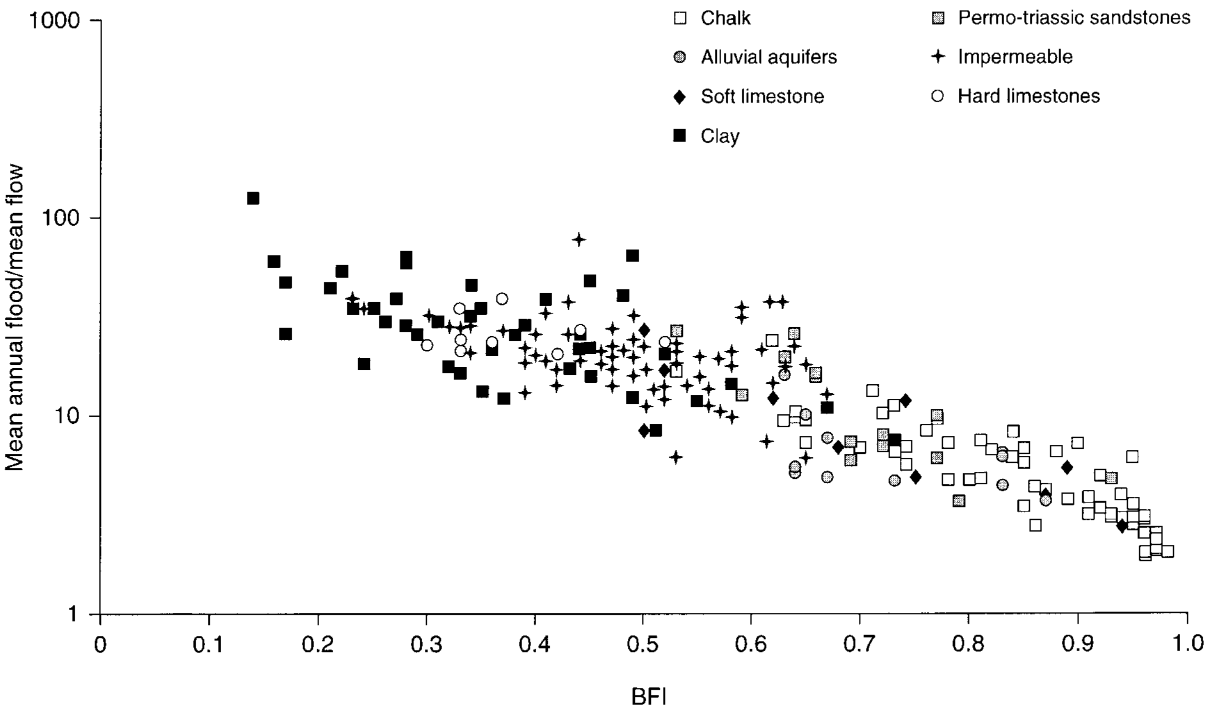


Figure 4. Hydrological diagnostics diagram for UK groundwater dominated and other runoff-dominated river

WATER QUALITY CHARACTERISTICS OF UK GROUNDWATER-DOMINATED RIVERS

The water quality signature from UK streams is complex and necessitates careful consideration of the intra- and inter-catchment controls on stream water quality. Diagnostic indicators such as water temperature (lower range in groundwater) and dissolved oxygen (generally lower in groundwater) may locally influence stream water quality close to the groundwater source, but this effect rapidly falls off with increasing distance from source. The suggestion is that true groundwater dominance is reserved for very local patches of the river network, and that these patches will vary depending on the lithology and hydrogeology of the aquifer. Data from the Harmonised Water Quality Monitoring Programme was used to investigate the water quality characteristics of UK streams. This dataset spans the period from 1975–1996 and represents a sample of 103 rivers for which a range of determinands are collected. However, sample intervals are often wide and result in an absence of storm events during each year. This should be recognised in the subsequent interpretation as it may result in lower sample variance. Sampling stations are located in the lower reaches of each river often close to the tidal limit. As such they contain few high BFI rivers indicating the general lack of groundwater dominance in the lower reaches of trunk streams. A sub-sample of 35 rivers was taken that spanned a BFI range of 0·26–0·95. Physical water quality characteristics were chosen that had been highlighted in the literature as being potentially diagnostic of groundwater dominated rivers. Scatterplots of the variance of each determinand are given in Figure 5. Variance was chosen in order to overcome the wide range of absolute values for determinands resulting from natural lithological controls. Figure 5 indicates some general trends that support previous observations, specifically a reduction in the variance associated with pH and conductivity as BFI values increase; however, no clear differentiation is evident for stream water temperature, and dissolved oxygen shows increasing variance with BFI. Figure 6 presents a similar analysis for four ion

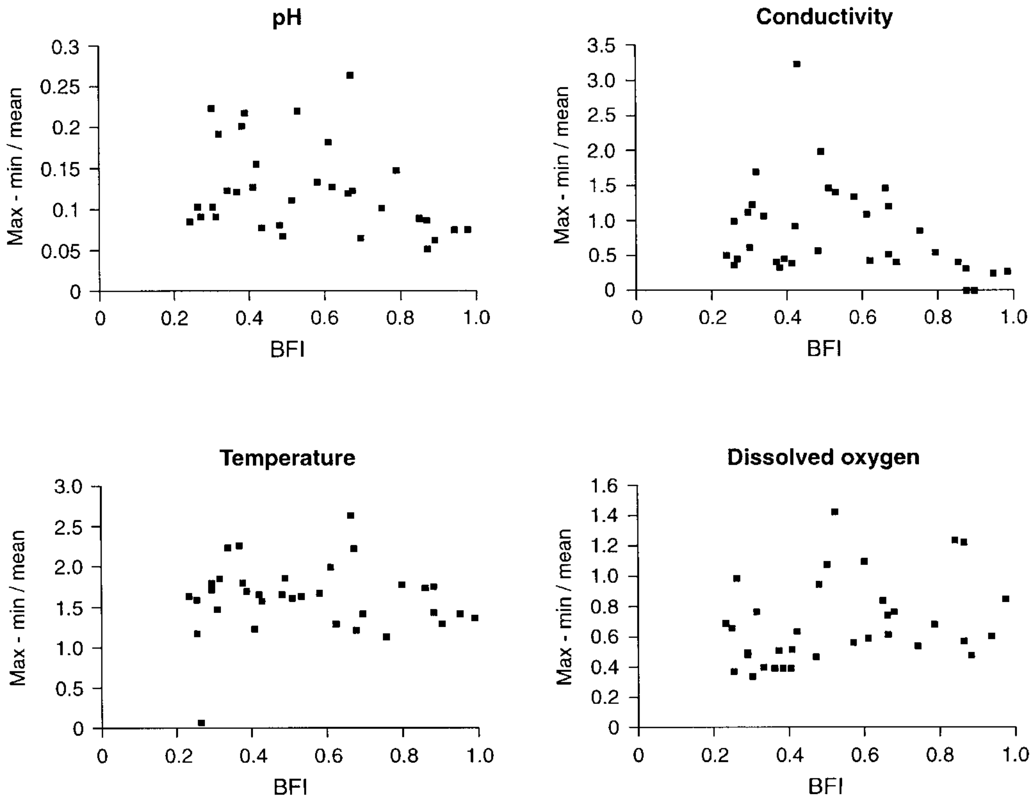


Figure 5. Physical water quality variation with increasing groundwater dominance for a selection of UK rivers

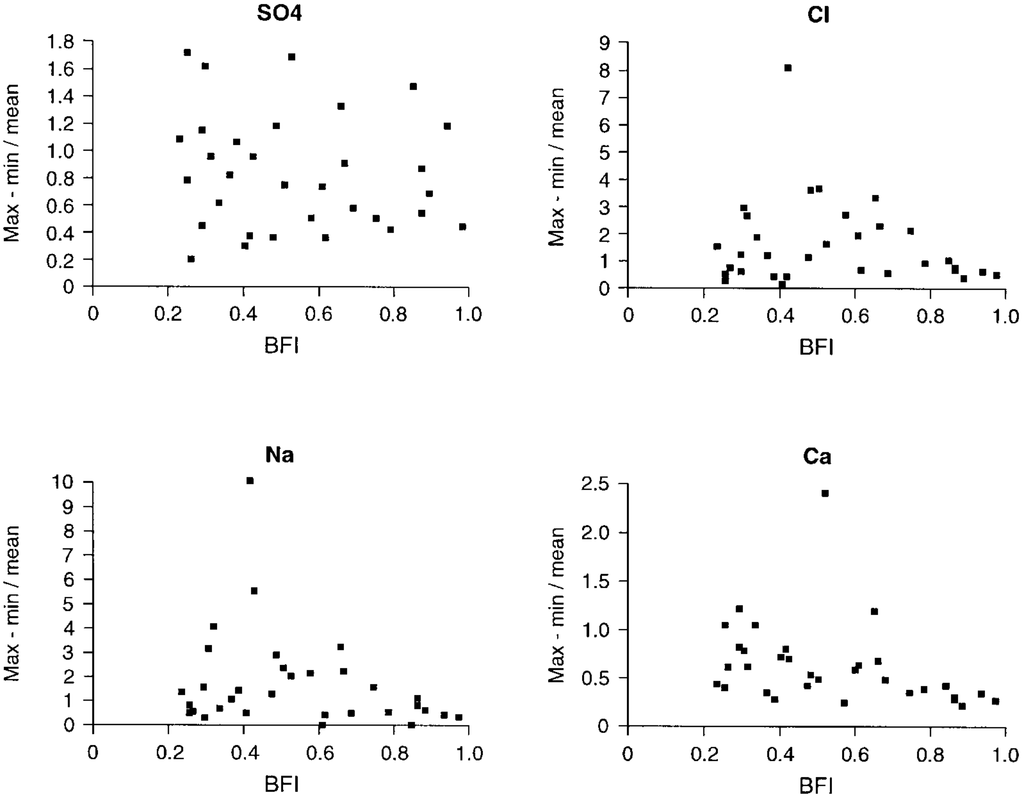


Figure 6. Chemical water quality variation with increasing groundwater dominance for a selection of UK river

concentrations, Cl$^-$, SO$_4^{2-}$, Ca^{2+} and Na$^+$. The scatterplots again reveal a weak trend towards lower variance with increasing BFI for CL$^-$, Ca^{2+} and Na$^+$ and a lack or any trend for SO$_4^{2-}$, however, the results are not conclusive. Chemical stability is a recurring diagnostic in groundwater and spring-fed rivers which the datasets presented in Figures 5 and 6 weakly support. A much more rigorous analysis is required that includes water quality data from springs and headwater catchments, with careful site selection that takes account of the influence of land use and water management before a groundwater dominated effect is confirmed.

GEOMORPHOLOGICAL AND SEDIMENTOLOGICAL CHARACTERISTICS OF UK GROUNDWATER-DOMINATED RIVER CHANNELS

Information on the physical habitat of groundwater dominated rivers was, until recently, not widely available. In 1994, a survey of the physical characteristics of UK rivers was established by the National Rivers Authority of England and Wales (now the UK Environment Agency) called the River Habitat Survey (RHS). The RHS is a standard nationally applicable method for evaluating river habitats in the UK for uses ranging from catchment planning to national reporting. The field survey attempts to encapsulate the habitat of 0·5 km sections of river by providing a context for assessing the quality of the river habitat based upon the presence, extent and pattern of physical features in terms acceptable to freshwater ecologists and geomorphologists. The end products include a working classification of the quality of river habitats by reference to those general conditions to be expected for that stretch of river. The character of different reaches of rivers in differing regions of the UK can reasonably be expected to be different in nature particularly under different physical conditions. The current separation to form 'segment' types with a minimum length of 5 km is based upon physical factors which include rate of change of energy i.e. the slope of the river, the total energy i.e. from the water discharge, and the substrate, i.e. the geological rocks, being affected by that energy, i.e. the erosion and movement of bank and bed materials. These physical interactions create the basis of the habitat which is then available for plants and animals but whose associations may be modified chemically by water flow from upstream in the catchment, and create the vegetational part of the habitat.

RHS is a rapid field form-based survey with regular 50 m transects and an overview of the 0·5 km section combined with the choice of description in 25 sections selected for ease of input for computer analysis and manipulation. This contrasts with the long-established, descriptive map-based method of River Corridor Surveys (RCS) which is designed to highlight habitats and features of special conservation importance for retention or enhancement during river management works. RHS also contrasts with the System for Evaluating Rivers for CONservation (SERCON) which is being developed to evaluate rivers based on the conservation criteria of naturalness, rarity, representativeness, diversity and fragility by computer processing of existing data on physico-chemical and biotic parameters. The location of each 500 m reach, was established using a 10 km by 10 km grid square within which three sites are chosen based on a randomly selected 2 km by 2 km square within which a watercourse is demarcated on the 1:250 000 scale maps series and which possesses a National Water Council water quality classification. A total of 6000 sites have now been recorded, representing the broad stream order categories of the UK river network. Each site is defined according to whether it has been modified in any physical way or whether it is semi-natural. Further information on the River Habitat Survey is available in Raven *et al.* (1998).

The information contained in the RHS database was sorted for semi-natural reaches, defined as those with none or only one recorded case of bed or bank modification. No reaches were included that were immediately downstream of reservoirs. The remaining 1021 rivers were sorted according to underlying geology. Five classes were chosen, chalk, Permo-Triassic sandstones, soft limestones (Jurassic/Oolitics), hard limestone (carboniferous series), clays and impermeable, largely metamorphic rocks (Figure 7). The first two represent the major UK aquifer rocks, with the largest outcrop areas, specific water yields and highest baseflow indices although different water chemistry (Grey *et al.*, 1995). The hard limestones represent cavity flow dominated aquifer rocks with carbonate chemistry and a variable baseflow index. The clay and impermeable rock groups represent low to medium baseflow index streams dominated by storm runoff during autumn and winter. In addition to the RHS dataset, a further dataset of 484 semi-natural rivers was used from a study of the geomorphological content of RHS data (Clark *et al.*, 1995). This dataset had been filtered for geomorphological information, and supplemented by the addition of bankfull discharge, slope, sinuosity, and catchment area (generated from 1:25 000 Ordnance Survey maps). This data was processed according to the method outlined above and the results are given in Table IV.

For each 500 m reach recorded in the full RHS dataset, riffle spacing (standardised by dividing the reach length of 500 m by the number riffles counted and dividing by bankfull width), average number of vegetated and unvegetated sediment storage features (point bars, mid-channel bars, side bars) per river type and total count of sediment size classes (expressed as a percentage) per river type were estimated. The study of Clark *et al.* (1995) had revealed some concern for the recording of geomorphological features which was the subject of further training prior to the collection of the current RHS dataset. Nevertheless, the information is considered to be a good representation of the morphological diversity at each site.

Figure 8 illustrates the sediment classes associated with each aquifer type. In practice, steep upland catchments will be associated with hard limestones and impermeable lithologies, and thus the substrate classes show increasing frequency of cobble and bedrock substrate classes. The lowland impermeable clay catchments shown for comparison with the lowland groundwater dominated catchments, do exhibit a clearer bimodality of substrate size class that suggests extensive areas of gravel/pebbles and areas of silty clay. Chalk streams and those draining Permo-Triassic catchments have mixed substrates with lower frequencies of gravel/pebble beds interspersed with areas of finer sands, silts and clays. Although qualitative, the information reveals significant substrate variation between groups irrespective of groundwater

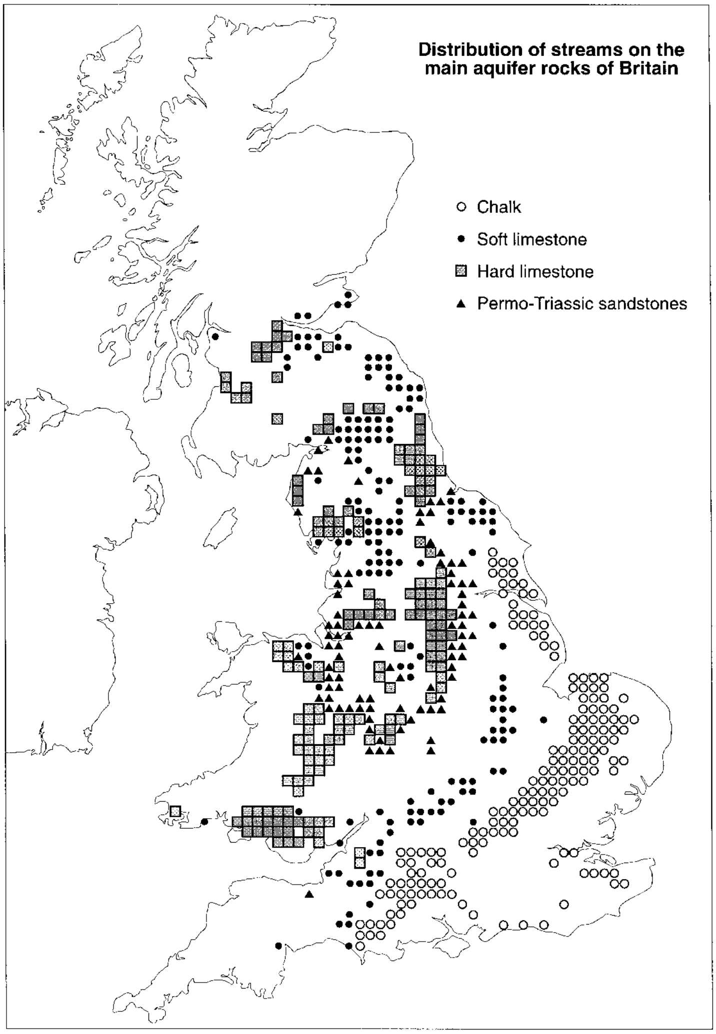


Figure 7. Distribution of semi-natural River Habitat Survey sites associated with main UK aquifers

dominance, reflecting the availability of substrate types at the local scale and the influence of slope on sediment sorting.

Assessment of the hydrogeomorphological features recorded for the same stream types in Table IV, reveals further diversity within groundwater dominated rivers although there is some evidence that the lowland rivers do share some features in common. Table IV suggests a correlation between stream power (standardised by catchment area) and ability to undertake geomorphic work. Thus at one level, high stream power is associated with higher frequency of sediment storage features in the channel, lower sinuosity and shorter riffle spacing regardless of groundwater dominance. Within the lowland groundwater dominated rivers, those rising from chalk aquifers show significant differences to other lowland river types. Chalk rivers are characterised by low stream power per unit area, relatively large width depth ratios, long inter-riffle spacing, high sinuosity and very infrequent in-channel sediment storage features. There is an intuitive discrepancy between the presence of high width:depth ratios, and a lack of sediment storage and high sinuosity. This may be explained in part by the inability of chalk streams to mobilise their gravel beds due to the low stream powers and concretion of the substrate by calcareous deposition. Instead, sediment storage is

Table IV. Geomorphological features associated with main UK aquifer and impermeable catchment lithologies. Data derived from RHS and Clark *et al.* (1995)

Aquifer/Lithology	**Power (W/km^2)**	**Bankfull width (m)**	**W:D**	**Riffle Spacing/ width bf**	**Mean number VSSF/ 500 m**	**Mean number DSSF/ 500 m**	**Sinuosity**	**n**
Chalk	6·1 (17·8)	8·7 (4·4)	18·4 (14·0)	51·0	0·1	0·1	1·29 (0·47)	98
Soft limestones	15·6 (31·6)	7·7 (4·5)	11·0 (7·1)	27·2	0·8	1·0	1·24 (0·41)	91
Permo-Triassic sandstone	6·8 (13·9)	10·8 (8·3)	9·2 (6·3)	20·9	0·6	0·6	1·25 (0·24)	50
Clay	6·3 (19·3)	6·1 (3·8)	7·8 (5·4)	31·0	0·4	0·5	1·31 (0·33)	200
Hard limestones	72·1 (236)	9·2 (7·9)	11·7 (8·5)	15·4	0·7	1·2	1·22 (0·26)	96
Impermeable lithology	25·4 (81·8)	10·3 (10·6)	10·0 (9·3)	15·1	1·4	1·5	1·20 (0·25)	486

Figures in brackets are standard deviations of sample population.
W : D = 'Form ratio' of bankfull channel width to bankfull depth.
VSSF = Vegetated sediment storage features (point bars, mid channel bars and side bars).
DSSF = Dynamic sediment storage features (point bars, mid channel bars and side bars).

dominated by the passage of fine silts and sands that can be stored in the long reaches of pool that also characterise chalk river geomorphology. This is broadly supported by the observations of Whiting and Stamm (1995) discussed above, who also recorded low numbers of bars (sediment storage units). Clay rivers, in contrast have similar stream powers, but much higher frequencies of sediment storage features than chalk streams, and very different cross-section form. This reflects the nature of the cohesive boundary materials that can support a narrower, deeper channel.

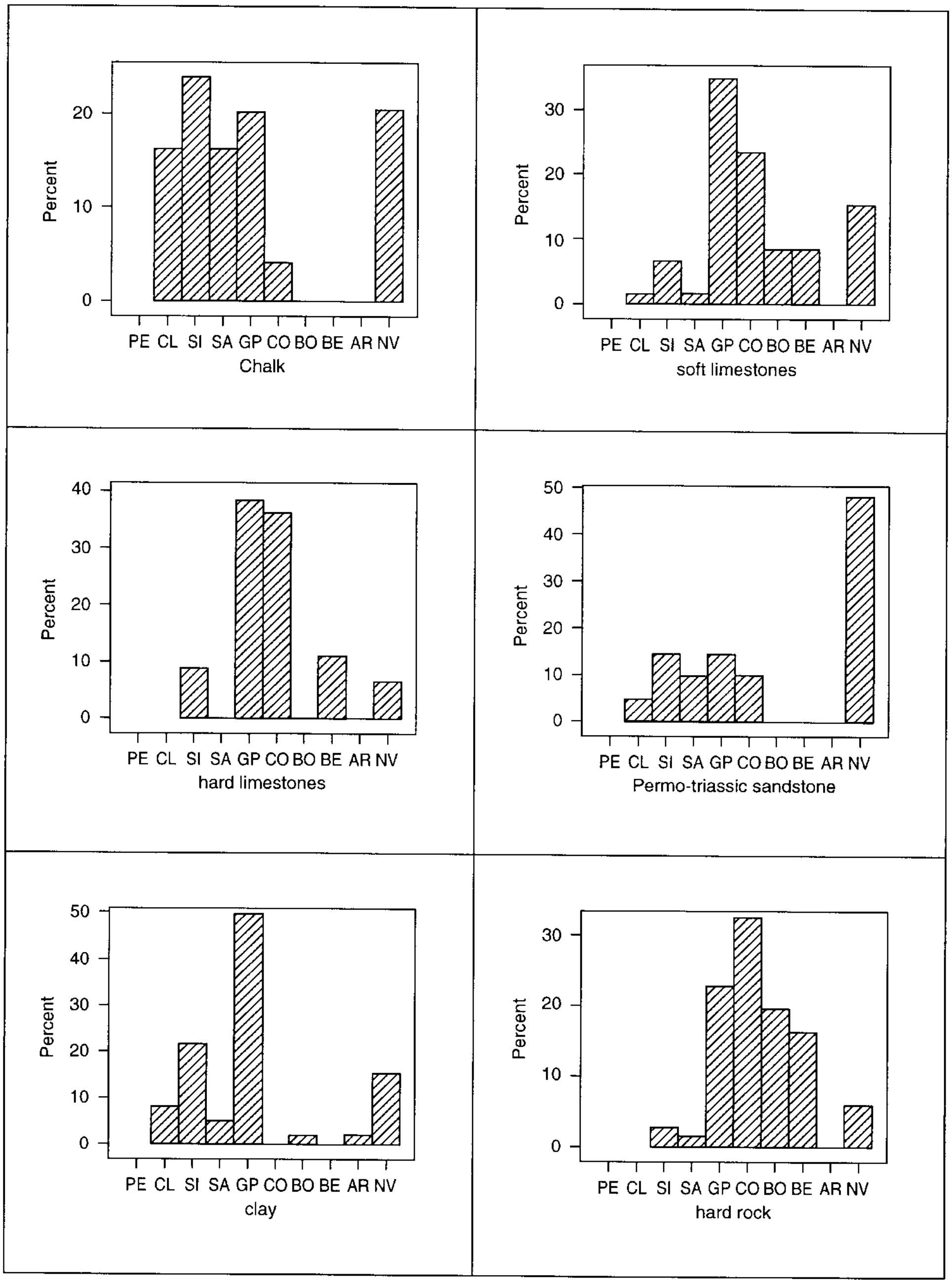
A scale of increasing hydrogeomorphological diversity appears to coincide with decreasing groundwater dominance, but in fact this is probably more a reflection of the availability of coarse sediments and energy within the system to conduct geomorphological work (Clark *et al.*, 1995). The lack of morphological diversity associated with impervious lowland clay streams broadly support this view, although it does not explain the different characteristics of chalk streams. A geomorphological characteristic of groundwater-dominated streams appears to be a lack of sediment storage units and relatively high width:depth ratios

ECOLOGICAL CHARACTERISTICS OF UK GROUNDWATER-DOMINATED RIVERS

Of the main aquifer geologies the most ecological research effort has been directed towards the chalk streams of southern England (Berrie, 1992). Historically chalk streams probably flowed in ill-defined channels through alder and willow fen (Ladle and Westlake, 1976). Between the 17th and 19th centuries most of these fen areas were cleared and drained to provide additional land for agriculture. Systems of water meadows were constructed which, by controlled flooding, providing new grass for sheep. Over the past 40 years much of the land in the catchment areas has been ploughed and used for arable crops and ley pastures and the use of inorganic fertilisers has increased. In addition to the rise in agricultural use, demands for water for supply purposes have also risen in the past two decades and chalk streams have been heavily abstracted. This combination of factors has meant that human impacts on these systems have been and continue to be great.

Chalk streams are characterised by stable flows and support a high diversity and density of river biota including an economically valuable salmonid fishery. Ecological studies have addressed the effects of the human impacts on flow, physical habitat, and the river biota and have been reviewed in Ladle and Westlake (1976) and more recently by Giles *et al.* (1991) and Berrie (1992).

Specific studies on Oolitic (soft) limestone streams and those deriving water from Permo-Triassic sandstone are few. Mackey *et al.* (1982) examined a site on the River Coln, a tributary of the Thames arising on Jurassic limestone. They found that the biotic characteristics of their main site, Fairford, were very similar to those of Bagnor, (a site on the Lambourn, a southern England chalk stream). *Ranunculus* was the dominant



PE	Peat	CO	Cobbles
CL	Clay	BO	Boulders
SI	Silt	BE	Bedrock
SA	Sand	AR	Artificial
GP	Gravel	NV	None visible

Figure 8. Frequency counts of River Habitat Survey sediment classes associated with groundwater dominated and impermeable river catchments in the UK

macrophyte and the fauna was similar but slightly richer at Fairford. This is attributed to the fact that Fairford lies further downstream (44 km) than the Bagnor site (20 km).

The River Perry is a lowland stream arising in Bunter sandstone and flowing into the River Severn. Detailed studies on the stream were carried out for a period of five years as part of an impact analysis of the effects of the Shropshire groundwater augmentation scheme (Anon, 1978) and more recently Harper (1990) has described the ecology of the river based on five years' collections made in May and August between 1980 and 1985. The river has been canalised in parts and is subject to flow regulation and receives continuous treated and discontinuous untreated organic effluents from a number of sources. The plant community is dominated by the alga *Cladophora glomerata*, and the angiosperms *Elodea canadensis*, *Myriophyllum spicatum*, *Ranunculus fluitans* and in the faster riffle and run stretches *Potamogeton pectinatus*. The invertebrate fauna is rich in species (104 species in 60 families with no specific identification within Diptera, Bivalvia, Hydracarina and Oligochaeta) and its distribution reflects the changes in the original substratum (glacial deposits and alluvial silts and clays) brought about by channel modifications, canalisation and regulation.

In order to examine the possibility that a groundwater dominated river has a specific set of ecological characteristics, data on macroinvertebrate distribution collected for the development of RIVPACS (River Invertebrate Prediction and Classification system) (Wright *et al.*, 1993; Wright *et al.*, 1995) have been used to compare faunal communities along rivers deriving their water from groundwater sources. RIVPACS is a system developed by the Institute of Freshwater Ecology in the UK for the classification and prediction of macroinvertebrate communities in running water. Over the past two decades about 600 species of macroinvertebrate have been identified from more than 600 unpolluted sites throughout Great Britain for which environmental data have been recorded. The species lists have been used to construct a national classification of lotic sites and to develop a technique for predicting the probabilities of occurrence of individual taxa at sites of known environmental characteristics. This large data base provides a standard against which to assess the fauna of new sites and also places the site in a national context. The TWINSPAN analysis used in RIVPACS to classify the sites into groups according to the invertebrates present provides an opportunity to test the hypothesis that groundwater dominated rivers possess distinct faunal communities.

The position of sites along the length of chalk, soft limestone, sandstone and clay streams (for comparison) within the TWINSPAN classification was examined (Figure 9). If the communities present at the sites were similar all sites would be expected to fall into a single group; however it is clear that they are widely distributed in the classification with sites on chalk streams occurring between groups 8 and 34. The chalk stream set includes examples of rivers from southern, eastern and northern chalk and Table V shows how these are distributed amongst the TWINSPAN groups. Sites within group 8 are all located in the upper reaches of the river and include northern, eastern and southern chalk streams. The mid to lower reaches of southern chalk streams occur mainly in group 25. The lower reaches of southern chalk streams occur in group 27 but this also includes some middle-reach eastern sites and an upper site on the River Avon in Hampshire. Sites on the mid to lower reaches of the eastern and northern chalk streams are found in group 33. Thus even within a single geological type there is considerable variation in faunal community.

It is clear that faunal assemblages vary with the specific geologies despite the common feature of being groundwater dominated. The softer limestone, chalk and sandstone rivers have features in common but in the final analysis the faunal communities will be most influenced by local hydraulic conditions which in turn will be affected by local conditions (drift geology, channel morphology) and distance downstream. The perception of what is a typical chalk stream or groundwater dominated river is probably never realised along a whole river. Recent studies in the River Frome in Dorset (Cannan and Armitage, this volume) support this view where a detailed examination of sites along the whole river revealed the existence of four separate groups which appear to relate to local changes in geology although it is difficult to separate these from the downstream trends.

The fish populations of groundwater dominated streams, particularly chalk streams have been the subject of much study, particularly with respect to the effects of dry weather conditions and low flows (Giles *et al.*, 1991). Characteristic species of fish found in unpolluted examples of these rivers are Trout, Salmon, Grayling,

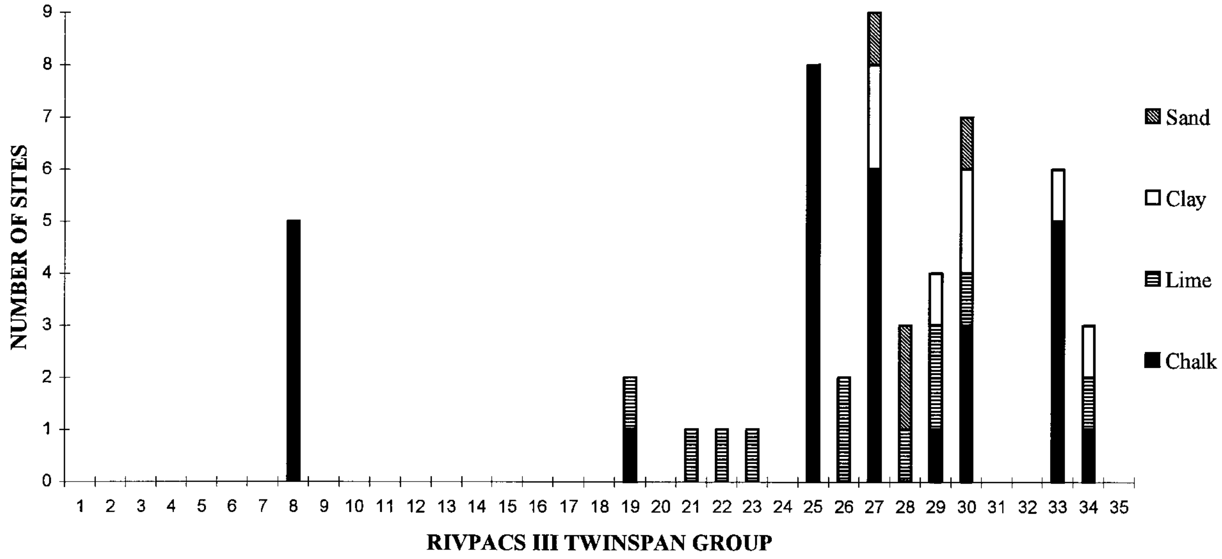


Figure 9. The TWINSPAN classification of sites on selected lowland rivers with contrasting geology, extracted from the RIVPACS III data base

Dace, Roach, Minnow, Gudgeon, Pike, Eel, Bullhead, Stone-Loach, and Three-spined Stickleback. In general the proportions of these species will vary along the length of the river with increased abundance of cyprinids in the downstream reaches and the highest densities of salmonids in the upper and middle reaches. Thus although there is a particular fish community associated with 'typical' chalk streams this typically is not found along the length of the stream and in the same way as invertebrates are influenced by specific hydraulic conditions so the distribution of fish is strongly influenced by local channel and hydraulic features.

CONCLUSIONS

This paper has focused on the instream characteristics of rivers with a large proportion of flow derived from groundwater and has sought to advance a preliminary assessment of a 'groundwater dominance' effect in four specific areas — hydrological regime, sediment and morphological character of the river channel, surface water chemistry and instream ecology. The failure to detect a specific groundwater effect in the datasets examined for this review, does not preclude the notion that aquifer:surface water interactions exercise strong local and in some cases catchment scale controls on river processes and ecology. There is sufficient distinction between rivers dominated by groundwater and those that are not, to merit further research, and certainly consideration in management strategies. Figure 10 illustrates some of the main issues identified as being of importance to the future management of groundwater dominated rivers and streams. Many are under threat from water resource management, and environmental change. In these rivers, the effect of over-abstraction is most profound, leading in some cases to an increase in the frequency and duration of network diminution which may result in significant ecological changes. Continued development of floodplains threatens the connectivity between shallow groundwater and surface water systems and reduces the diversity of aquatic habitats in the valley floor. At a local scale, synergism between land-use change and low-flows can result in changes in benthic sediments requiring reach scale management for fisheries rehabilitation, whilst long term application of chemicals to catchment landsurface and as discharges to the river network may alter both groundwater and surface water quality.

Groundwater dominance is difficult to determine at a regional level instead, it should be assessed at a local scale, in terms of the nature of the aquifer:surface water interaction, and the scale of the influence (local or

Table V. TWINSPAN classification of sites on chalk streams in southern (S), eastern (E) and northern (N) England. TWINSPAN group number and distance from source are indicated for each site. (Avon H, Hampshire Avon)

River	Location	Site	Distance from source (Km)	TWINSPAN group
Hull	N	LD	1·6	8
Great Eau	N	RU	2	8
Frome	S	CH	3	8
Great Eau	N	SW	6	8
Bure	E	COR	8	8
Itchen	S	CH	14	19
Frome	S	FR	13	25
Frome	S	LB	25	25
Avon (H)	S	BU	27	25
Itchen	S	OW	30	25
Frome	S	M	35	25
Itchen	S	CH	39	25
Avon (H)	S	ST	40	25
Frome	S	ES	43	25
Avon (H)	S	RU	11	27
Yare	E	NOB	20	27
Yare	E	EAR	30	27
Avon (H)	S	BR	61	27
Avon (H)	S	MO	80	27
Avon (H)	S	CH	94	27
Avon (H)	S	PA	5	29
Hull	N	WA	9	30
Great Eau	N	BE	10	30
Itchen	S	IS	22	30
Itchen	S	AB	4	32
Bure	E	WFF	16	32
Hull	N	CO	13	33
Great Eau	N	TH	17	33
Bure	E	BM	31	33
Bure	E	CB	36	33
Little Ouse	E	BR	43	33
Little Ouse	E	BRCK	64	34

catchment). Definition at a range of scales is possible, and results in the identification of a number of groundwater river types, and scales of dominance. Hydrological definitions based on runoff regime provide a way to discriminate between groundwater (high baseflow) rivers. However, at a general level, this distinction is not reflected in the reach-scale geomorphology or ecology of groundwater dominated rivers. Rather, each aquifer type has a geological signature that masks the effect of groundwater dominance. Aquifer lithology largely determines water chemistry, substrate composition and through these, instream ecology. Catchment relief provides a further control on the energy available to undertake geomorphological work that is reflected in the features associated with each river type. Thus, whilst groundwater dominance exists, the operation of other allogenic controls necessitates the definition of strong sub-types of groundwater dominated river. Of these sub-types of groundwater dominated river, the chalk stream environment is revealed as clearly distinct from other lowland groundwater dominated rivers or impermeable lowland streams, although true groundwater dominated chalk streams (as opposed to streams that are underlain by chalk aquifer rocks) may be

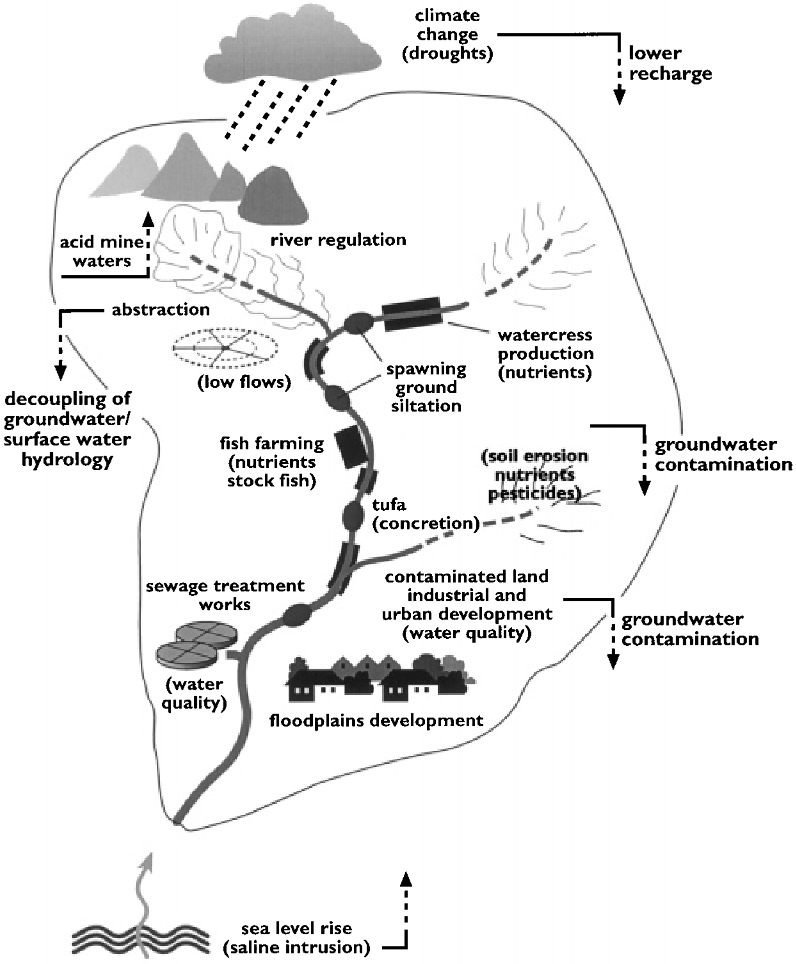


Figure 10. Management issues and impacts in groundwater dominated rivers

quite rare. A combination of low stream powers, low drainage density and mixed substrates, result in relatively little geomorphic activity and a low morphological diversity relative to other lowland stream types. At this stage it is impossible to state whether these diagnostic features result from the strong groundwater signature associated with these streams or from allogenic factors, however in an era when environmental change threatens to put water resources under increasing pressure, the identification of the role that groundwater plays in sustaining river and floodplain habitats would seem to be of fundamental importance for their future management.

Table VI provides guidance on the contribution made by the papers in this volume to understanding instream and floodplain river processes under four broad headings. Whilst progress towards the understanding of chalk stream environments has been made (see Table VI), less work has been conducted on streams draining other major aquifers. Specifically, there is a clear need to take a more holistic approach to the understanding of the role of groundwater in surface water ecosystems. In a similar vane, the scale of this research and its translation into management guidance must expand the current focus on instream hydroecology and geomorphology to fully take account of the valley floor, hyporheic zone and aquifer hydrogeology.

Table VI. A guide to the papers in this special edition classified according to broad areas of subject specialism

Paper	Hydrological Regime	River channel geomorphology & sedimentology	River water quality	Instream ecology	Other
Acornley			X	X	Salmonid spawning
Acornley and Sear	X	X		X	Sediment transport
Armitage and Cannan				X	Scale effects
Clarke and Webb			X	X	Thermal regime & ecology
Elliot *et al.*	X			X	Modelling
Holmes	X			X	Macrophyte/drought impacts and recovery
Petts *et al.*	X			X	Hydro-ecological models of GWDR
Power	X		X	X	Groundwater controls on thermal regimes in frozen rivers
Sear *et al.*	X	X	X	X	Definition of groundwater dominance
Shackle *et al.*		X		X	river management — gravel cleaning
Strevens				X	River management — fisheries
van Lanen and Djiksma	X		X		Aquifer: river interactions
Walling and Amos	X	X			Sediment transfer and sediment sourcing
Ward *et al.*			X		Groundwater and floodplain processes in alpine valleys
Webb and Zhang			X		Heat budgets
Wood and Petts	X			X	Drought impacts — invertebrates
Wright and Symes	X			X	Drought impacts — invertebrates

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