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Floodplain rivers:

hydrological processes and ecological significance

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Preface

This volume contains research first presented at a conference focusing on floodplain rivers and in particular their hydrological processes and ecological significance in a UK context. The conference, *Floodplain Rivers: Hydrological Processes and Ecological Significance*, was held at the School of Geography at the University of Birmingham in June 1996, where a series of papers were presented under the broad headings of hydrological and geomorphological processes, hydrology and vegetation, and floodplain management and restoration. Special thanks are due to Professor Geoff Petts, Professor Angela Gurnell and Mrs Sue Lane at Birmingham for ensuring a very successful meeting. Acknowledgement is also given to Dr George Heritage and Dr Paul Younger, Newcastle University and John Griffin, Institute of Hydrology, for advice on the production of this occasional paper.

Contents

		Page
	Linking floodplain hydrology and ecology - the scientific basis for management *A.R.G. Large*	1
1	**Woody debris and river-floodplain interactions** *A.M. Gurnell*	6
2	**Investigations into hydrological influences on the establishment of riparian tree species: the River Isere, France** *F.M.R. Hughes, K.S. Richards, A.S. El-hames, T. Harris, J.-L. Peiry, G. Pautou and J. Girel*	17
3	**Floodplain vegetation and overbank erosion and sedimentation** *A. G. Brown and A. Brookes*	30
4	**Hydrochemical-vegetation interactions on a Scottish floodplain mire** *N.J. Willby, K.J. Murphy, D.J. Gilvear, I.C. Grieve, and I.D. Pulford*	40
5	**Groundwater-surface water interactions in a major Scottish floodplain** *M. Chen & C. Soulsby*	53
6	**How the hydrology of a Thames flood meadow determines vegetation patterns** *D.J.G. Gowing and E.G. Youngs*	69
7	**The role of rivers in the preparation of water management plans at wetland sites** *R. Lawson and R. Wistow*	81
8	**Urban watercourses: restoration and rehabilitation** *J.B. Ellis*	93
9	**River and floodplain restoration: principles and practice** *R.D. Hey*	104
10	**Restoration in the Rivers Skerne and Cole: impact on flood hydrology** *K.R. Fisher*	120

Introduction

Linking Floodplain Hydrology and ecology - the scientific basis for management

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Interest in floodplains as integral components of fluvial hydrosystems in the United Kingdom increased over the period of last two decades and a series of volumes have charted this trend, most notably the publication in 1992 of *River Conservation and Management*, edited by Phil Boon, Peter Calow and Geoff Petts. Other volumes of note have included the two volume *Rivers Handbook* (Calow and Petts, 1992; 1994), *The Ecological Basis for River Management* (Harper and Ferguson, 1995) and *Floodplain Processes* (Anderson *et al.* 1996). Many of these volumes are the result of conferences to promote discussion of recent results of research into the ecological basis of river and floodplain management. These discussions typically involve both the scientific community and the management community.

1. HYDROLOGICAL AND ECOLOGICAL PROCESSES

Being organised under the auspices of the British Hydrological Society the papers contained in this volume all have a hydrological theme running through them. As discussed by Gurnell in her paper on river-floodplain interactions (Chapter 1), woody debris plays an important role in both geomorphological and ecological processes, governing fluvial ecosystem functioning. The morphological and ecological role of woody debris accumulations, their effect in ameliorating the transfer of bed material and suspended sediment, and their possible impact on water quality provide a strong range of benefits. River valleys across much of the world were once extensively wooded - a key factor in maintaining interaction between the river and its floodplain. However, clearance of woody debris coupled with deforestation and drainage of floodplains, and engineering of river channels has led to far-reaching changes in river systems.

An understanding of the interactions between river hydrology and geomorphology and the regeneration of floodplain vegetation is critical to the success of any river management initiative. To successfully model vegetation changes, and to properly define both minimum and optimal flows for riparian vegetation communities, detailed research on target species is essential, as concluded by Hughes *et al.* in their paper (Chapter 2) describing results of investigations into hydrological influences on the establishment of riparian tree species along the River Isere, France. One interesting outcome of this research has been, for certain floodplain sediments, identification of the response of groundwater levels and soil moisture

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status to channel water levels which represents a potentially useful input to flow management by defining the timing and maintenance of stage changes for the purposes of encouraging the regeneration of riparian species. However, creation of new sites suitable for regeneration of early successional species would require flood events capable of initiating geomorphological change through bank erosion, bar construction, channel migration, and spatially-varied deposition patterns - unlikely components of UK river management. The results of this study, nevertheless, suggest practical options that exploit both an understanding of groundwater response to river level variation and the ecological impact of that response, and the effects of local geomorphological processes on species success.

The accretion rate of floodplains is the product of both overbank deposition and overbank erosion and, in Chapter 3, Brown and Brooks describe how plants may have an important, dynamic and non-linear role in the processes of floodplain deposition and erosion, as different species will intercept different quantities of suspended sediment. Brown and Brookes discuss how floodplain deposition varies through the year with the phenology of the vegetation and management (e.g. grazing), and how rates of floodplain accretion may be affected by *in-situ* changes in floodplain land use as well as any hydrological changes of catchment or climatic origin. They point out that further work in this field is urgently required as these processes have theoretical implications for modelling past sediment budgets and practical implications for the management of floodplains in order to strip suspended sediment and associated contaminants from river systems.

2. HYDROLOGY AND VEGETATION

Hydrological and hydrochemical gradients on floodplain mires are primarily controlled by inputs and outputs from precipitation, groundwater and surface waters. Even quite minor alterations in watertable regime and chemical composition of the incoming waters can lead to significantly different vegetation communities. This has important implications for ecosystem functioning as this vegetation can, in turn, affect water tables and chemical composition through differential uptake of nutrients and water. This is the subject of Willby *et al.*'s investigations on the Insh Marshes bordering the River Spey in Inverness-shire, the largest floodplain mire complex extant in the British Isles today. To manage floodplain wetlands such as these successfully, Willby *et al.* emphasise (Chapter 4) that an understanding of the role of hydrology in determining wetland nutrient status and hydrochemical-vegetation interactions is needed, and that a detailed insight into floodplain hydrology and hydrochemistry is thus vital if the nature conservation value of such sites is to be safeguarded.

Still in the Spey catchment, but moving from hydrological and ecological processes to management, Chen and Soulsby describe groundwater-surface water interactions in a major Scottish floodplain (Chapter 5), pointing out that, despite the presence of abundant surface water, groundwater in Scotland is a valuable resource which provides water to domestic, industrial and agricultural consumers in many rural areas and in some important urban locations. Despite having been neglected in the past, groundwater resources have, in recent years, been receiving increasing attention due to high costs of surface water treatment resulting from the water quality requirements of the EC Drinking Water Directive 80/778/EEC. The Spey Abstraction Scheme is one of the first large scale developments in the UK which involves indirect river water abstraction through the alluvial gravels adjacent to the river bank. Compared to traditional direct river abstraction, significant improvement in

water quality can be gained due to biological and chemical processes in the alluvium which result in much reduced water treatment costs. However, there have been few studies of river-aquifer interactions in Scotland and the published literature regarding groundwater protection is limited. Chen and Soulsby's research, describing a conceptual and numerical model of the Spey river-aquifer system which quantifies river-aquifer interactions under stressed conditions and delineates the travel time related capture zones of the wellfield, thus provides a timely input into this area of research.

In wet grasslands, a habitat type common on UK floodplains, the soil water-table regime is the main environmental factor determining the relative competitive abilities of plant species. In order to understand the distribution patterns of both individual species or whole communities, spatial variation in the water regime has to be known. Gowing and Youngs' paper points out that water-table depth is perhaps the most important environmental factor to be considered when studying the vegetation of floodplain grasslands (Chapter 6). Their approach illustrates the need, in managing the hydrology of these habitats effectively, to consider the stresses imposed on the vegetation by waterlogging separately from those imposed by drought. Such hydrological modelling should permit the identification of the time of the year when interspecific competition within the vegetation is most intense, important because the water-table behaviour at these critical periods has the greatest impact on the plant community composition.

3. FLOODPLAIN MANAGEMENT AND RESTORATION

Once the requirements of communities are quantitatively defined, the scope for active management to maintain the appropriate level is increased. Such hydrological information is of great value in guiding management of the floodplain habitats in the interests of ecological conservation. As Lawson and Wistow's paper shows (Chapter 7), Water Level Management Plans (WLMPs) provide a means by which the water level requirements for a range of activities in a particular area can be balanced and integrated. They are management tools which summarise the water level management practices and objectives of an area, fully taking into account the objectives of all interested parties. While WLMPs offer a powerful tool to operating authorities in the operational management of wetland SSSI sites where water level control is central to conservation, Lawson and Wistow describe them as working documents subject to regular review and refinement and conclude that, in many cases, early versions of WLMPs will not achieve their objectives in terms of management prescriptions. Successful WLMPs should ultimately propose target water levels which have been reached through consultation and with the consensus of all parties. However it is crucial to note that WLMPs are still in their infancy, and this ultimate goal cannot be achieved at all sites straight away.

A final selection of three presentations in this Occasional Paper discuss the future management of rivers and river-floodplain complexes. As Brookes and Douglas Shields Jr (1996) state, a multi-functional approach to river management (and, by implication, restoration and rehabilitation) is needed, encompassing disciplines including hydrology, hydraulics, geomorphology, water quality, ecology and landscape - features addressed in the first six papers in this volume.

In addressing urban situations, engineers, hydrologists and ecologists have to scale the temporal and spatial variability of the hydraulic and chemical factors influenced by storm-water runoff. This, as Ellis describes (Chapter 8), requires quantification and mitigation of

ecological impacts such that existing regulated channels having poor water quality and depressed habitats with low specific retention capacities can be restored or re-created to achieve intermediate specific capacities with phased successions closer to natural conditions. Here, the use of patch dynamics concepts based on the quantification of key controlling parameters for community loss provides a planning level evaluation procedure for comparing the impacts of alternative urban runoff management measures. Techniques and measures supporting post-failure recovery become all the more important, as recovery analysis is essential to the integrity and success of sustainable urban runoff management.

It remains a paradox, that whilst many of the key problems in ecology refer to large scale processes in space and time, much of the ecological research effort has been focused on mechanisms that operate on small, short-term scales. The emphasis in the UK in the early 1990s on Integrated Catchment Management, now taken up by the Environment Agency in the form of Local Environment Agency Plans (LEAPs) demands a more holistic and interdisciplinary approach to river management. Although the adoption of more enlightened procedures will, hopefully, prevent future canalisation projects, there remains a legacy of existing works which require restoration or rehabilitation. As Hey describes (Chapter 9), most river restoration projects in Europe have however been designed to improve landscape and conservation value often with little regard for channel stability over longer temporal scales. To recreate a sustainable natural channel, Hey concludes that it is necessary to determine the stability, morphology and geotechnical characteristics of the river, and to develop 'soft' engineering designs based on the survey data. Thirdly, it is also necessary to evaluate the stability of the design.

The final chapter in this volume by Fisher (Chapter 10) describes how European *LIFE* funding has enabled restoration work on three demonstration sites, two in the UK on the Rivers Skerne and Cole, and a third on the River Brede in Denmark. Here restoration has aimed to reintroduce natural habitats and features into damaged rivers, reconnect rivers with their floodplains and demonstrate the benefits of river restoration. The aims of the project demonstrate well the objectives we need to carry forward into the 21st century if centuries of degradation of the UKs rivers and floodplains is to be halted and even reversed. Firstly, demonstration sites are needed which apply new and state-of-the-art techniques to the restoration of natural habitats in damaged rivers and their floodplains. Secondly, restoration efforts must demonstrate the benefits of river restoration for integrated catchment management in terms of nature conservation, water quality, river hydrology, flood prevention and amenity by monitoring the physical, chemical and biological effects of their activities. Schemes must involve, motivate and train those who influence or undertake river management work and well as influence those outside the direct restoration effort. Finally, schemes have a duty to widely disseminate information about their success and, in cases, their failure in order to properly influence legislative, policy and institutional arrangements for the future.

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1

Woody debris and river-floodplain interactions

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Abstract

River valleys across much of the world were once extensively wooded such that fallen trees, branches and leaves formed a significant component of the river environment and a key factor in maintaining interaction between river and floodplain. However, clearance of woody debris coupled with deforestation and drainage of floodplains, and engineering of river channels has led to far-reaching changes in the morphology, stability and ecology of river systems. This paper reviews the ways in which woody debris accumulations impact on woodland river environments. The morphological and ecological role of woody debris accumulations, their effect in ameliorating the transfer of bed material and suspended sediment, and their possible impact on water quality provide a strong range of benefits which mitigate against debris clearance. Furthermore, the costs of debris removal are substantial and the major reasons given for removal are shown to be less significant than has been suggested. A more flexible approach is required to the management of woody debris within river systems. The first stages of such an approach are proposed.

1. INTRODUCTION

Gurnell (1995) has recently reviewed the intimate association between vegetation, inundation frequency and floodplain geomorphic processes and features on genetic floodplains (Nanson and Croke, 1992): the areas adjacent to river channels where habitat patches, their composition and arrangement, are determined by the contemporary regime of fluvial processes (flooding, erosion, deposition) (Petts, 1996). Several recent reviews have also explored the role of woody debris within river systems (eg Bisson *et al.*, 1987; Harmon *et al.*, 1986; Gurnell *et al.*, 1995; Maser and Sedell, 1994). This paper focuses on woody debris accumulations within the river channel system as an important control on river-floodplain interactions across forested floodplains.

River valleys across much of the world were once extensively wooded with the consequence that fallen trees, branches and leaves formed a significant component of the river environment. Whereas floodplain deforestation has a long history in Europe, tree and driftwood clearance has been more recent in the Pacific Northwest of the United States. Here settlement did not

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commence until the 19th century, and so research undertaken here has clearly documented the impact of deforestation and dead wood clearance on the aquatic environment (Maser and Sedell, 1994; Sedell and Froggatt, 1984). Figure 1.1 illustrates the changing planform of a section of the Willamette River, due mainly as a result of the removal of snags of woody debris (65000 snags and streamside trees removed between 1870 and 1950) and the use of some of the debris to close off side channels. The morphological results of debris removal are summarised by Sedell and Froggatt (1984, p1833) and illustrate the importance of woody debris accumulations for river-floodplain interactions:

> *'The pristine river was a series of multiple channels, sloughs, and backwater areas. Historically, the floodplain and valley had extensive marshes. Numerous downed trees helped to create and maintain shoals, multiple channels, oxbow lakes, and complex aquatic habitats at the outside of bends on the river. After 80 years of snag removal and riparian forest destruction, there now exists one main channel, few downed trees, relatively simple and homogenous habitat for aquatic vertebrates, and over a four-fold decrease in river shoreline.'*

Such historical studies of the role of natural debris provide us with important information for river management (Swanson *et al.*, 1976).

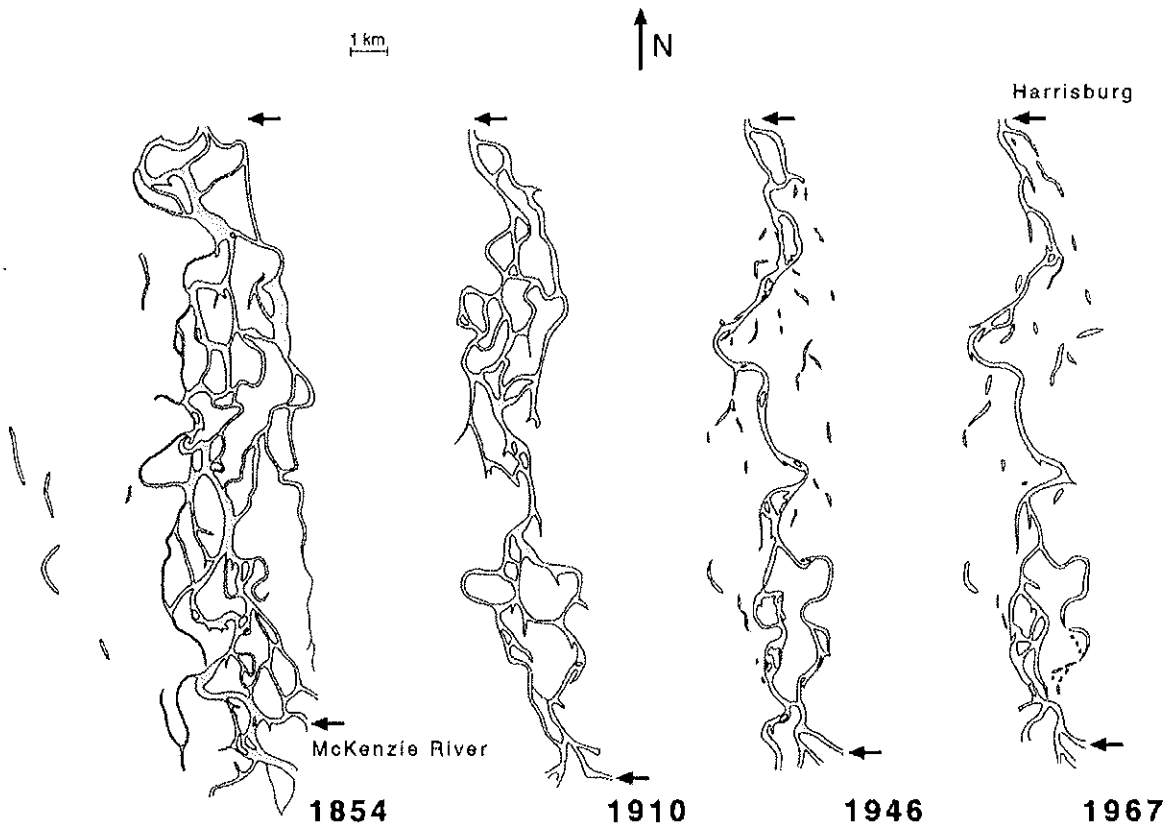


Figure 1.1 *The changing planform of the Willamette River 1854-1967 (reproduced with permission from Sedell and Frogatt, 1984).*

Clearance of wood from rivers has been undertaken with the following objectives: to maintain the capacity of river channels to transmit flood waters; to avoid blockage and damage to structures such as bridges, piers and weirs; to improve navigation; and to improve fish passage.

The adverse impact of woody debris clearance has been magnified by the widespread deforestation and drainage of floodplains and the engineering of river channels to completely new forms through straightening, dredging and bank stabilisation (Brookes, 1988; Petts, 1990). Such actions have led to far-reaching changes in the morphology, stability and ecology of river systems. Of particular relevance to the present discussion is that the research literature clearly demonstrates that the removal of debris dams is not consistent with the maintenance of a healthy aquatic ecosystem. Indeed, the contrary is true (Bisson *et al.*, 1987; Gurnell *et al.*, 1995; Piégay and Maridet, 1994, Sedell *et al.*, 1988). Woody debris has been shown to have at least three levels of important impact on woodland river environments:

- Woody debris directly affects the dissipation of river energy (Keller and MacDonald, 1995; Marston, 1982) leading to influences on the hydraulics of in-channel flows (Shields and Smith, 1992) and the distribution of overbank flows (Gurnell *et al.*, 1995); and thus on the transport and storage of sediments and organic material within the river channel system (Ehrmann and Lamberti, 1992; Mosley, 1981; Petersen and Petersen, 1991) and on the floodplain (Hickin, 1984). Comparative studies between streams where debris has been retained or removed, show that sediment yields can increase by an order of magnitude and enhanced sediment yields can persist in channels as a consequence of debris clearance (Heede, 1985; Smith *et al.*, 1993).

- Influences on flow hydraulics and sediment storage and transport lead to secondary impacts on the geomorphology of woodland river channels including the average condition and variance in channel dimensions (Hogan, 1986; Keller and Tally, 1979); the magnitude and distribution of pools and riffles (Bisson *et al.*, 1982); and the overall stability of river channels. Channels containing woody debris accumulations have a greater over-all stability, and physical habitat diversity (both within and between debris accumulations) than those without debris (Gregory and Davis, 1992; Marzolf, 1978).

- River channels containing accumulations of woody debris store and transmit sediments, including organic material (Bilby and Ward, 1991), in a well-regulated manner. The well-regulated storage, break-down and release of organic matter provides temporally- and spatially-regulated food sources for aquatic biota (Anderson and Sedell, 1979; Bilby and Likens, 1980). The complex physical structure of woodland river channel networks and their floodplains provides a variety of habitat patches which can support a wide variety of organisms at different stages of their life cycles. As a result, the removal of woody debris has been observed to cause a reduction in the diversity, density and/or biomass of invertebrates and fish (Benke *et al.*, 1985; Lestelle and Cederholm, 1984; Smock *et al.*, 1985, 1989, 1992).

2. SPATIAL PATTERNS IN THE SIZE AND CHARACTER OF WOODY DEBRIS ACCUMULATIONS

The river and its associated floodplain is affected by longitudinal, lateral and vertical process gradients (Amoros *et al.*, 1987). This section appraises the degree to which the character of woody debris accumulations may reflect or impact upon such gradients.

Church (1992) provides a morphological classification of river channel types within three longitudinal groups: small, intermediate and large channels, where channel size reflects the ratio of channel to boundary particle size. Fluvial processes and geological constraints determine the

morphology of large rivers, whereas within the range from intermediate to small channels, secondary factors, particularly individual roughness elements such as rocks and pieces of wood become increasingly important influences on channel morphology. Church (1992) explicitly discusses the role of woody debris in the morphodynamics of small and intermediate channels. Furthermore, the ecological significance of longitudinal gradients, and the important role of woody debris, is encapsulated in the River Continuum Concept (RCC: Vannote *et al.*, 1980) which identifies some broad characteristics of lotic communities related to three groupings of stream size, which are similar to those identified by Church (1992): headwaters (stream orders 1-3); medium-sized streams (orders 4-6) and larger rivers (order >6).

The amount of woody debris within a river channel reflects the balance between local inputs, imports from upstream, exports downstream, and decay. Keller and Swanson (1979) review such mechanisms and show how local input decreases in importance and imports from upstream become more important in a downstream direction. The resulting debris budgets have differing downstream trends with an increase in the mass of woody debris per unit area of channel being observed in a downstream direction in low gradient channels (Benke and Wallace, 1990; Gregory *et al.*, 1993; Robison and Beschta, 1990b) and a decrease in high-gradient channels (Keller and Tally, 1979; Lienkamper and Swanson, 1987). There are two important thresholds in the form of woody debris accumulations in the downstream direction, which approximately correspond to the boundaries between the three longitudinal river types described above. The first occurs in the zone where the river becomes competent to transport (float) a reasonable proportion of the debris supplied to it - this marks the transition between mainly randomly-distributed debris pieces, and the accumulation of debris into dams, whereby smaller pieces float and accumulate behind larger less-mobile pieces. As the channel width increases, an increasing proportion of the debris pieces become mobile, so that the dams of debris become larger and more widely spaced. The second threshold occurs where the river channel width increases beyond the size of the major debris pieces so that cross-channel dams are less likely to occur, and debris accumulations are mainly distributed longitudinally along the channel margins.

The RCC was extended by Sedell *et al.* (1989) to incorporate the lateral dimension, particularly in the case of large rivers where the ratio of floodplain width to river channel width may be large, and where interaction between river and floodplain may be complex and geomorphologically and biologically significant. Hickin (1984) observed the important role of woody debris in this lateral dimension through the vertical development of mid-channel and scroll bars, the process of chute cut-off, the closure of channels around islands, and the acceleration of the development of concave bank benches. These observations coupled with the great variety of river channel types defined by Church (1992) within his 'large channel' category, and the variability in the nature and extent of channel dynamics within each type, emphasises the importance of considering the geomorphological style of the river channel (i.e. the lateral dimension) in relation to the character and mobility of coarse woody debris.

Piégay and Gurnell (submitted) consider the relationship of river geomorphological style with woody debris accumulation character and dynamics. Larger rivers have a greater ability to transport woody debris downstream and onto the floodplain during overbank events. In the case of some French braided rivers, the riparian margins mainly consist of pioneer vegetation, restricted in its development by frequent floods. Such margins are unable to supply large amounts of dead wood and are also unable to retain pieces of wood which are in transit because of the low trap efficiency of the channel and the lack of secondary channels narrow enough to stop the transit of wood. Thus, debris jams are extremely rare and two main types of dead wood

have been observed: open jams of branches and broken or isolated logs in the active channel zone; and a discontinuous line of woody debris located on eroded, forested banks. In the active channel, dead wood can provide locations for sedimentation and stabilisation of gravel bars (Malanson and Butler, 1990; Nakamura and Swanson, 1993; Robison and Beschta, 1990a). The discontinuous line of debris exists only sporadically and represents a relatively low mass of debris in comparison with the mass accumulated within the active channel zone. In some larger wandering rivers, the sites for preferential deposition of woody debris are situated along the floodplain and not within the active channel. Debris is continuously supplied by erosion of the river banks. The wood is deposited at the edges of the main channel and along the axes of overbank flows within the forest. Debris deposition occurs as log jams which form a more or less continuous debris line. The total mass of debris is considerably higher than that observed in braided river courses.

The vertical dimension emphasises the important exchanges that occur between the alluvial aquifer and the river system. In small to medium sized rivers, and in the side-channel and backwater areas of large river systems, accumulations of woody debris cause (i) local ponding of water within the channel system, which must be associated with complex local channel - bank - bed seepage, and (ii) sites of flow avulsion onto the floodplain, which must impact on the spatial distribution of river - aquifer hydrological interactions across the floodplain. To the author's knowledge, there is no published research on this aspect of the influence of woody debris, although it is highlighted as one of four important future research directions by Swanson and Franklin (1992).

3. SIGNIFICANCE OF WOODY DEBRIS FOR RIVER-FLOODPLAIN PROCESSES

3.1 Permanence of debris accumulations

North American research has indicated that debris dams in rivers within mature, relatively-undisturbed forests may have residence times as long as 200 years (eg Keller and Tally, 1979) and that woody debris pieces are surprisingly stable (eg Benke and Wallace, 1990). In contrast, Evans *et al.* (1993) and Gregory *et al.* (1985) conclude that there is a dynamic equilibrium in the number and types of dam present in their study streams in New Zealand and in the New Forest, southern England, and stress the mobility of individual wood pieces and the variability in the location and/or classification of specific debris accumulations. The explanation for these differences probably lies in the size of debris in unmanaged and managed forest rivers. Certainly, wind-blown debris was shown to be extremely mobile within a New Forest river immediately after channel clearance of large debris pieces (Gurnell and Gregory, 1995). Hogan (1986) concluded that logging decreases the proportion of large debris pieces entering the river system and increases the proportion of smaller (floating) pieces. As a result, there is a change in the size-distribution and orientation of stored debris, with an increase in debris pieces oriented parallel to the flow in logged channels in comparison with unlogged channels, where debris is frequently oriented perpendicular or diagonal to the flow direction. As a result, debris accumulated in larger, less-stable dams in logged channels in comparison to unlogged channels. Effective management of debris should, therefore, depend on identifying and preserving rather than removing large stable debris pieces, since these have the ability to trap and stabilise smaller debris pieces. Large debris removal is likely to result in the increased mobility of the small debris delivered from managed woodland, which may then accumulate in large unstable dams.

3.2 Hydrological and hydraulic effects

Debris clearance is frequently justified on hydraulic grounds, since the debris represents a major roughness element in the river channel which is thought to increase the frequency of overbank flows. Such an hydraulic impact could, however, be seen as an advantage in attenuating the downstream passage of floods. Furthermore, flume experiments have shown that although the hydraulic effects may be severe at low flows, they become less significant at high flows. Indeed, Young (1991) concluded that the amounts of debris found in lowland Australian rivers would seldom have a significant impact on flooding, and that when a problem did arise, reorientation would be preferable to removal.

There is no doubt that debris accumulations impede low to medium flows, producing a step-pool sequence in smaller rivers, and a variety of plunge-, marginal and backwater pool habitats in medium-sized rivers (Bisson *et al.*, 1987). This is advantagous in maintaining and enhancing pool areas (MacDonald *et al*, 1982), and in causing local variations in bank hydrology (Gurnell and Gregory, 1987) during low to medium flows. The attenuation of low to medium flows and the enhanced interaction with the alluvial aquifer may have very important impacts on water quality as well as on the hydrology of the river system. Debris accumulations also dissipate the river's energy at specific locations, resulting in the development of plunge pools and local sorting of bed material in small rivers and the development of marginal scour zones limited by debris ribbons in larger rivers (Piégay and Gurnell, submitted).

3.3 Attenuation of the transfer of sediment

The impact of debris accumulations on sediment storage in small to medium-sized rivers is particularly important from both a channel management and an ecological perspective. Keller and Tally (1979) estimated that 30% and 40% channel area in Prairie Creek and Little Lost Man Creek, respectively, were zones of woody-debris controlled, sediment storage. Megahan (1982, cited in Bilby, 1985) estimated that 49% of total sediment storage in seven Idaho streams was debris associated. Mosley (1981) showed how debris-associated sediment storage attenuated the transfer of sediment downstream. Even when dams collapsed, the sediment only moved a short distance before being deposited. Clearly this is not the case in the catastrophic debris torrents which have been observed in North America, but these are associated with extreme hydrological conditions and very steep watersheds. Therefore, from a channel management perspective, woody debris accumulations can play an invaluable role in regulating sediment transfer from headwater streams and thus reducing downstream gravel accumulation problems.

From an ecological perspective, the role of woody debris accumulations in trapping organic material is particularly important. Twigs and leaves can be broken down in an attenuated manner to act along with the woody debris as a food source for aquatic organisms throughout the river system.

3.4 River channel character and dynamics

The dynamics of small to medium sized rivers can be strongly affected by debris accumulations. Not only is the physical diversity of river channels greatly enhanced by the presence of debris, but the dynamics and character of the channel planform is also affected. During high flows, major dams can become the sites of flow avulsion onto the floodplain. If the dams are particularly efficient at ponding back the flow, they can become semi-permanent sites of flow diversion where new channels can be cut. Gurnell *et al* (1995) identified three classes of

channel controlled by debris accumulations in a small river system in the Rocky Mountains: perennially-flowing channels; intermittent channels that were well-defined, clear of vegetation and occupied throughout the snowmelt season; and poorly-defined, vegetated, ephemeral channels, which were occupied during particularly high-flow events. Some of the ephemeral and intermittent channels contained debris dams in addition to those located in the perennially-flowing channel. These additional 'floodplain' dams provided sites where pools of water could be retained after the recession of the hydrograph. This patchwork of river channels and pools provides a variety of hydrological regimes within which different organisms can develop at different stages in their life cycles.

4. WOODY DEBRIS, RIVER CHANNEL AND FLOODPLAIN MANAGEMENT

Woody debris has been shown to play a critical morphological and ecological role in pristine rivers within forested river corridors. It has also been shown to make a major contribution to the management of bedload and suspended sediment movement, and it may also be significant for water quality management. Therefore, the reappearance of woody debris in heavily-modified British rivers could be seen as a significant step in river restoration and enhancement.

In addition to the many advantages that accrue from the retention of woody debris accumulations, this paper has shown that woody debris removal is unlikely to meet the criteria that have been used to justify it:

- *Transmission of flood waters.* Woody debris is not as serious a problem as might be thought, and can be seen as a flood management tool if retained in areas of flood storage. The dynamics of debris and its role in enhancing flood risk varies with the type of river and with the nature of floodplain land use. Thus a flexible approach to CWD management is required to maximise environmental benefit and minimise associated risks. Selective removal in response to carefully established guidelines is an appropriate management strategy.

- *Blockage and damage to structures such as bridges, piers and weirs.* Removal of stable woody debris may actually make this problem worse. Once more, selective removal under carefully constructed guidelines is an appropriate strategy.

- *Improvement of fish passage.* Research in North America has shown that woody debris only causes problems for fish when very large accumulations include a substantial proportion of fine debris from logging operations. Otherwise, woody debris accumulations do not adversely affect fish passage. Furthermore they have the positive impacts of providing cover from predators, a variety of in-channel and floodplain habitats for different life-cycle phases, and additional and varied food sources which together enhance the fish population.

- *Improvement of navigation.* This is the one area where debris removal has undeniable advantages.

New guidelines are needed for woody debris management based on three groups of factors: flooding vulnerability; ecological criteria; and economic criteria. In general, the ecological gains represented by retention and the significant costs involved in removal imply that minimal removal is the best strategy.

As a first step in refining the management of woody debris, Piégay and Gurnell (submitted) suggested that guidelines should relate to river size. In small streams, where the length of trunks is frequently greater than the channel width and thus the hydraulic impact of the debris is at a maximum, removal of large debris pieces at locations where flooding has significant economic consequences is highly cost-effective. In larger rivers retention of debris is not only of ecological and economic benefit, but it provides a buffer to the movement of debris pieces rather than allowing them to move freely downstream to accumulate at more flood-sensitive sites. In larger rivers debris is unlikely to create major obstructions to flow and so does not represent a significant influence on floodplain inundation frequency except where structures such as narrow bridge openings and weirs impede the transfer of the debris. At these locations removal is highly beneficial to flood alleviation, but elsewhere debris should be left because its environmental benefits and high removal costs heavily outweigh any small hydraulic benefits.

One final topic, which deserves consideration here is the reinstatement of floodplain forests (eg Peterken and Hughes, 1995). Such reinstatement has many environmental and economic benefits. Reinstatement of rivers running through these forests should also be a major aim and should principally be directed at re-establishing the interaction between the river and its floodplain. Woody debris plays an essential role in ensuring that such reinstatement is sustainable in the medium to long term, since its hydraulic effects ensure that even in low-energy environments, the dissipation of that energy is concentrated so that channel adjustment can be naturally (if slowly) achieved.

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2

Investigations into hydrological influences on the establishment of riparian tree species

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Abstract

In order to study the hydrological influences which affect the regeneration of early successional woody riparian species in a series of floodplains in the Rhone River basin, France, three approaches have been used and integrated. These include (i) field monitoring of water table response to different channel flows and associated vegetation studies of seedling regeneration and establishment, (ii) laboratory experiments using specially constructed apparatus to subject seedlings to artificially controlled water table regimes and (iii) numerical modelling to simulate the available soil moisture in the unsaturated zone in both the field and laboratory experiments. Results indicate that it is possible to define the moisture needs of individual species in their establishment phase and to identify at what channel water stages these moisture conditions occur in the adjacent floodplain sediments. It is suggested that development of the approach used here could have a useful input to flow management for riparian ecosystems.

1. INTRODUCTION

An understanding of the interactions between river hydrology and geomorphology and the regeneration of floodplain vegetation is critical to the success of any river restoration initiative. Many different approaches to river restoration have been suggested, ranging from complete restoration which involves structural and functional return to a pre-disturbance

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state, through partial rehabilitation to abandonment of cases for which recovery is deemed improbable (ECON, 1993; Boon, 1992). In all projects hydrological considerations are the most important design elements, because flooding and water table recharge patterns, along with the associated nutrient additions to the floodplain, will fundamentally affect the success of the restoration initiative.

Where floodplain restoration is not possible or indeed not necessary, there is considerable interest in the ways in which flows are allocated to different uses. In different river basins the potential users of river water vary greatly but, until recently, most consideration has been given either to the need to abstract water for industrial, domestic and agricultural use, or for the needs of instream species of fish and aquatic plants. It is only since the interest in floodplain habitats and their restoration has developed that the water needs of riparian species have been seriously considered within the context of river flow allocation. For example, in the Kruger National Park in South Africa, a methodology is being developed which is intended to accommodate the water rights and demands of riparian ecology (Moon *et al.*, in press). However, the problem is more complex than an identification of the total water needs of riparian vegetation. In order to maintain existing and restored floodplain vegetation communities and to ensure their long-term regeneration, it is also important to determine optimal magnitudes, frequencies, durations and timings of flow favoured by individual species. In the case of most riparian tree species with life cycles of at least 100 years, while minimum flows are necessary for their maintenance once established (Stromberg and Patten, 1990), varied intra-annual, inter-annual and inter-decadal flows are necessary to meet particular life-cycle needs, particularly at the regeneration and establishment stages. These long-term flow sequences are also key determinants of the process of community succession (Pautou and Décamps, 1985; Bradley and Smith, 1986; Baker, 1989; Virginillo *et al.*, 1990; Hughes, 1994).

The means of allocating flows for riparian species as opposed to instream species remains little studied. This is in large part because riparian vegetation patterns have to be defined and explained in terms of the changing and complex interactions between river flows, water table recharge and available soil moisture, the competition for above and below-ground resources between different species and the geomorphological changes that occur over the lifetime of individual plants because of erosion, deposition, channel migration and associated substrate changes. Interpretation of vegetation patterns and the habitats occupied by different species over the life-cycle of most riparian trees is further complicated by the many human-induced changes to rivers over the same time-period (Pautou and Arens, 1994; Hughes, 1994), and to historical floodplain land use (Girel, 1994). There is a great need for detailed definition of the optimal habitats of many riparian vegetation species, and for the incorporation of this information into models of floodplain response to changing inputs of water, sediment and nutrients. Several researchers are currently devising models (often reach-based) which will allow prediction of changes in different river reaches in response to changing water and sediment availability. Some concentrate on minimum flows for maintaining channel form, and predict changes in the absence of those minimum flows (for example, King and Tharme, 1994; Moon *et al.*, in press). However, in order to include vegetation changes within such models, and to define both minimum and optimal flows for riparian vegetation communities, further detailed research on target species is essential.

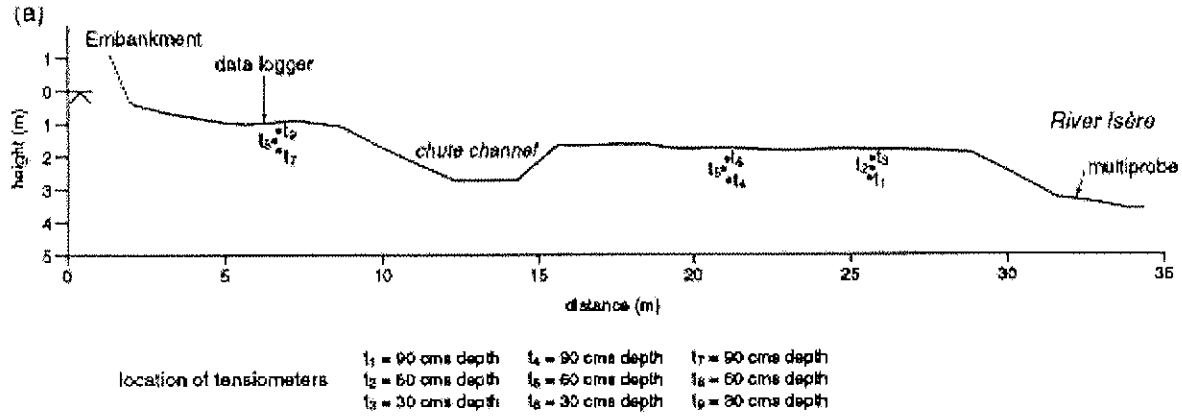
2. RESEARCH METHODS AND RESULTS

In the study decribed here, a combination of three approaches (field monitoring, laboratory experiments and numerical modelling) have been used to obtain the baseline information necessary to identify the needs of floodplain vegetation, and to develop ideas for the management of floodplain ecology. The field investigations reported here were carried out in two tributaries of the heavily-managed and channelized Rhône River basin (the Isère and the Drac) in the French Alps and consisted of detailed field measurement of watertable response to different channel flows, and associated vegetation studies of seedling growth and spatial patterns of vegetation in relation to substrate and soil moisture conditions. This research was supplemented by experimental 'laboratory' research carried out in greenhouses, which involved subjecting selected riparian tree species from the field area to different water table conditions in a controlled situation. Finally, a numerical groundwater flow model capable of dealing with saturated-unsaturated flow conditions was used to simulate the available soil moisture in the unsaturated zone in both the experimental studies and the field floodplain sites. Success in simulating the critical soil moisture conditions in the laboratory and field cases then justifies use of such a model to extrapolate to field conditions with different morphologies and sedimentologies, although there remain difficulties associated with appropriate measurement of soil physical properties (common to most physically-based hydrological modelling).

2.1 Field monitoring

The field installations designed for this research project involved transects of tensiometers similar to those described by Dowd and Williams (1989). The transducers were connected by cable laid in underground pipes to a multiplexer and data logger installed in trees above flood level. Figure 2.1a illustrates in section the arrangement at the site on the River Isère; this is similar to that installed on the Drac. The Isère site consists of a patch of incipient floodplain about 15m wide and 100m long in the form of a linear, detached bar developing within a channelized reach 15km north of Grenoble, with a chute channel between it and a narrow (5m) strip of floodplain at the foot of the embankment (Figure 2.1b). In addition to the three sets of three tensiometers, water level recorders were installed in the main and chute channels, and other parameters were monitored including temperature and specific electrical conductivity.

The sediments at the Isère site are sandy silts extending to a depth of 1-1.5m, where channel gravels are encountered. Between the basal gravels and sandier surface deposits, the material is uniformly silty but with a general upwards fining. The surface sands were deposited by over-bar flows during the study period. Resurveys in December 1993 and December 1994 revealed significant average aggradation of 0.40m. The topographical data for the site have been combined with water level and discharge data to create a model of the spatial variation in depth and the extent of flooding across the site between January 1994 and August 1995; during June 1994 the bar was completely submerged for a period of 9 hours during a major flood, and partially submerged for over 48 hours. Data collected on suspended sediment transport during this high flow period demonstrate very high concentrations (6.1-11.2 gm./l), giving a deposit of 0.20-0.30m in less than 10 hours at the site.



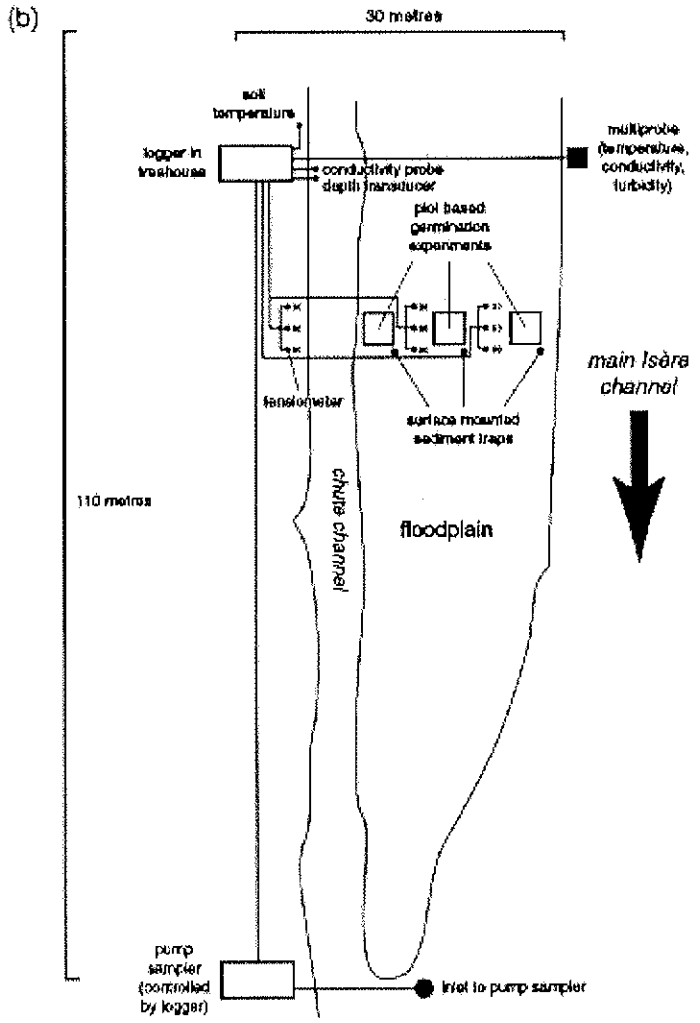


Figure 2.1 *(a) Instrumentation at the Isère site, showing the tensiometer transect (b) A plan view of the Isère site, showing the bar and chute channel*

Figure 2.2 shows the relationship between the main channel water level and the water pressure and tension recorded during the latter half of June 1994 (including the flood on 26-27 June) by the three tensiometers in the centre of the island. As expected, during the low flow period prior to the flood, the tensiometers at depths of 0.30 and 0.60m record suctions,

which vary in relation to fluctuations in water level (which are here frequent and rapid because of releases from hydro-power reservoirs, and of the order of 0.50m). The deepest mid-bar tensiometer, however, displays positive water pressures indicating a water table at elevations of about 0.20-0.30m above the tensiometer (elevations of about 0.80-1.00m, consistent with the water levels in the channel). Although the conditions are dry in most of the upper soil column, this indicates a close relationship between the groundwater levels and those in the main channel. This is reinforced by the evidence of close correlation in the fluctuations of water level in the channel and in the soil moisture status, the latter being more damped towards the surface of the sediment column. During the flood, the water pressures recorded at each piezometer (tensiometer) are consistent with their different elevations, and soil saturation is maintained during the recession period below 0.30m although the period of saturation above this is only about 36 hours.

The water table variations identified in the data from the Isère site (Figure 2.2) suggest rates of water table lowering during periods of low river water level of between 1.5cm/day and 7.5cm/day, presumably in part associated with evapotranspiration losses. Rates of drawdown of up to 25cm/day occur during the early phase of hydrograph recession as the river water level drops. Rates comparable to the former (up to 3.0cm/day) were employed in experimental studies of the effects of moisture availability on rates of seedling growth.

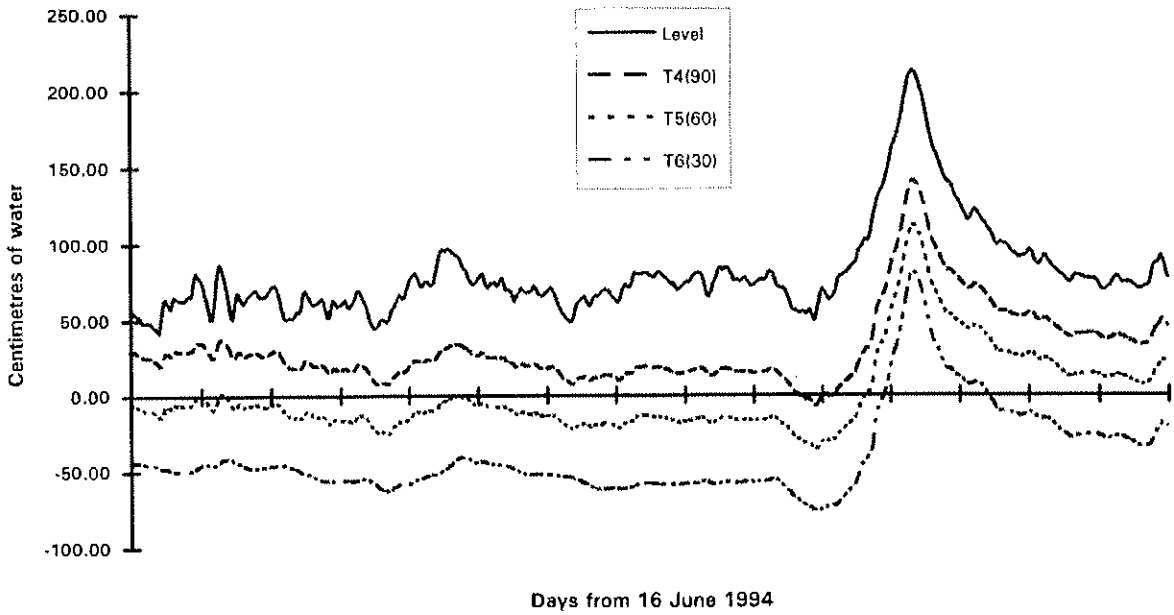


Figure 2.2 *Water level variations in the Isère in the second half of June 1994, and water pressure and suction variations monitored by the mid-bar tensiometers at 90cm, 60cm and 30cm beneath the surface*

2.2. Greenhouse experiments

The greenhouse experiments (Hughes *et al.*, in press) were designed to study the response of early successional woody riparian species to different soil moisture conditions, and were initially carried out on *Alnus incana* (L.) Moench, the European grey alder. The apparatus used in the experiments is based on a design by Mahoney and Rood (1991), and is referred to

as a "rhizopod". Each rhizopod consists of a central water well connected to 16 growth tubes 1.2m in height and filled with sediments collected in the field. In the experiments conducted on *Alnus inacana*, each of five rhizopods had eight growth tubes filled with fine sandy silts from the Isère River and eight growth tubes filled with coarse gravelly sands from the Drac River. The stratigraphy of the field sites was recreated in the rhizopod tubes By varying the water levels in the central water wells, it is possible to provide different water table conditions for plants growing in the side tubes of a set of rhizopods. The drawdown rates applied to the five rhizopods were 3cms/day, 3cms/day plus a weekly application of 1cm rainfall, 1cm /day, 0.5cm/day and 0cm/day. During the 155 days of the experiment, measurements were made to monitor the growth and health of the alder seedlings, including shoot height, leaf number, leaf length and leaf health. Leaf area, shoot weight, root weight and the weight of nitrogen-fixing nodules were measured at the end of the experiment; root length was measured at the start and maximum root depth at the end of the experiment. In two of the rhizopods (those with water decline rates of 1 cm/day and 3 cm/day) soil suction readings were logged automatically using tensiometers inserted in selected growth tubes.

Average shoot growth rates of the *Alnus incana* seedlings are plotted in Figure 2.3. These results indicate that better performance occurs in seedlings grown in the finer-grained and generally more moist Isère soils, although this only becomes noticeable after about 50-60 days. In the coarse Drac soils, growth rates are very low throughout the experiment in the rhizopod experiencing the 3cm/day drawdown regime, and for the first 70 days in soils experiencing no drawdown except through evapotranspiration. Seedlings also show high mortality rates in the soils experiencing rapid water table drawdown. All rhizopods have high initial water tables and, and it is noticeable that seedling growth rates are low at the start of the experiment, but accelerate once the upper parts of the soil profiles have drained. This suggests that both drought and waterlogging inhibit growth. In the finer Isère soils, *Alnus incana* seedlings in the slowest draining soils (0 cm/day) performed least well while the fastest draining water regimes promoted the best growth in the experiment (both 3 cm/day and 3 cm/day plus 1 cm/week of rain).

The experimental work has allowed identification, initially for *Alnus incana,* and more recently for *Populus nigra,* critical soil suctions in the two different alluvial sediment types. In the coarser Drac soils, once the suction becomes greater than around 60-70cm of water (equivalent in this soil to a moisture content of $<0.10 cm^3\ cm^{-3}$) in the rooting zone, seedlings become drought stressed and growth tails off. Critical suctions were rapidly reached when water table drawdown rates were ≥1cm/day. In the field these drawdown rates are frequently experienced on the Drac because of the operation of hydroelectric reservoirs, and relatively localized fine-grained sites are the only ones able to support regeneration of this species. By contrast, in the Isère soils, drawdown rates of 1cm/day and 3cms/day gave ideal soil moisture conditions. Soil suctions in these treatments were of the order of 80-110 cms of water in the rooting zone but were associated with moisture contents of between 0.25 and 0.40 $cm^3\ cm^{-3}$ in the different layers of this fine-grained sediment stratigraphy.

These suctions and soil moistures occur in the field for quite long periods from August until March; furthermore, Figure 2.2 illustrates that even in the growing season in June, when river levels are higher, such suctions occur in the upper 0.50m of the soils in the Isère bar. However, during the critical seedling establishment period (May to July), conditions at this site become saturated during floods. The rhizopod experiments demonstrate an intolerance by *Alnus incana* to such conditions, with lower growth measurements in all seedlings grown in the moister regimes. In fact, regeneration of *Alnus incana* has been recorded only on the

highest parts of the Isère field site and at low densities (12-150 individuals per $100m^2$), despite an abundant supply of seed from adjacent trees. It seems likely that unfavourable soil moisture conditions during the first weeks following germination are a contributory factor.

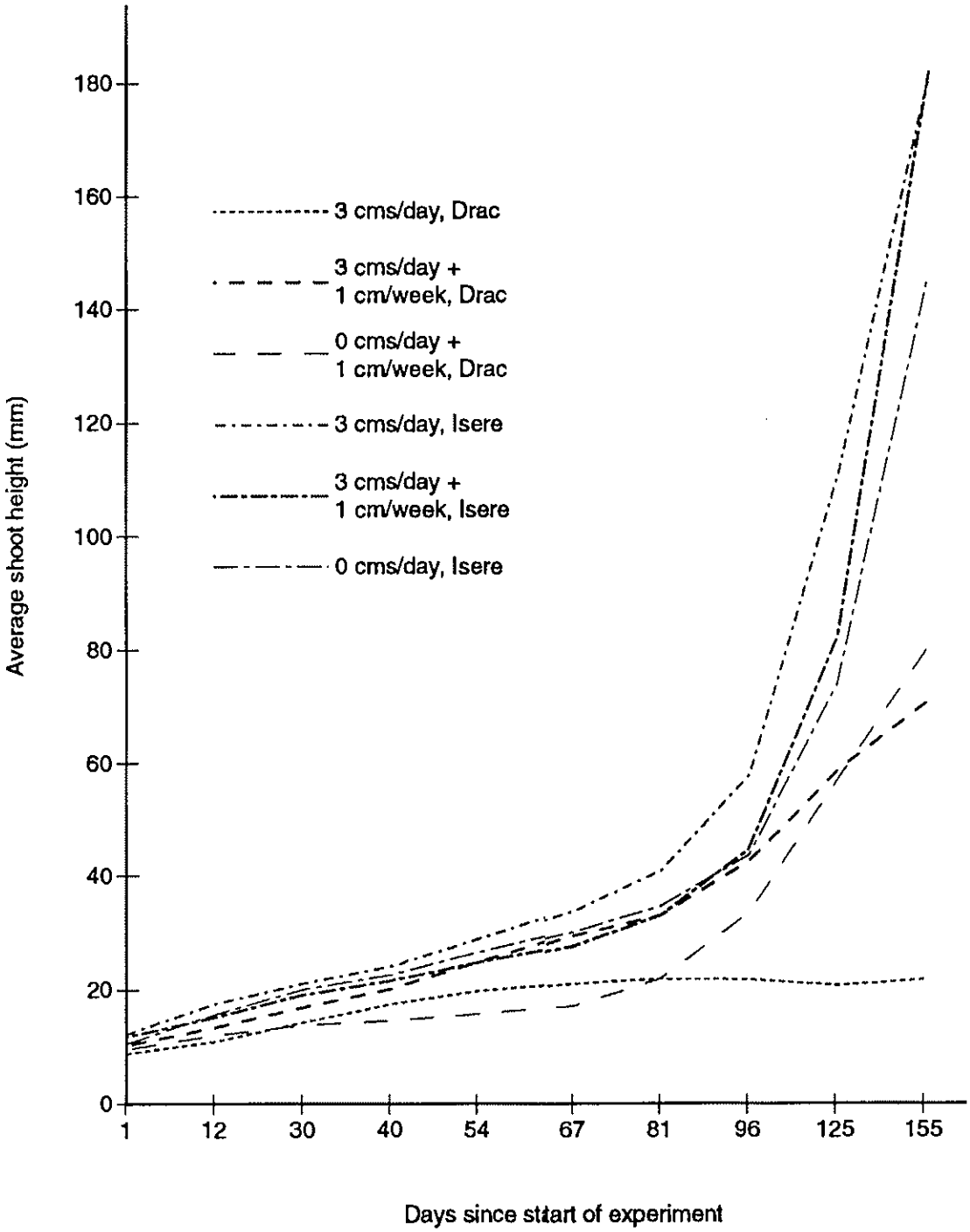


Figure 2.3 *Experimental results showing shoot growth by* Alnus incana *under three water table regimes in two different sediment types (from the Isère and Drac field sites)*

2.3 The numerical simulation of soil moisture variation in floodplain sediments

An infiltration model was developed to simulate water table and soil moisture changes in both the rhizopods and the floodplain cross-sections. The purpose of developing such a model was twofold. It was anticipated, firstly, that it would provide soil suction data that are more relevant to the plant physiology than are water table levels alone, and that it would provide more detailed information on the distribution of suctions above the water table than could be gained using tensiometry. Secondly, the model would provide a physical basis for extrapolation, through which information about water tables and soil suctions could be gained at other locations of interest for which the topography and soil properties could be measured, but at which the installation of soil moisture monitoring equipment was impossible on cost and access grounds.

The model needed to be capable of dealing with an external water level control, such as an adjacent and variable river water level or a rhizopod reservoir water level, as well as with the ponded head of water that occurs during flood period recharge. It also needed to accommodate the typically stratified soils found in floodplain environments. The general flow equation for the unsaturated-saturated zone (the Richards' equation; Richards, 1931) is physically based, and although computationally demanding, it has been widely shown to be capable of providing realistic predictions of moisture distribution in complex soil profiles under the variety of boundary conditions likely to be encountered in these applications.

2.3.1 Initial testing of the models

An initial requirement after development of the 1-D and 2-D versions of the numerical model was to test it for efficiency and robustness, and this was undertaken using extreme cases from the literature (Hills *et al.,* 1989 and Warrick 1991), ranging from homogeneous soil with a high hydraulic conductivity, through ponded head examples, to simulations for stratified soils with from two to six layers (similar to the Isère and Drac cases). Boundary conditions ranged from very wet to very dry sandy soils, and included simulations comparable to the rhizopod or floodplain problems where an external water level control exists. There was good agreement between the published results and the output of the new model providing confirmation that the 1-D numerical solution of the Richards' equation and its computer implementation are reliable.

The robustness of the 2-D version of the model was also tested by applying it to the 2-D experiment conducted by Vauclin *et al.* (1979). In addition, the model was checked in terms of its ability to conserve mass. Comparison between this model's predictions and the published data are again in good agreement. This confirms the robustness of the model, and justifies its application to 2-D problems.

2.3.2 Application to the rhizopod case

Having confirmed the reliability of the model, it was first applied in its 1-D form to simulate soil moisture distribution in the rhizopods employed in the experimental greenhouse studies. As described above, these were designed to investigate the effect of moisture content on the growth rate of different plant species, but their scale allows only limited tensiometry and a

numerical model was considered to be a preferable means of describing the suction variation through the rooting zone.

Results were printed at 30 and 60 cm depths for the Isère soil and at 15 and 30 cm for the Drac soil, to allow comparison with suction values recorded by tensiometers installed at these depths in the greenhouse rhizopods. Results show good agreement between recorded and measured values in the Isère experiment (Figure 2.4). At 30 cm depth results diverge somewhat, but the general trend is satisfactory. Although this divergence amounts to 15 cm of suction, this is insignificant when converted to moisture content. Results for the Drac experiment at 30 cm were also acceptable, although an instability problem initially caused unrealistic behaviour in the simulations at a depth of 15 cm.

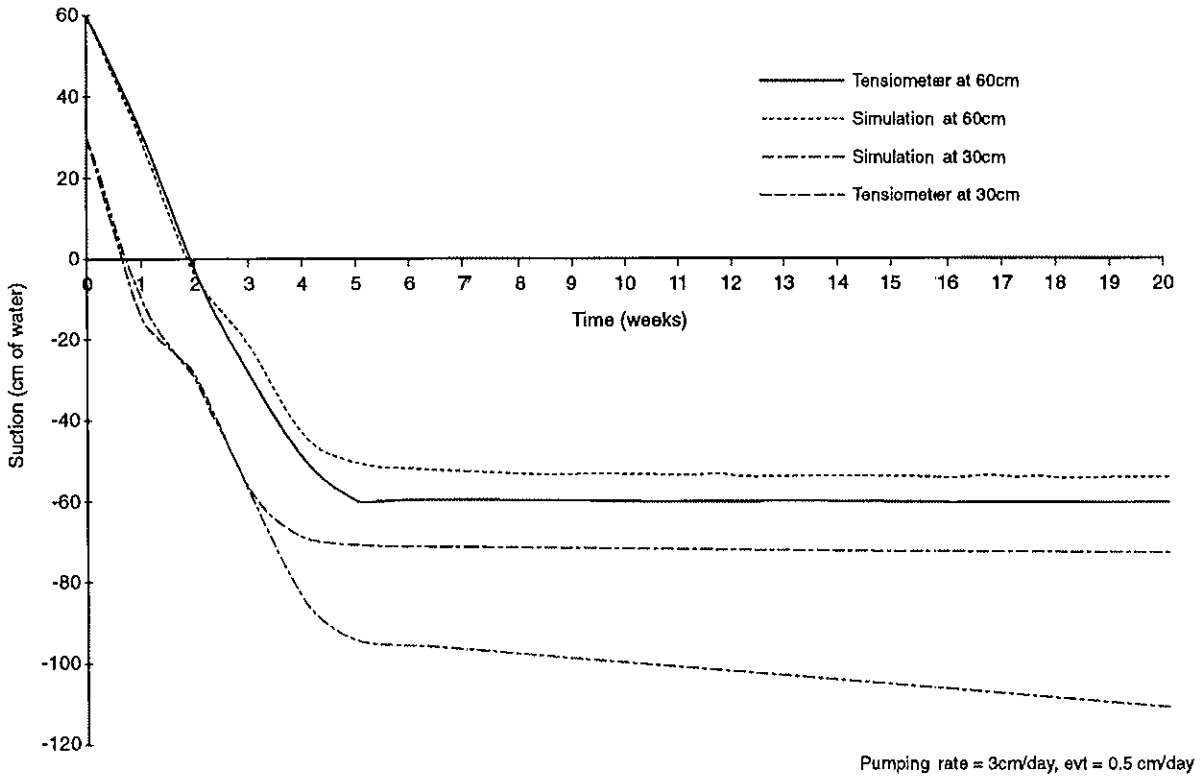


Figure 2.4 *Comparison between the tensiometer data collected during the rhizopod experiments for one soil column of Isère sediment, and simulated soil moisture variations (as suctions) for the same soil*

2.3.3 Application to the Isère cross section

One requirement of the 2-D version of the model was that it had to handle complex channel cross sections with breaks in the soil columns in both the horizontal and vertical directions. These breaks reflect the existence of channels, which may be occupied by either water or air (non-soil media). The model jumps across grid cells defined as containing water or air, but does not ignore their effect on any neighbouring soil cells. This method deals successfully with complex geometries, and results in a rapid solution. To test the model, the geometry of the Isère cross-section was approximated using a 50 cm (horizontal dimension) by 25 cm (vertical dimension) grid (Figure 2.5), resulting in a simulation cross-section 28.5m wide and 2.75m deep. Six soil layers, based on those for which field measurements had been made and

from which samples had been obtained in order to measure hydraulic conductivities and suction-moisture curves, were defined for the simulation (Table 2.1).

Layer	Thickness (cm)	Hydraulic Conductivity K_{sat} (cm min^{-1})
1 (Surface)	25	0.100
2	50	0.136
3	25	0.150
4	25	0.114
5	25	0.107
6 (Gravel)	75	0.694

Table 2.1 *The properties of soil/sediment horizons defined for the simulation of channel-groundwater coupling using the 2-D model*

Starting from a fully saturated initial condition and imposing the late June peak flood level shown in Figure 2.2, the model was used to simulate the drawdown of the water table in the bar sediments in response to the declining water level in the main and chute channels during the flood recession. This resulted in relatively rapid simulated lowering of the water table by about 20cm in the first 24 hours (largely because of evaporative drying at the surface), but then a much slower change which failed to generate soil water suctions at depths of 30 and 60 cm beneath the surface. A second simulation was undertaken with the initial condition being a water table level in the centre of the bar at about 90cm below the surface (Figure 5a), and moisture contents and suctions in the sediments above this at values indicated by the field tensiometers immediately prior to the flood event (Figure 2). The effect of the late June hydrograph on soil moisture was then simulated (Figure 5b, 5c, 5d).

The behaviour shown is more complex than that which occurs in a sandy gravel with a saturated hydraulic conductivity an order of magnitude higher, such as that at the sites studied on the Drôme and Drac rivers. Accordingly, it is evident that decisions about flow management for the riparian vegetation must be based on a proper understanding of the relationships amongst soil moisture, groundwater recharge, and river water levels in floodplains with different topographic and sedimentological characteristics. Whilst the model provides a basis for achieving this, and of identifying the wide range of floodplain soil moisture behaviour, it is not without its problems. Indeed, although both simulations described above are representative of cases that are likely to be encountered in the field, they do not replicate the Isère data (Figure 2) particularly well. Since the tests of the model were satisfactory, and it produces acceptable results in relation to the rhizopod data, it seems likely that the laboratory measurements of the soil moisture characteristics curves do not replicate well the field condition of the sediment, probably because the rapid deposition rate in the field results in low compaction and bulk densities by comparison with those employed in the laboratory experiments to measure the soil properties. This objective necessitates careful planning of the range of model cases, and rigorous sampling and measurement in order to calibrate the model for those cases.

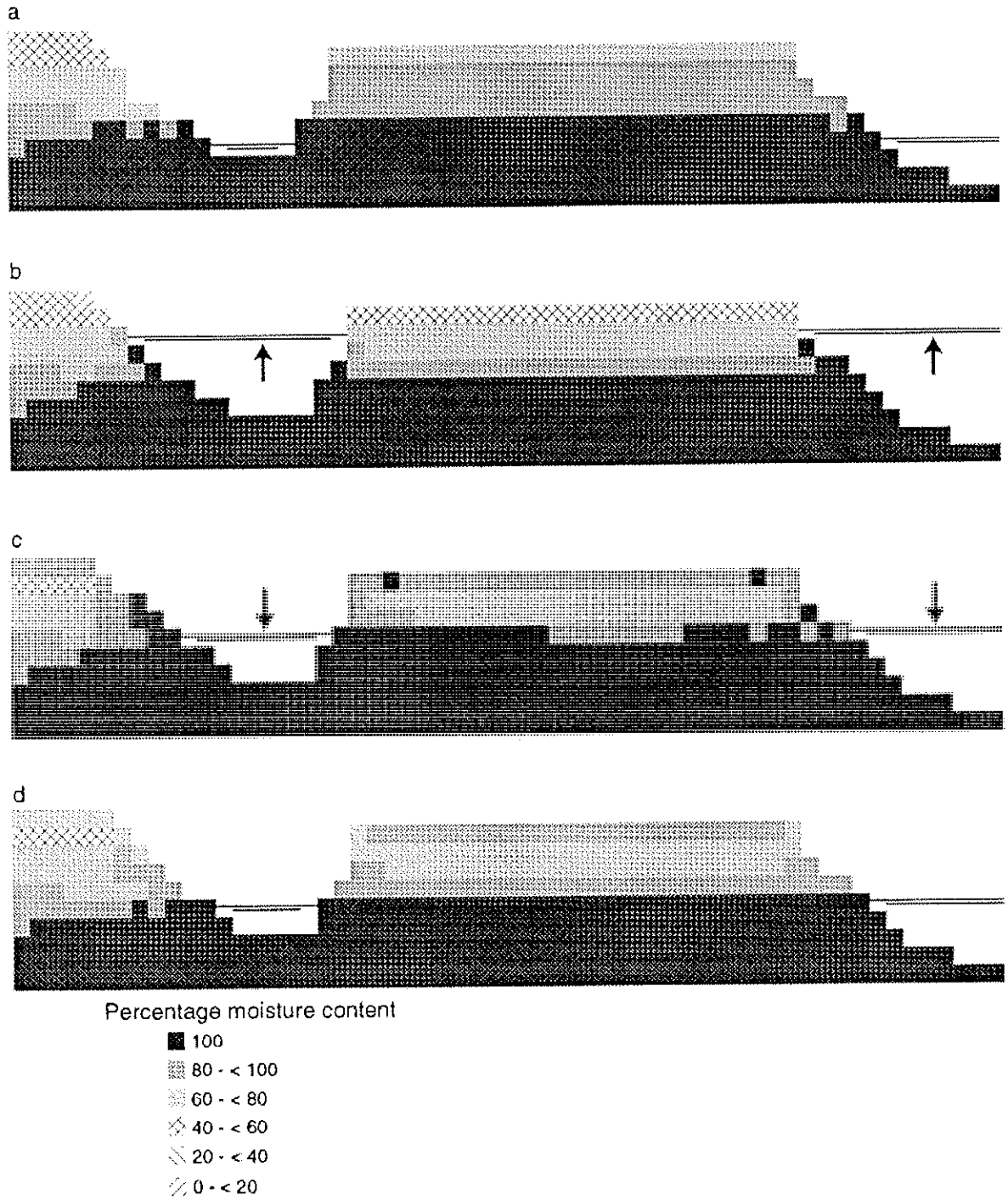


Figure 2.5 *Two-dimensional simulation of water table and soil moisture variation in the bar at the Isère site up to and after the flood peak experienced on 27 June 1994. The values mapped are the moisture contents as a percentage of saturated moisture content; (a) is at time t = 0 on June 26, (b) is at t = 24 hours on the rising limb of the hydrograph, (c) is at t = 48 hours on the recession limb of the hydrograph, (d) is at t = 96 hours*

3. DISCUSSION AND CONCLUSIONS

One interesting outcome of this research has been, for certain floodplain sediments, identification of the response of groundwater levels and soil moisture status to channel water levels. This makes it possible to match observed or simulated suctions to the limiting soil moisture conditions for seedling growth, and alone could represent a useful input to flow management by defining the timing and maintenance of stage changes for the purposes of encouraging the regeneration of riparian species. However, it is clear that in many cases a cost-benefit analysis of the value of water for various conflicting purposes is likely to prevent the option of reserving water for purely ecological purposes; it would be necessary to maintain particular patterns of water level change along considerable lengths of river reach in order to encourage germination and early growth of seedlings. In addition, creation of new sites suitable for regeneration of early successional species would require flood events capable of initiating geomorphological change through bank erosion, bar construction, channel migration, and spatially-varied deposition patterns. All of these processes are required in order to create new niches for colonisation in order to maintain ecological diversity, but in many cases are unlikely to be practically feasible components of river management. The results of this study, nevertheless, suggest practical options for river management that could exploit, firstly, an understanding of groundwater response to river level variation and the ecological impact of that response, and secondly, a recognition of the effects of local geomorphological conditions on the maintenance of conditions conducive to regeneration.

Acknowledgments

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3

Floodplain Vegetation and Sedimentation/Erosion

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Abstract

This paper briefly reviews methods of estimating overbank accretion rates and presents some preliminary data which suggests that plants may have an important, dynamic and non-linear role in the processes of floodplain deposition and erosion. Observations at two sites on the floodplain of the River Soar, Leicestershire have shown differences between overbank deposition and suspended sediment concentrations both within and between wooded and grassed areas. Flood deposition on both living and dead leaves varies with both location and species. Simple settling experiments in the laboratory suggest that both the quantities and form of on-leaf sedimentation varies with species and that it is an active process with leaves scavenging sediment from the water column. Further work is urgently required to measure the magnitude and constancy of these effects in order that they can be used in the management of water quality.

1. INTRODUCTION

Rates of overbank deposition are highly variable both floodplain to floodplain and within floodplain reaches. Post-flood observations have produced rates varying from practically zero to over 10 mm yr^{-1} (Bridge and Leeder, 1979, Simm, 1995). It is generally assumed that this variation is some function of distance from the channel, flow depth and sediment concentrations. Recent attempts to model overbank deposition have been based on diffusion equations which produce an exponentially decreasing rate of coarse-medium sand away from the channel and a slower linear decrease in fine sand (James, 1985; Pizzuto, 1987) and this has been substantiated by field observations (Marriott, 1992). However, the systematic measurement of overbank sedimentation is extremely difficult. Artificial turf mats produce estimates which vary from rather low values of 0.001-0.1 mm per event (Walling *et al.* 1986) to 0.1-10 mm yr^{-1} in the same floodplain reach of the River Culm in Devon (Simm, 1995), and it is difficult to compare these estimates to conveyance losses. In the same reach, estimates of floodplain accretion averaged over 35 years using the ^{137}Cs method show a comparable range of 0-7 mm yr^{-1} but with most of the floodplain experiencing a rate of only 0-4 mm yr^{-1}. Both

methods show high spatial variability related to micro-topography, distance from the channel and flow conditions. It is apparent that these rates cannot have been sustained throughout the Holocene since even a rate of 0.1 mm yr^{-1} would produce an overbank unit of 10m thickness which is over three times the observed thickness. Radiocarbon dating of overbank alluvial units shows that the rates are not linear and that variation occurs as catchment and floodplain vegetation changes (Brown, 1983a; Brown and Barber, 1985). The frequently observed inverse relationship of the overbank deposition rates to topography has been regarded as resulting from greater flow depths and competence; however there are also well known relationships between vegetation type and topography even within grassland ecosystems (Gowing and Youngs, Chapter 6 this volume) and the surface with which turbid flow interacts is in most cases entirely vegetated.

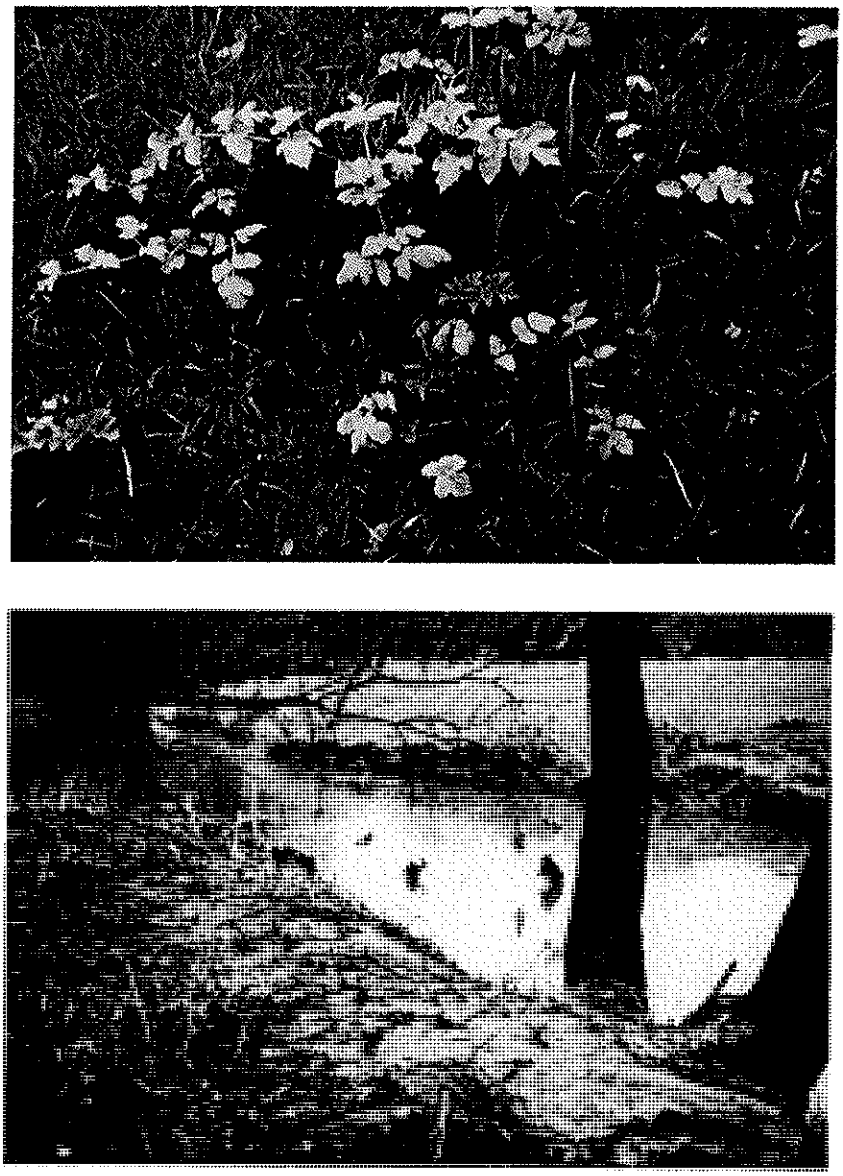


Figure 3.1 *Top: a veneer of sediment deposited on dicotyledonous plants in grassland after a flood on of the River Soar at Jubilee Park in 1993; bottom: a lobe of medium-coarse sand migrating from the channel after the same flood of the Soar at Narborough Bog in 1993*

Several workers have observed variations in local accumulation rates which seem to be related to vegetation variation. In particular after floods the authors have observed nettles (*Urtica dioica*) and other dicotyledonous plants covered in sediment adjacent to grass leaves with no visible sediment layer (Figure 3.1). There are also a number of studies which have pointed towards a relationship between sedimentation rates, sediment-form and grain size and vegetation (Anderson and Calver 1977; Brown, 1983a; Teisseyre, 1985). A flood on the River Stour in Dorset in 1980 deposited coarse sand flow-moulded mounds on the downstream side of dead tussocks of *Molinia caerulea* (Brown, 1983b). These mounds had a mean maximum height of 38 mm, a mean maximum width of 345 mm and a mean maximum length of 453 mm; when spatially averaged the equivalent depth was 2.1 mm. The mounds were within 100 m of the channel downstream of a flow constriction (bridge) and are typical of the high rates of sand deposition that occurs in the levee and crevasse-splay zones. The mechanism of deposition is that of the movement out of the channel of a bedload sheet of sand, which in cases of high overbank velocities is deposited preferentially in the dead zones downstream of obstructions. In some cases the mechanism can be observed such as where there is a depression in the channel bank and a sediment lobe with an avalanche face which has not been reworked by returning flow (Figure 3.1).

2. STUDIES ON THE RIVER SOAR

In order to establish the magnitude of any vegetation affects on overbank sedimentation, two sites were monitored on the River Soar in Leicestershire over the winter of 1993-1994. Although only 800 m apart, the sites are of different character. The upstream site, Narborough Bog is an area of semi-natural floodplain woodland with a reedbed underlain by peat, while the downstream site, Jubilee Park is an area of mown recreational grass with few obstructions to overbank flows. Both sites flood regularly, and there are no flood embankments along this reach. During autumn floods of it was noticed that deposition occurred on both living and dead leaves and so these were used as natural traps and collected after floods from seven sites at Narborough and eight sites at Jubilee Park. Rates were found to be very variable ranging from 0.5 mg cm^{-1} to 14 mg cm^{-1} and there was no clear pattern such as a decrease with increasing distance from the channel. The only statistically-valid difference (Mann-Whitney U test) was between living stinging nettles (*Urtica dioica*, mean 3.10 mg cm^{-1}), dead alder (*Alnus glutinosa*, mean 1.08 mg cm^{-1}) and birch leaves (*Betula pendula*, mean 0.16 mg cm^{-1}). Other than the highest rates being on the channel banks/levees, across the rest of the floodplain there was no decrease in sedimentation. This may be partially explained by spatial variations in suspended sediment. Whole water column sampling was undertaken during floods and this showed a variable spatial pattern during the flood with no decrease away from the channel but greater variation at Narborough Bog than at Jubilee Park (Figure 3.2). This suggests either that the overbank flows are either not completely mixed or that there is an interchange between the flow and the floodplain surface which is altering the suspended sediment concentration.

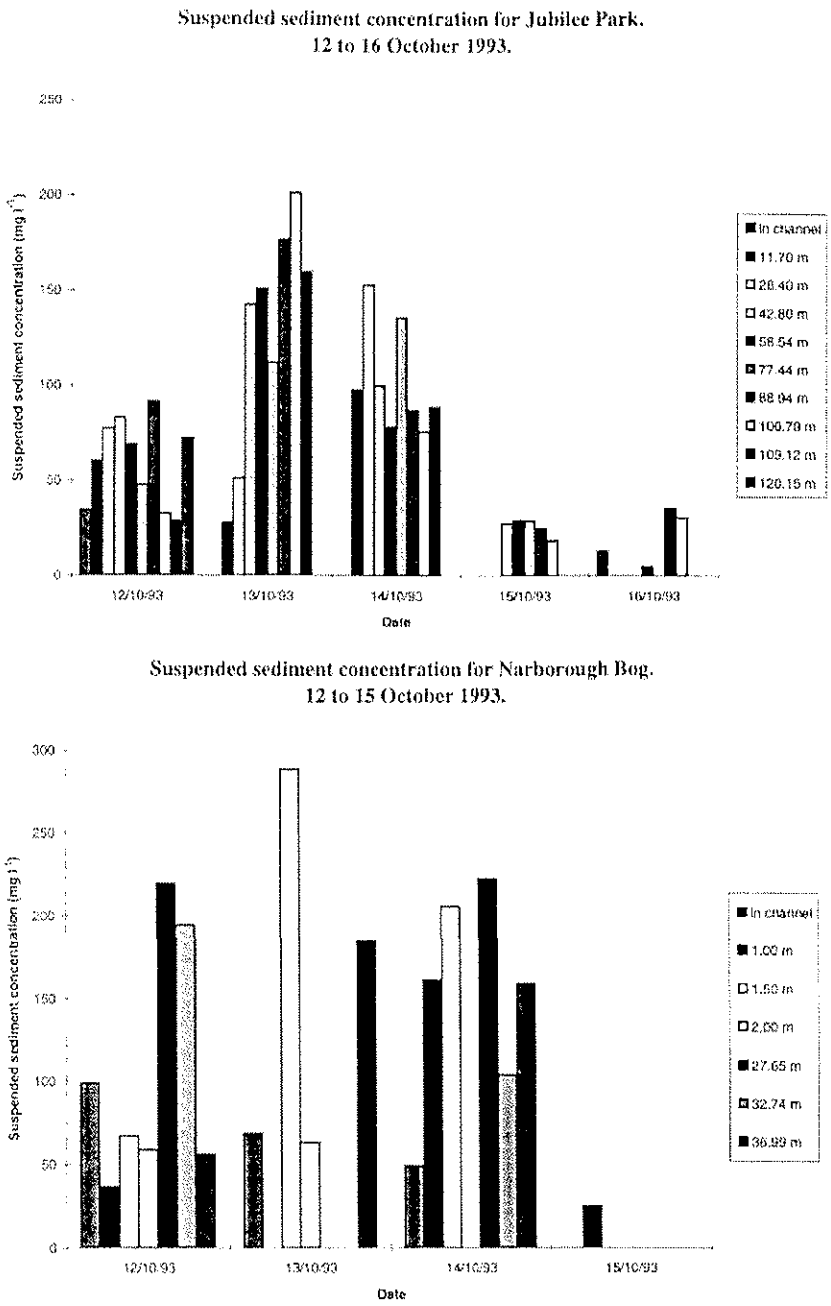


Figure3.2 *The suspended sediment concentrations at different points across the floodplain during a flood in the autumn of 1993*

3. SIMPLE LABORATORY EXPERIMENTS

In order to measure rates of deposition on living leaves whole plants were removed from the floodplain and placed into a temperature controlled settling tank. Three species were used; stinging nettles (*Urtica dioica*), great hairy willowherb (*Epilobium hirsutum*) and goldenrod (*Solidago virgurea*). The suspended sediment used was re-suspended topsoil from the Soar floodplain. There was in most runs no relationship between leaf depth and leaf catch (Figure 3.3), indicating that sedimentation is not the result of a settling front but the impact of particles or aggregates with the upper leaf surface.

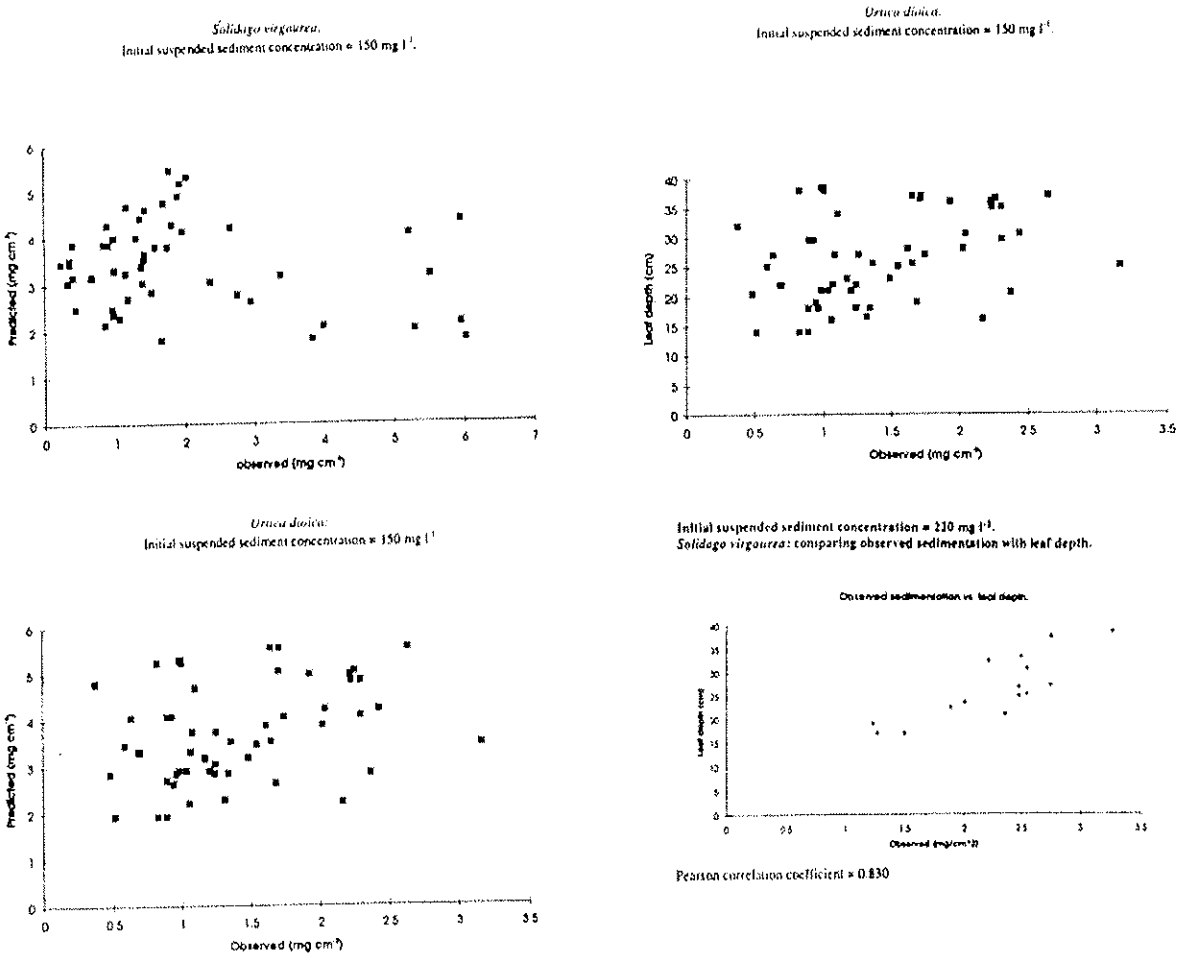


Figure 3.3 *Observed sediment deposition rates in the settling tank against leaf depth and predicted rate (concentration x leaf depth)*

In an experiment with goldenrod at 220 mg l^{-1} a relationship did develop; the reason for this is not known but flocculation might have occurred (although this was not actually observed). What was most noticeable in all runs was the high leaf-to-leaf variation, probably partly caused by interference between leaves and turbulence. It is also significant that species caught different quantities of sediment per unit surface area, even when placed in the same tank. Scanning electron micrographs showed that the form of sedimentation also varied between species with particles and micro-aggregates deposited on and around the leaf hairs of stinging nettles but deposited as a sheet over the surface of the goldenrod leaves (Figure 3.4). It was further observed that the deposited sediments could then break-off as aggregates which could re-join the water column.

These and many other riparian species have a high affinity for nutrients, particularly P which is preferentially bound to suspended sediment (Ongley, 1983; Ongley, *et al.*, 1992). The high frequency of herbs with leaf hairs in riparian communities (e.g. nettles, willowherb, comfrey, meadowsweet) may also have a functional role as part of an adaptation to high rates of overbank deposition of MG1 grassland communities (e.g. *Urtica dioica* and *Filipendula ulmaria* sub-communities, Rodwell, *et al.*, 1992).

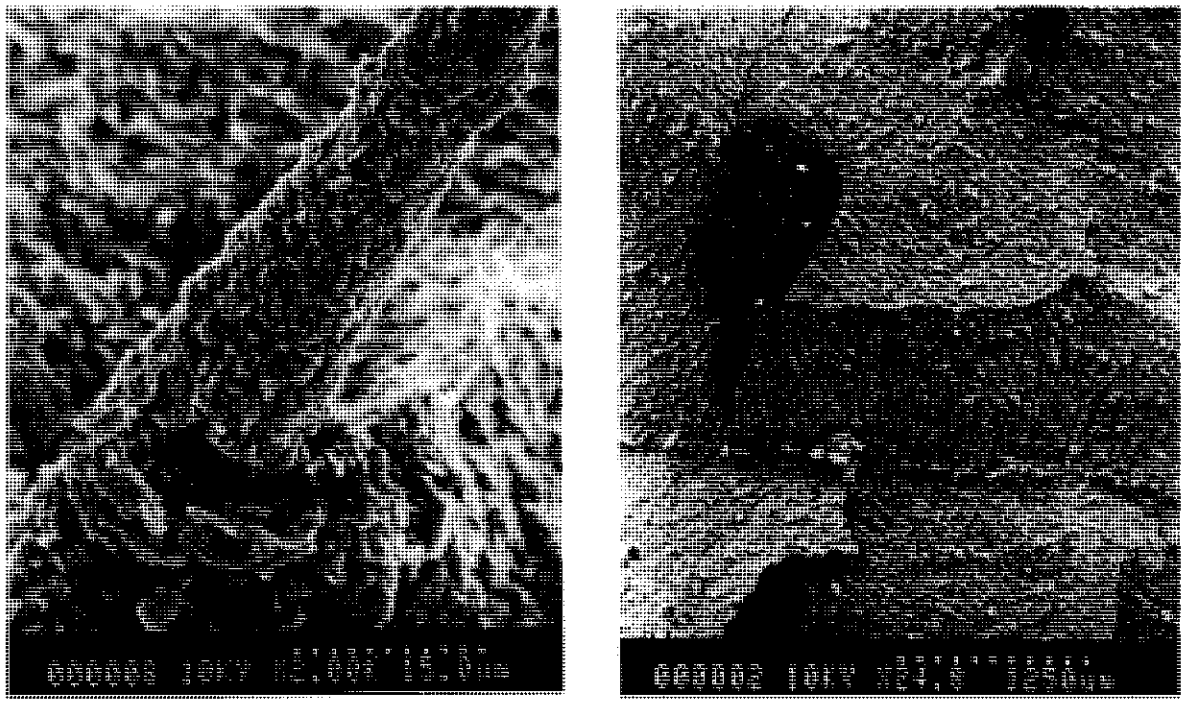


Figure 3.4 *Left: SEM microphotograph of sediment deposition on the leaf surface of a stinging nettle plant (*Urtica dioica*). Right: SEM of sediment deposition on the leaf surface of a golden-rod plant (*Solidago virgurea*)*

4. OVERBANK EROSION

The accretion rate of floodplains is the product of both overbank deposition and overbank erosion. Significant overbank scour is rare on fully vegetated temperate floodplains, particularly those under grass. However, there are situations where it has been reported, such as when the floodplain has been ploughed and where overbank flows are constricted by hedges, walls or gates. Observations from a rare semi-natural floodplain from S.W. Ireland, the Gearagh in County Cork, also suggests that it is much more common under fully wooded conditions. There are several floodplain features on the islands of the Gearagh which can only be explained by overbank scour, including ring-depressions around the base of trees and coppice stools, large boat-shaped depressions which are enlarged tree-throw pits, and scoured flood channels well above the channel bed heights (Brown *et al.,* 1995). Observations of flood velocities in one area of the woodland support this as high velocity threads of flow were seen to be formed on the floodplain by topographic variations and the distribution of trees (Harwood and Brown, 1993). It is also relevant that in the four years the Gearagh has been monitored no flood sedimentation has been observed on any plant leaves. The work on the Gearagh suggests that, in a dense, complex wooded floodplain, high overbank velocities and turbulence induced by macro-roughness elements prevents overbank deposition of fines and favours overbank scour. There is some support for this in the literature particularly from studies of larger, less managed central European floodplains in Poland (Teisseyre, 1985) and Russia (Popov and Gavrin, 1990).

At present there is insufficient data to allow estimates to be made of the relative effect of different vegetation communities on standardised sedimentation rates. However, given the records of rates from grasslands and the observations of scour induced deposition caused by tussocks and trees, it seems highly likely that it is non-linearly related to vegetation variables such as biomass or structural complexity (Figure 3.5). The experimental evidence obtained thus far does indicate that there will be a wide range of values, probably associated with hydrological and hydraulic factors.

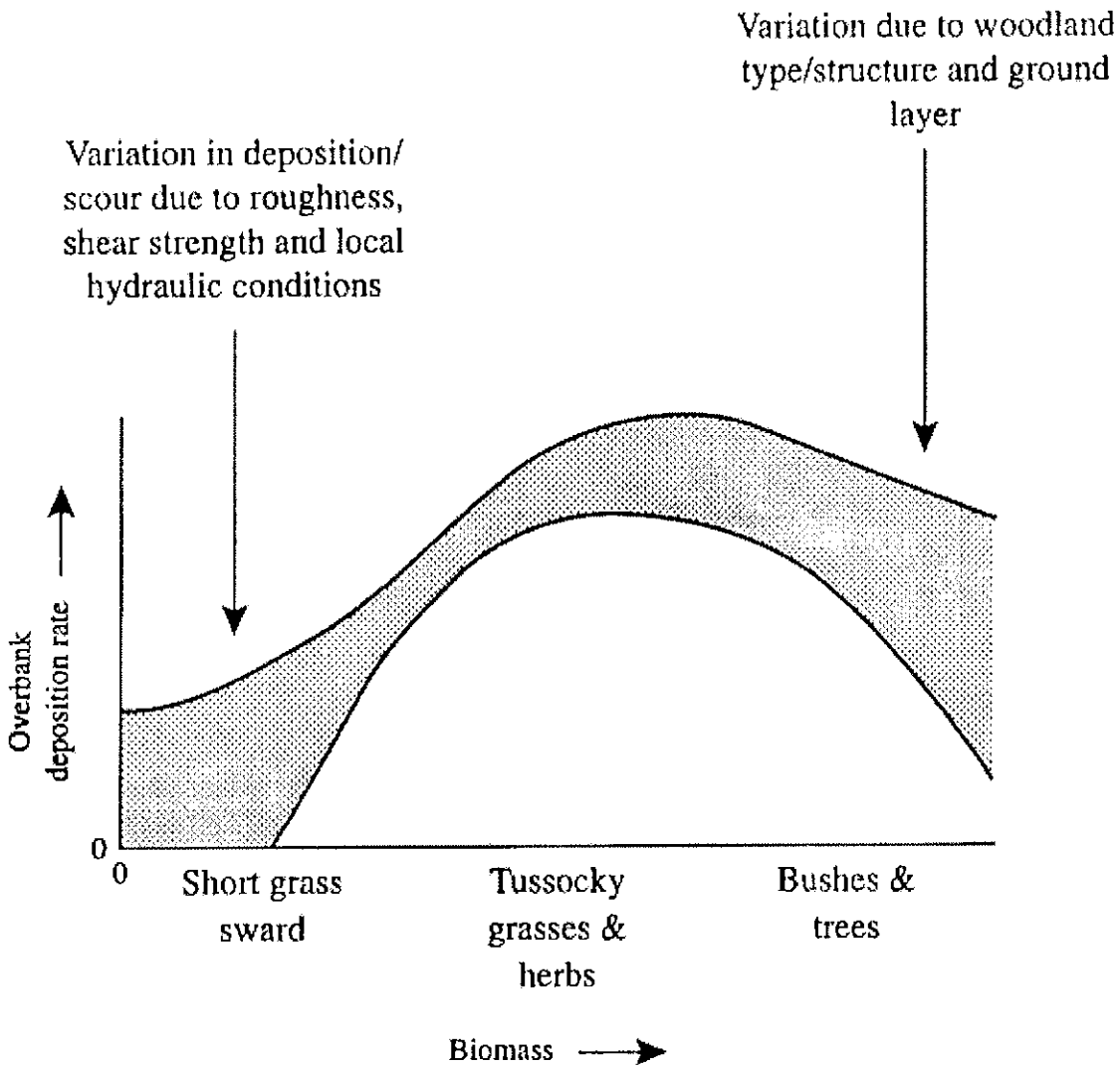


Figure 3.5 *Hypothetical relationship between floodplain vegetation and deposition illustrating its probable non-linearity and high variability*

5. PRELIMINARY CONCLUSIONS

The preliminary work in this field by the authors and others suggests a number of process-related factors which need to be taken into consideration in future studies of floodplain formation and sediment conveyance.

1. Vegetation presents a highly complex and variable surface that is many times greater than the planimetric surface area of the floodplain and one which varies during the year.

2. Observations at a variety of scales suggest that, whilst coarse and medium sand deposition may be primarily the result of decreasing velocities away from the channel and floodplain roughness, deposition of finer sediment may be an active process whereby the sediment is 'scavenged' by vegetation from the constantly moving water column. Although many processes may be acting at the particle scale, the term 'impact sedimentation' is probably most appropriate and leaves may be acting an a manner similar to sedimentation plates in reducing the effective settling distance.

3. Different species with different life-forms, structural rigidity and leaf-surface characteristics will probably catch different quantities of suspended sediment from the same water column and the occurrence of floodplain scour.

If this is the case then it follows that;

(a) Floodplain deposition may vary through the year with the phenology of the vegetation and management (e.g. grazing).

(b) Rates of floodplain accretion may be affected by *in-situ* changes in floodplain land use as well as any hydrological changes of catchment or climatic origin.

Further work in this field is urgently required as these processes have theoretical implications for modelling past sediment budgets and practical implications for the management of floodplains in order to strip suspended sediment and associated contaminants from river systems.

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4

Hydrochemical-vegetation interactions on a Scottish floodplain mire

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Abstract

Groundwater heads and chemical composition were measured at approximately monthly intervals during the summer of 1995 along a 1km transect across the Insh Marshes in Inverness-shire, Scotland. Close to the valleyside infertile, acid, peaty soils with high DOC, Mn and Fe reflect a high water table maintained by drainage from upland areas. Midway between the valley side and the river, a relatively stable and high water table, increased pH and conductivity and peaks in Ca and to a lesser extent Mg are apparent. These probably reflect upwellings of base rich groundwater. Close to the river, drainage reduces summer water tables and marked increases in potassium, sulphate and nitrate concentrations indicate an increased importance of topogenous nutrient inputs. From floristic data collected in 1995 along the line of the transect there is a close correspondence between vegetation patterns and hydrological and hydrochemical gradients. *Carex nigra*, *C. panicea*, *Eriophorum angustifolium* and *Molinia caerulea* form a complex mosaic on peaty soils with a high water table. *Carex aquatilis* and *Carex vesicaria* form pure or intermixed stands in flood-prone areas mostly adjacent to the Spey, but also parallel to the major lateral drains. The remaining large sedge, *C. rostrata*, occurs in association with a high water table/low redox potential. *Phragmites commune* is found as relatively short, open depauperate stands amongst the dominant mire and tall sedge communities. *Phalaris arudinacea* and *Deschampsia cespitosa* dominate in drier areas. Biomass and canopy height exhibit a similar pattern of change characterised by low values on the peaty, Mn- and Fe-rich areas and to a lesser extent on the base-rich areas, and increased values at sites with elevated K, Cl, NO_3 and SO_4 concentrations. This pattern is manifested as a general increase in biomass and plant height with increasing proximity to the river. Litter cover and stem width also increase towards the

river and in groundwater recharge zones, and there was a marked decline in species richness towards the river reflecting the progressive change to competitively dominant riverine swamp communities

1. INTRODUCTION

Hydrological and hydrochemical gradients on floodplain mires are primarily controlled by inputs and outputs from precipitation, groundwater and surface water. Relatively small changes in water table regime and chemical composition may result in different vegetation communities. The vegetation in turn can affect water tables and chemical composition through uptake of nutrients and water. To manage floodplain wetlands succesfully, an understanding of the role of hydrology in determining wetland nutrient status and hydrochemical-vegetation interactions is therefore needed.

Despite the widespread realisation that hydrology and hydrochemistry are important controls on wetland vegetation, few studies have investigated hydrochemical-vegetation interactions on floodplain mires. Notable exceptions include the work of Giller and Wheeler (1988), Wassen *et al.* (1990), and Wassen and Barendregt (1992). The water balance of a floodplain fen is important for a number of reasons. Firstly, it has a large influence on the nutrient budget, because it determines the mix of precipitation, riverine floodwater and hillslope inputs each of which is chemically different. Secondly, it determines the availability of water throughout the year. Thirdly soil moisture and water fluxes determine the retention time and thus availability and input-output characteristics of nutrients. Hydrochemical and hydrological variations within a floodplain mire can occur due to intrasite variations in the relative importance of water sources (Giller and Wheeler, 1988; Gilvear *et al.*, 1997; Grieve *et al.*, 1995). In addition to its direct influence on vegetation, the chemical composition of mire water can also affect mineralisation and adsorption/desorption processes (Mitsch and Gosselink, 1986). The overall purpose of the research described here was to assess the significance of hydrological and hydrochemical gradients identified on the basis of sampling in 1993 (Grieve *et al.*, 1995) to floodplain mire vegetation composition and structure. Grieve *et al.* (1995) explained the hydrochemical gradients across the marsh by water source variability.

2. SITE DESCRIPTION

The Insh Marshes, the largest extent of floodplain mire in the UK lies within the middle reaches of the valley of the River Spey, Scotland (Figure 4.1). The River Spey rises about 30 km west of Newtonmore in the Monadhliath Mountain range and flows in a north-easterly direction towards the Moray Firth and North Sea. The Spey valley to the south is bounded by the Cairngorm Mountains. This upland area, which locally rises above 1200 m OD is characterised by a major granite intrusion and a range of schists and gneisses of Precambrian age (Young, 1978). At Ruthven Bridge close to the study site the River Spey has a catchment area of 534 km^2 and a mean annual flow of 9.3 m^3s^{-1}. Mean annual rainfall for the catchment is 1448 mm.

Along the southern bank of the Spey, the Insh Marshes are approximately 7.5 km in length, although the sinuosity of the river here results in a channel length of 10 km (Figure 4.1). Three major tributaries flow over the marsh into the Spey, the Gynack, Tromie and Raitts, and several small streams drain from the surrounding valley sides into the marsh area. Within the study area, all the major river courses have 18th and 19th century flood embankments but these have generally fallen into disuse with a number of breaches. On the south side of the river a large lateral drainage ditch and a series of internal parallel and perpendicular interconnected drainage ditches criss-cross the marsh and empty into Loch Insh via a culvert at Coull (Figure 4.1). The valley floor in the vicinity of the marshes is infilled with Pleistocene to recent fluvioglacial deposits of interbedded sands and gravels overlain by alluvial deposits (Grant and Birse, 1953). Loch Insh to the north of the Marshes is an infilled kettle hole. A shallow stratigraphic survey of the Insh Marshes was carried out in 1991 (Johnson *et al.*, 1991). Near to the river shallow sediments were largely made up of interbedded organic silts and towards the centre of the Marshes silts graded into alternating layers of dark brown silty peat and brownish grey silty peat. Yet further from the river large proportions of peat and mud were found, with dark and fibrous peat with little or no mineral content close to the valley side.

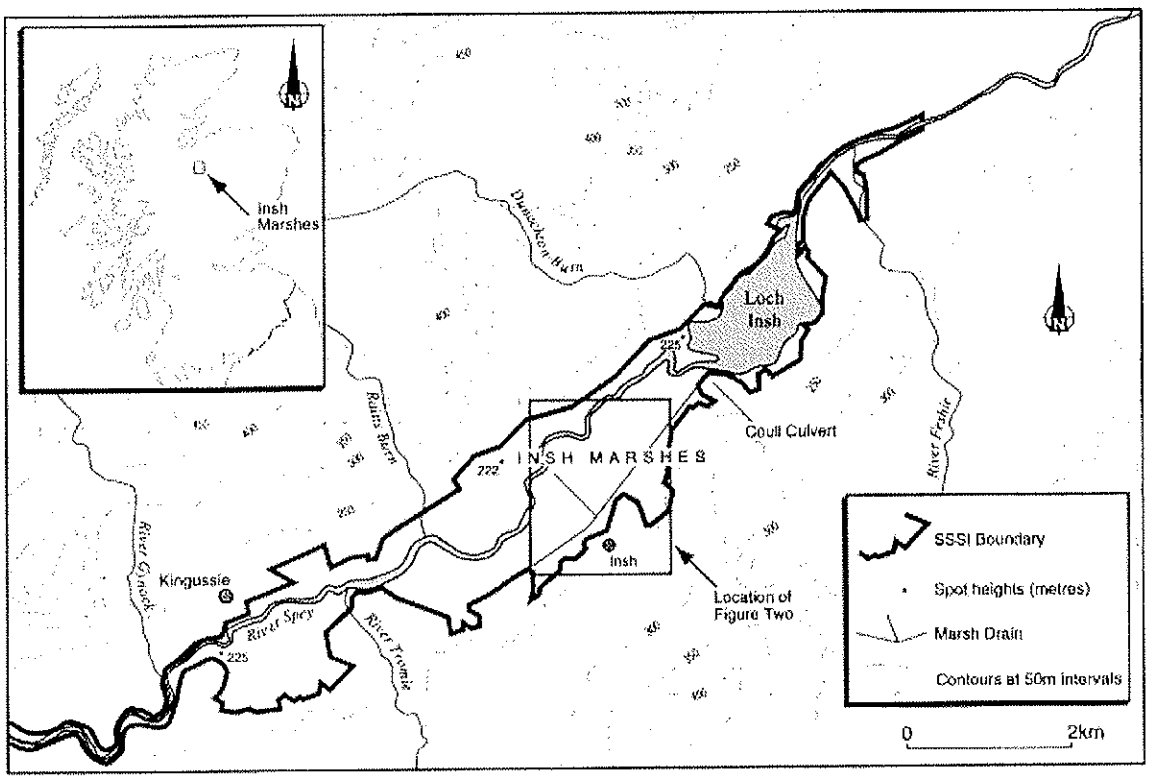


Figure 4.1 The Insh Marshes and location of the study area

The Insh Marshes are widely recognised as a wetland site of international importance. The area was designated a Site of Special Scientific Interest (SSSI) in 1963 and subsequently given Ramsar wetland status and is a proposed Special Protection Area and Special Area of Conservation under EC legislation. It is currently managed as a reserve by the RSPB. The botanical importance is reflected by the presence of six nationally scarce aquatic plant species, five terrestrial plant species of national importance and one terrestrial plant species of

international importance. Additionally there are populations of eleven fly species and one beetle species listed within the UK Red Data Book (RDB), along with seventeen breeding or wintering RDB rare bird species plus a further fifteen RDB candidate species, many at high numbers or densities on this site (Johnson *et al.*, 1991). The major wetland vegetation communities present are tall fen/swamps dominated by *Carex aquatilis/C. vescaria* (S11), *Phragmites australis* (S4), *Carex rostrata* (S9), *Equisetum fluviatile* (S10). *Meryanthes trifoliata-Potentilla palustris* (S27) or *Phalaris Arudinacea* (S28); low sedge mire communities variously dominated by *Carex chordorrihiza, C. limosa, C. Lasioscarpa, C. echinata, C. dioica or C. rostrata* (M4,5,6,9,10 and variants of S9); floating rafts of pure Spagnum (M1,2); herb *rich Molinia caerulea-potentilla erecta* mire (M25); mesotrophic grassland dominated by *Deschampsia aspitosa* and various rush pastures (M23).

3. METHODS

A transect of piezometers were installed across the Insh Marshes in 1993 perpendicular to the flow of the River Spey (Figure 4.2). Full details of the transect are given in Grieve *et al.*, (1995).

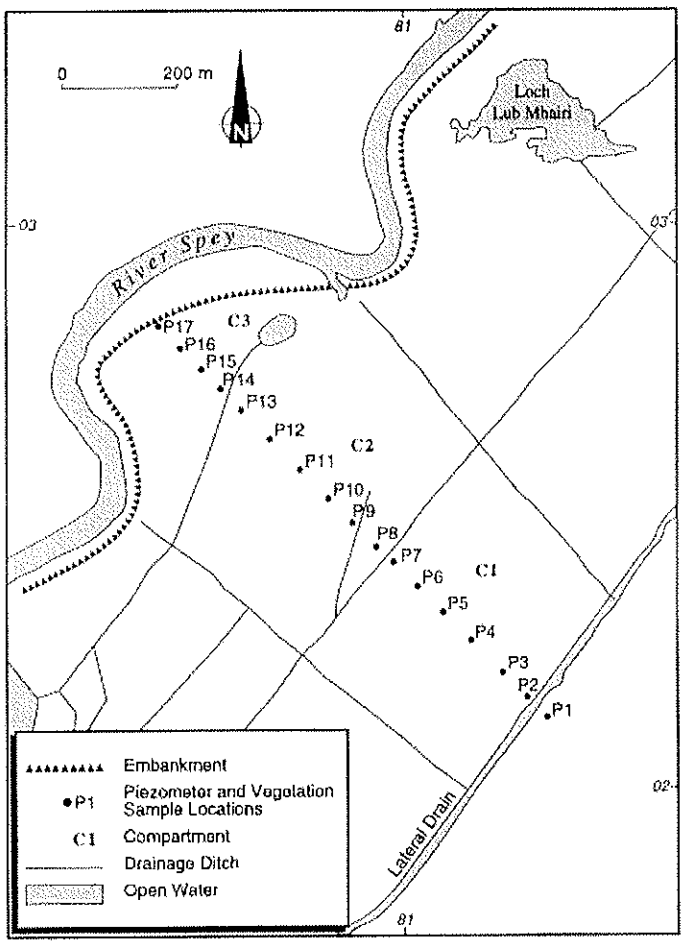


Figure 4.2 Insh Marsh transect location and layout

Between February and November 1995 water level measurements and water samples were collected from the shallow piezometers (0.50 metres depth) on the transect at approximately monthly interals. Samples were collected in a 1000ml glass flask using a suction pump and transported to 250-ml polythene bottles for transport. The representativeness of these samples is discussed in Grieve *et al.* (1995). On return to the laboratory, pH and conductivity were measured on aliquots of the sample using laboratory pH and conductivity meters. Samples were then filtered through glass fibre filters (Whatman GF/C) to remove suspended material and analysed for major cations and anions.
In August 1995 surface soil samples were collected to allow determination of soil organic matter (loss on ignition), and pyrophospate extractabale soil iron and manganese concentrations. Ca, Mg, Fe and Mn were determined using atomic absorption spectrometry, K and Na using flame spectrometry and Cl, NO_3 and SO_4 by ion chromatography. DOC concentrations were measured using a TOCSIN aqueous carbon analyser. Exact procedures are described in Grieve *et al.* (1995). During August 1995 vegetation at each piezometer site was also sampled in 1m * 1m quadrats. Variables measured included species richness, mean stem density, stem diameter, nearest neighbour distance, density of reproductive structures, canopy height, litter cover and biomass (0-0.1m,0.1m-0.2m, 0.2m+ strata).

4. RESULTS

4.1 Variation in Hydrochemistry

Table 4.1 and Figure 4.3 support previous evidence (Grieve *et al.* 1995) that variation in shallow groundwater chemistry along this transect is essentially determined by the relative contributions of three principal water sources, viz; base-poor hillslope runoff, rising base-rich groundwater and floodwater inputs mainly from the Spey. This results in infertile, acid, peaty soils with high DOC, Mn and Fe at the edge of the marsh reflecting the permanently high water table maintained by drainage from siliceous upland areas.

Variable	Dist	%Organic	Mn	Fe	Eh7	GWD	pH	Cond	Ca	Mg	K	Cl	NO_3	SO_4
Organic	---	+++												
Mn	---	+++												
Fe	---		+++											
Eh7														
GWDmax	+		--	---	+									
pH	+	---	-				+							
Cond														
Ca				+										
Mg	-	+	+			-								
K	++	-	--	---		++				-				
Cl	+		-	--		+++		+			+			
NO3	+		---	---		+++			-		+	+		
SO4	++					+		+++		--	++	+		
DOC		+++					---		-			+		

GWD signifies depth to the water table. Distance signifies distance along transect from valley side end.

Table 4.1 *Simplified correlation matrix illustrating significant intercorrleations between key hydrochemical variables measured during May-October 1995. Based on linear correlation coefficients +++,---,++,--, + or - signify positive or negative correlations at p=0.0001, 0.01 or 0.05 respectively*

Towards the centre of the transect (samplers 7 to 11) rises in pH and conductivity associated with peaks in Ca and to a lesser extent Mg (Figure 4.3) suggest upward seepage from a base-rich regional groundwater system. This is sufficient to maintain the water table within 35cm of the surface despite diversion of residual hillslope inputs into a lateral drain. With increasing proximity to the Spey, alluvial sediments predominate and there is a progressive increase in summer groundwater depth presumably resulting from discharge into lateral drains and the main river channel. Marked increases in potassium, chloride, sulphate and nitrate concentrations testify to the increase in topogenous inputs to the system. However, recorded maxima substantially exceed those recorded in the river implying significant in-soil chemical changes within these recharge zones. In the case of K, this probably involves release of K adsorbed onto riverborne sediment. The increases in sulphate may result from re-oxidation of sulphides formed during prolonged winter inundation. It is possible that this effect is magnified by the unusually deep water table related to the exceptionally low precipitation encountered during the period of this study. Superimposed on this general pattern is the influence of artificial drainage systems which result in local drawdown of the water table and modify groundwater chemistry by lateral seepage.

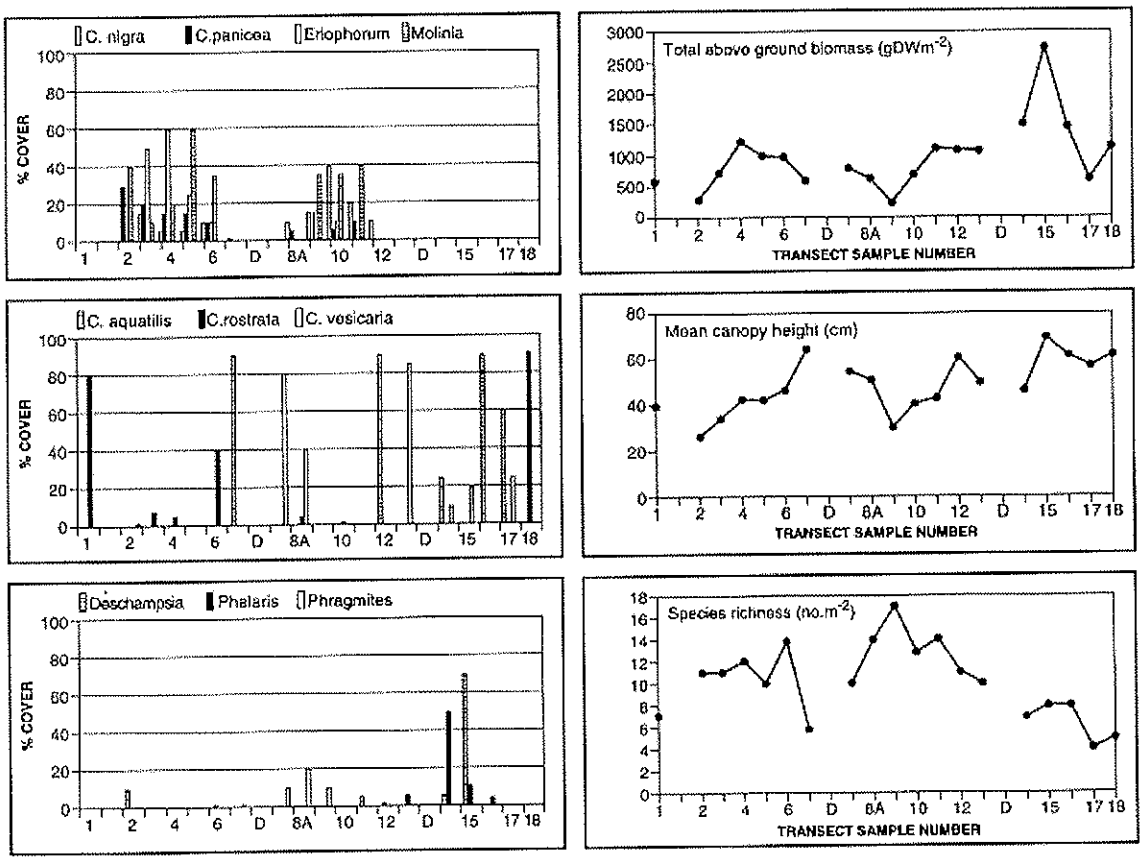


Figure 4.3 *Changes in key hydrochemical variables along the transect. Fe and Mn are August values and other variables recorded maxima during May-October 1995*

Samplers adjacent to ditches (e.g. 8, 13 and 14) are also characterised by increased potassium, chloride and sulphate concentrations since these drains form a focus for winter flooding due to backing up of water draining into Loch Insh or the main river. Sites 14 and 15 feature inorganic fine sandy sediment, deep groundwater and high nitrate and potassium concentrations and lie in a slightly elevated zone, less affected by winter flooding. Maximum nitrate concentrations again far outstrip those recorded in the river and it must be assumed that N-mineralisation within the well aerated soil is playing a significant role. It is also relevant that maximum nitrate concentrations were recorded during October when the groundwater table is rising, since population growth rates of soil microbes responsible for mineralisation are known to increase rapidly on wetting of aerobic soils.

4.2 Variation in Vegetation Composition

Changes in the representation of the dominant species along the transect (Figure 4.4) largely correspond with the pattern of hydrochemical variation described above. *Carex nigra*, *C. panicea*, *Eriophorum angustifolium* and *Molinia caerulea* overlap closely forming a mosaic of mire communities in compartments 1 and 2 on peaty soils with a high water table.

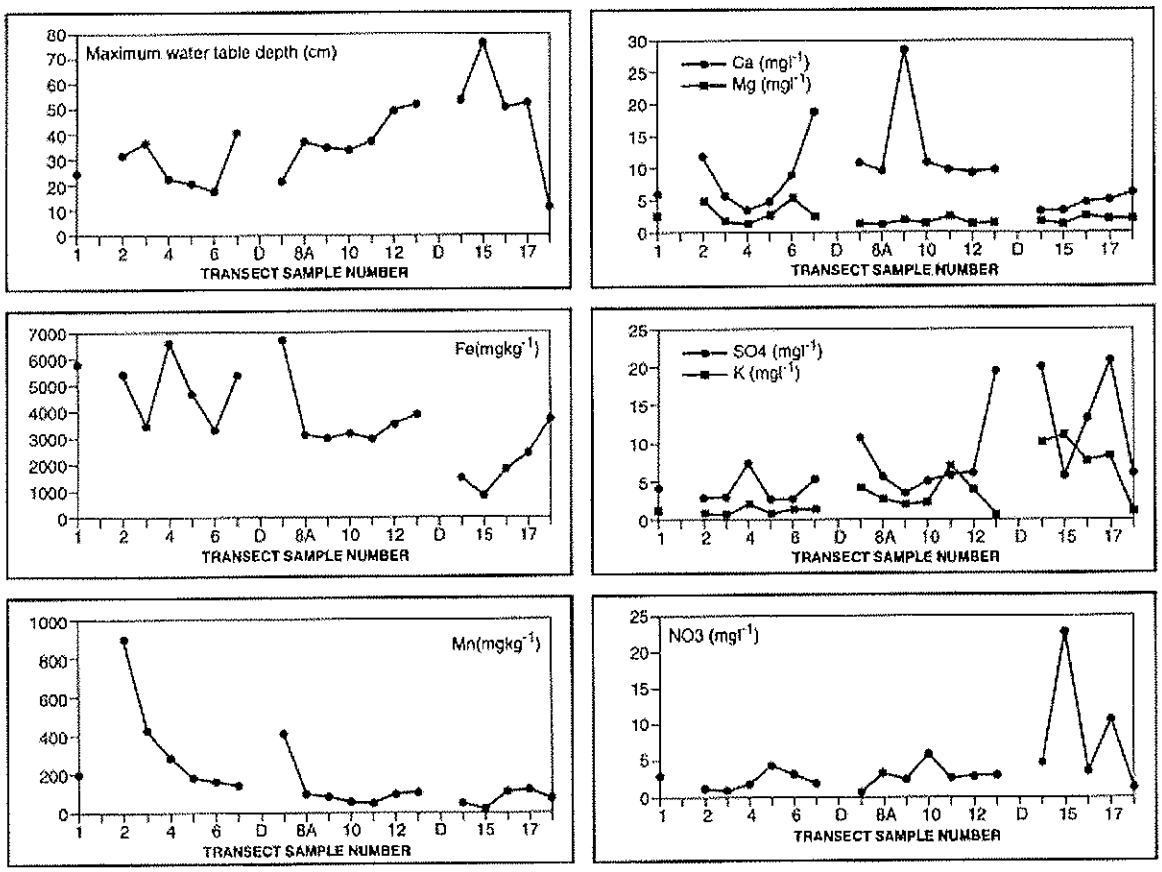


Figure 4.4 *Change in percentage cover of dominant species and selected vegetation state variables along the transect*

Correlations between the abundance of these species and Mg concentrations are caused mainly by upwelling of base-rich groundwater near the edge of compartment 2. *Carex aquatilis* and *Carex vesicaria* provide a stark contrast with the above vegetation by forming pure or intermixed stands in flood-prone areas mostly adjacent to the Spey but also parallel to the major lateral drains. These stations act as groundwater sinks during the summer with high sulphate and potassium concentrations testifying to the winter flooding regime. The remaining large sedge, *C. rostrata*, occurs at various sites along the transect but always in association with a high water table/low redox potential. *Phragmites* is found as relatively short, open depauperate stands amongst the dominant mire and tall sedge communities at the edge of compartment 2 and corresponds in its distribution only with peaks in calcium concentration. *Phalaris arudinacea* and *Deschampsia cespitosa* dominate at samplers 14 and 15 in an area of the transect characterised particularly by a deep summer groundwater table and increased NO_3 concentrations, but also experiencing increased concentrations of K, Cl and SO_4 symptomatic of the increased riverine influence.

4.3 Variation in Collective Vegetation Response

Biomass and canopy height exhibit a similar pattern of change characterised by low values on the peaty, Mn- and Fe-rich areas in compartment 1 and to a lesser extent on the base-rich areas in compartment 2, with values increasing at sites with elevated K, Cl, NO_3 and SO_4 concentrations. This pattern is manifested as a general increase in biomass and especially plant height with increasing proximity to the river (Figure 4.4). Litter cover and stem width generally increase towards the river and in sulphate-rich areas corresponding to groundwater recharge zones, while there was a marked parallel decline in species richness from mid-transect towards the river reflecting the progressive change to competitively dominant riverine swamp communities (Figure 4.4). The proportion of fruiting stems was poorly correlated to the measured hydrochemical variables but was generally higher in low redox areas with a high water table. This probably reflects the incidence of small sedge- and *Eriophorum*-rich mire vegetation.

5. DISCUSSION

5.1 Variation in Species Composition

The observed transition from small sedge mire through to tall sedge beds is consistent with previous evidence of changes in the relative contribution of base-poor soligenous inputs, upwelling base-rich groundwater and mesotrophic flood waters, given the documented ecological preferences of the dominant species and the communities that they form.

The *Carex echinata-Sphagnum* mire (M6) is the classic mire type on peaty soils irrigated with base-poor water (Rodwell 1991). Shifts towards a somewhat more productive *Molinia caerulea-Potentilla erecta* mire (M25), associated with an increase in the abundance of *Molinia,* may be due in part to amelioration of soligenous inputs by base-rich groundwater, as is suggested by the correlation between Mg and *Molinia* abundance, but selective grazing by sheep is probably also important. Dispersing surface water additionally creates runnels between *Molinia* stools thus promoting local dominance of this species. The influence of past management on the mire communities of Insh Fen is also evident from the extensive degradation of the *Sphagnum* carpet caused by muir-burn. The primary control on these communities is probably their requirement for a permanently high, but sub-surface water

table maintained by nutrient-poor sources, and low intensity winter flooding. They are therefore regarded as being indicative of dominant base-poor hillslope inputs.

Phragmites achieves local prominence across several plant communities in the centre of the transect although its growth performance is strongly suggestive of nutrient limitation. Between samplers 8A and 9 the vegetation displays certain affinities with a *Carex rostrata-Calliergon* mire (M9) which is characteristic of permanently moist soils in topogenous mires with a strong base-rich, calcareous input (Rodwell, 1991). In rich-fens *Phragmites* also commonly dominates on peats exposed to base-rich, calcareous and nutrient-poor waters (Wheeler, 1980). Elsewhere on the marshes, *Phragmites* occurs as a co-dominant in larger but again usually relatively open stands, forming various poorly defined swamp communities (e.g. with *Carex lasiocarpa*). These also tend to coincide with areas of inferred base-rich groundwater upwelling based on conductivity mapping (Gilvear, 1994) and it seems likely that a genuine association exists between *Phragmites* cover and calcium availability. The increase in *Phragmites* cover is interpreted as being indicative of diminished base-poor hillslope and riverine inputs and increased importance of upwelling base-rich deep groundwater.

The distribution and hydrochemical preferences of *Carex vesicaria* and *C. aquatilis*, the staple components of *Carex vesicaria* swamp (S11), are strongly indicative of increased topogenous influence related to backing up and overtopping of ditches or flooding from the Spey via embankment breaches. Throughout the Insh Marshes *Carex aquatilis* forms very extensive buoyant rafts in frequently inundated areas which can therefore accommodate rapid rises in flood water. In this respect *C. aquatilis* behaves as a mesotrophic analogue of *Glyceria maxima* swamp which forms similar floating rafts in eutrophic riverine wetlands (Lambert, 1947). Spring growth can thus commence early and developing plants can exploit the increased concentration of riverborne nutrients such as K. Although occurring predominantly in a groundwater recharge zone, *C. aquatilis* maintains hydraulic continuity with a falling water table during the summer via a thick rhizomatous mat which may penetrate to depths of more than 0.8m (N.J.Willby. *pers. obs.*). The distribution of *Carex rostrata* is not especially characteristic of the signature of any particular water source although variations in the growth performance of the plant are suggestive of spatial differences in nutrient availability. *C. rostrata* occurs throughout the Marshes in a variety of swamp and fen communities. These include (i) tall, robust, virtually monodominant stands (*Carex rostrata* swamp S9) fringing lochans, ditches and the main river in moderately deep water, (ii) sparser stands mixed with *Potentilla palustris* and *Menyanthes trifoliata* (*Carex rostrata - Potentilla palustris* tall-herb fen S27) in very shallow water, natural depressions or growing as floating rafts on occluded ditches, and (iii) smaller plants mixed with various Sphagna in mire communities (e.g. M9). The dependency on a high water table, noted by Spence (1964), is however, ubiquitous.

The examples of *Phalaris arundinacea* tall herb fen (S28) and *Holcus lanatus-Deschampsia cespitosa* grassland (MG9) at samplers 14 and 15 respectively provide an interesting deviation from the main pattern of variation in plant communities across the transect. Both communities occur on a band of periodically inundated mineral sediment with a widely fluctuating water table which may indicate the line of a former river channel. These communities occur elsewhere on the marshes when this combination of conditions is reproduced. Although MG9 is a typically mesotrophic neutral grassland community, *Phalaris arundinacea* commonly occurs in inferile situations on gravel shoals in upland rivers and around lakeshores. It is perhaps therefore the seasonally low water table, preferential for both

dominant species (Spence, 1964) but probably unacceptable for *C. aquatilis* swamp, which underlies their presence at this site, rather than the sudden change in nutrient status.

5.2 Variation in Collective Vegetation Responses

The change from small-stemmed, short and relatively species-rich vegetation to productive, robust stemmed, species-poor and, above all, tall vegetation with increasing proximity to the river complements the above changes in species composition but also provides evidence for a general underlying fertility gradient. This is likely to depend on changes in the availability or uptake potential of one or more of the major plant nutrients (N,P,K) caused by variations in flooding (mainly K-related), concentrations of base cations (Ca and Mg) and concentrations of reduced metal ions (Fe and Mn). It is unlikely that NO_3 concentrations can account for the observed vegetation gradient since, apart from spikes at samplers 15 and 17, they were remarkably uniform across the transect. Waughman (1980) and Wassen *et al.* (1990) obtained similar results in studies of peatlands in southern Germany and Biebrza, Poland respectively. Wassen *et al.* (1995) concluded from analyses of plant tissue that N-limitation was a general factor affecting the vegetation in non-flooding fens and bogs at Biebrza, but not in flooded areas, thus supporting their earlier assertion (Wassen *et al.* 1990) that variation in vegetation composition in these areas was determined primarily by K and P supply. We are also inclined towards this view, although at Insh the evidence for N-limitation over the entire transect (ie. rarely and regularly flooded sites) is equivocal because there is no significant correlation between mean NO_3 concentrations and total above-ground biomass or cover of the main swamp and mire forming species.

K-limitation, reported for *Eriophorum* communities by Goodman & Perkins (1968), may be a general constraint on vegetation in the central areas of compartments 1 and 2 due to dilution of topogenous inputs by K-poor hillslope drainage and upwelling groundwater. The differential in K concentrations in compartments 1 and 2 is insufficient on its own to account for the variation in vegetation structure and composition unless either base cations reduce K uptake potential by complexing or K is selectively leached in the more organic acid soils to depths where it is unavailable to the vegetation. This would make K limitation potentially more acute in compartment 1. On the other hand Malmer (1986) provides evidence that leaching rates of K increase in calcareous soils in which case K might become limiting in areas of upweling groundwater.

Variations in P concentrations could be an important additional constraint on productivity although this study provides no evidence for this. It is unlikely that P is limiting in areas exposed to regular riverine flooding but P availability might be locally reduced in the central area of the fen if the upwelling base-rich groundwater source is naturally P-deficient. Calcium concentrations are too low for P to be immobilised by co-precipitation with calcite, a mechanism demonstrated for rich fens by Boyer & Wheeler, 1989), but microbial conversion of inorganic P to organic forms unavailable to plants, which has been shown to be more efficient in Ca-rich soils (Wilson & Fitter, 1984), may be significant. Certainly the strong inverse correlation between Ca concentrations and above-ground biomass (Table 4.2), which is similar to that observed in rich fens (e.g Giller & Wheeler, 1988), warrents further investigation. Conversely in chronically acidic, low redox, Fe-rich soils P-limitation might occur due to adsorption by amorphous organically bound Fe, by precipitation as insoluble ferric phosphate, or, alternatively, through increased leaching of reduced soluble forms as a consequence of waterlogging (Partrick *et al.* 1973). Thorough evaluation of these hypotheses

will demand an increased sample size combined with monitoring of P concentrations in groundwater and supported by measurements of N, P and K concentrations in plant tissue.

SPECIES	Dist	% organic	Mn	Fe	Eh7	GWD	pH	Cond	Ca	Mg	K	Cl	NO_3	SO_4	DOC
Carex Aquatilis	+					+					+			+	
Carex nigra	---	+	+	+								--		-	
Carex panicea						-				+		-		--	
Carex rostrata					---	--					-				
Carex vesicaria						+		+		--				++	
Deschampsia			-	--		++			-		+	+	+		
Eriophorum	-					-				+		--		-	
Molinia	-					-				+++		-		--	
Phalaris	+	-	-	---		+++					+	+++		++	
Phragmites	+								+				+		
VARIABLE	-													+	
Litter cover	+													-	
Species richness	+								+			-		+	
biomass	+	-	---	--		+			---		+	+	+	+	
stem diameter	+	-								--				+	
Canopy Height	++	--	--	-		+	+			-	+		+		
Fruiting stems					-	-									

Table 4.2 *Simplified correlation matrix depicting significant correlations between species cover, collective vegetation variables and hydrochemistry along transect. See Table 4.1 for explanation of symbols*

6. CONCLUSIONS

Large variations in groundwater chemistry and water table regime have been shown to occur across the base-poor mire system of the Insh Marshes. These variations are most probably linked to the varying influence of hillslope drainage, river and drain inundations and groundwater. Variations in groundwater chemistry and water table are spatially correlated with vegetation species composition, structure, biomass and biodiversity across the 1 km width of the floodplain. Changes in the hydrology of the system or in the chemical composition of any of the contributing waters may have implications for the vegetation beyond the simple effects of changing wetness. Concentrations of N, P and K and the base status of the contributing waters are particularly crucial here. A detailed understanding of the hydrology and hydrochemistry is therefore vital if the nature conservation value of such floodplain wetland sites is to be safeguarded.

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5

Groundwater-surface water interactions along a major Scottish floodplain river

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Abstract

One of the largest Scottish groundwater abstraction schemes was developed in early 1995, along the River Spey. It involves a wellfield of 36 production boreholes in the alluvial aquifer of the lower catchment. The scheme aims to provide a maximum of 27000 m^3/day to meet increasing water demands up to the year of 2011. This yield itself is significant as it represents one-third of the current total groundwater abstraction for public supplies in Scotland.

Groundwater-surface water interactions the Spey river-aquifer system were investigated using a 3-D numerical model (USGS MODFLOW). Three steady-state scenarios were simulated: pre-development, current pumping rate (16000 m^3/day) and projected maximum pumping rate. The pre-development water budget indicates that 94% of total groundwater inflow is discharged into the river, whereas the budgets for stressed conditions give the percentage of water abstracted from the river as 69% and 74% for current and maximum pumping rates respectively.

Aquifer management options were examined from the delineation of travel time related capture zones using a particle tracking program (MODPATH). Capture zones of 50-day (*zone 1*) and 400-day (*zone 2*) travel time to the wellfield are defined for the projected maximum pumping rate. These indicate that the river itself is the primary potential polluting source. However, extensive areas of the river floodplain also contribute significantly to abstraction, thus certain restrictions on potentially polluting activities are needed. Rigorous programs for monitoring water quality both in the river upstream, and along the perimeter of *zones 1* and *2* within the modelled catchment are therefore required to protect the Spey Abstraction Scheme.

1. INTRODUCTION

Groundwater in Scotland is a valuable resource which provides water to domestic, industrial and agricultural consumers in many rural areas and in some important urban locations. Abundant surface water has dictated that groundwater resources in Scotland have been neglected in the past, and current groundwater abstraction (90000 m^3/day) accounts for only 3% of public water supplies (Robins, 1990). However, in recent years, groundwater

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resources have been receiving increasing attention due to high costs of surface water treatment resulting from the water quality requirements of the EC Drinking Water Directive (80/778/EEC).

The Spey Abstraction Scheme is one of the first large scale developments in the UK which involves indirect river water abstraction through the alluvial gravels adjacent to the river bank. This offers many advantages compared with traditional direct river abstraction, the most important being a significant improvement in water quality due to biological and chemical processes in the alluvium which result in much reduced water treatment costs. Additionally, environmental impacts on river flow and migratory salmon fisheries can be reduced (Watt *et al.*, 1986). After comprehensive geological, geophysical and environmental investigations (Anon, 1983, 1988, 1990, 1993, 1994a, 1994b), the Scheme has recently been put into service following the completion of the engineering work in early 1995. The Scheme has been designed to provide a maximum of 27000 m^3/day to meet increasing demand forecasts in the Lower Moray and Banff coastal areas of Aberdeenshire by the year 2011 (Figure 5.1a). This yield itself is significant as it represents one-third of the current total groundwater abstraction for public supplies in Scotland.

There have been few studies of river-aquifer interactions in Scotland and the published literature regarding groundwater protection is limited. The objectives of this study are: (i) to formulate a conceptual and numerical model of Spey river-aquifer system; (ii) to quantify river-aquifer interactions under stressed conditions and (iii) to delineate the travel time related capture zones of the wellfield.

2. DESCRIPTION OF THE STUDY AREA

The River Spey, with a catchment area of some 3000 km^2, is one of the largest rivers in Scotland (Figure 5.1a). The scheme wellfield, south of Fochabers, extends some 3 km along the west bank of the river. Abstraction boreholes have been drilled into floodplain alluvium, and are generally located 50-100 meters from the river and are around 100 m apart (Figure 5.1b,c). The area modelled in the present study is approximately 6 km^2 of the floodplain in the lower River Spey catchment.

The scheme consists of a wellfield of 36 production boreholes (B1-B36), North and South control installations, and a twin transmission main to deliver the pumped water into the nearby Badentian reservoir where the facility for full treatment work may be available in the future. From the reservoir, the water is distributed into the lower Moray and Banff coastal areas (Figure 5.1b). It is intended that 32 boreholes will be used to provide the projected yield of 27000 m^3/day, each borehole will therefore produce an average yield of 850 m^3/day and up to 4 boreholes can be kept on standby or being serviced. Eight permanent piezometers M1-M8 (Figure 5.1c) distributed over the entire modelled groundwater catchment, together with other shallow and deep piezometers, form the long term groundwater monitoring network.

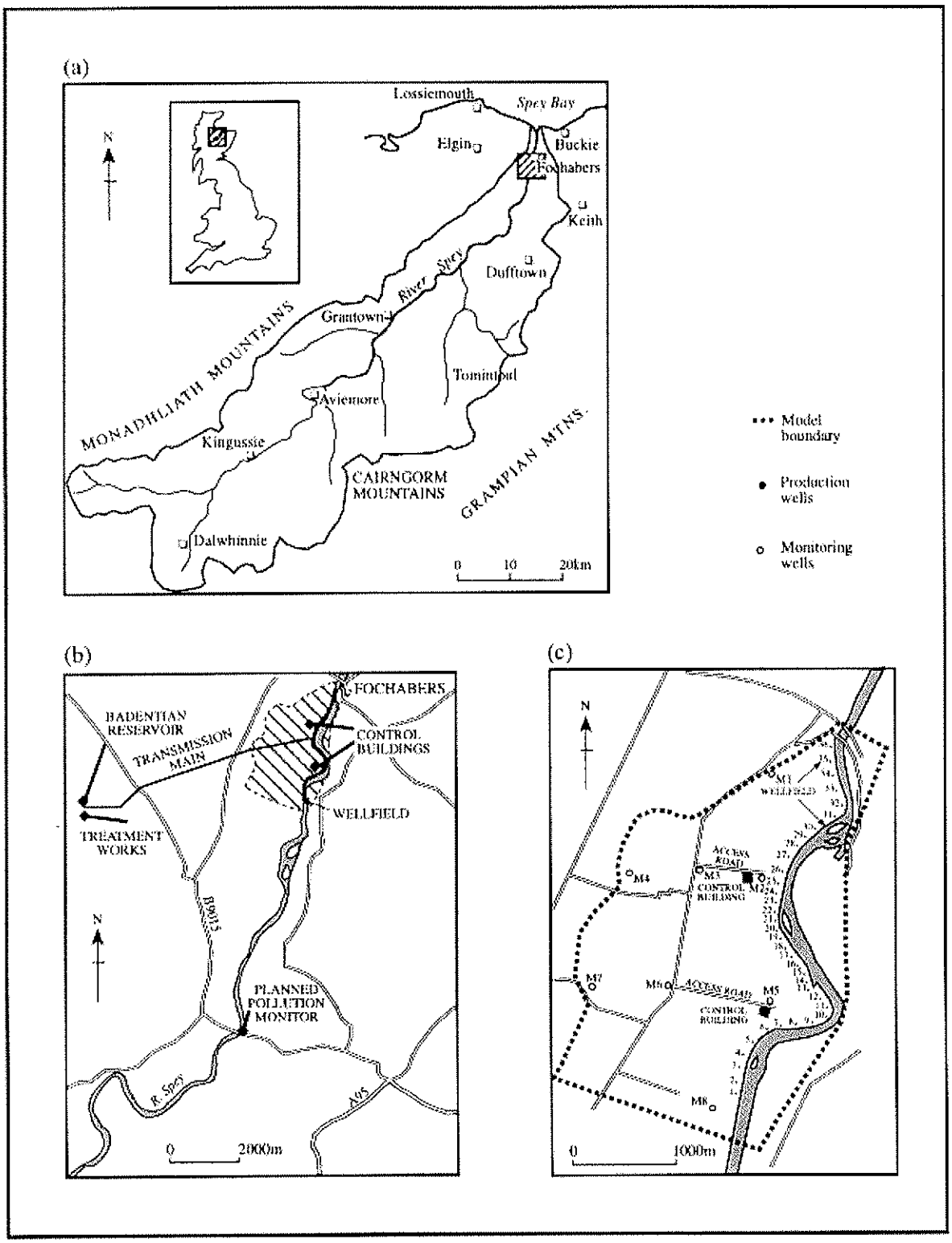


Figure 5.1 The study area showing (a) the River Spey catchment; (b) the Scheme layout and (c) wellfield layout

Geophysical investigations and subsequent borehole drilling programs indicated that the floodplain alluvium is generally between 10-15 m thick, and overlies less permeable Old Red Sandstone (Figure 5.2). The thickness of alluvium in the wellfield varies between 10-12 metres, thinning towards the north (Anon, 1983). The alluvium mainly consists of a rather mixed sand and gravel deposit with a grain size ranging from silty clays to cobbles (Watt *et al.*, 1986). It can be further subdivided into lower and upper alluvium, which are separated by a discontinuous silty layer usually less than 1 m thick. The average depth of the silty layer is about 7 to 8 m below the ground level.

Evaluation of pumping test data from the production boreholes indicates that the hydraulic conductivity of the alluvium varies considerably, between 20 and 200 m/day. The average value is 80 m/day and this reduces towards the edge of the floodplain. The storage coefficients of the alluvium range from 9×10^{-5} to 0.1 for the confined and unconfined alluvium respectively.

The river penetrates only partially into the upper alluvium, and the high discharges characteristic of the Spey dictate that no fine-grained river-bed materials lie between the river and the alluvium. The mean river flow of the Spey at the nearest gauging station, at Boat O'Brig some 6 km distance upstream of the wellfield, is 60 cumecs. The annual rainfall in the area varies between 600-800 mm. Thus effective recharge to the unconfined alluvium estimated from the rainfall minus actual evapotranspration ranges from 0.3 to 0.8 mm/day (Robins, 1990).

3. MODELLING GROUNDWATER-SURFACE WATER INTERACTIONS

3.1 Numerical Modelling Approach

Over recent years, groundwater modelling has been extensively employed in the simulation of river-aquifer system and groundwater protection programmes (for example Chen *et al.*, 1996; Chen and Soulsby, 1996; Papatolios and Lerner, 1993; Pucci and Pope, 1995; Sophocleous and Perkins, 1993; Younger *et al.*, 1993). The US Geological Survey MODFLOW, a three-dimensional finite-difference groundwater model developed by McDonald and Harbaugh (1988), has been used in this study with the river package being used to simulate the river-aquifer interactions. A traditional trial and error approach and MODFLOWP (Hill, 1992), a nonlinear regression method, were jointly employed during model calibration and sensitivity analysis.

The data input requirements of both MODFLOW and MODPATH are extensive and MODELCAD (Rumbaugh, 1993), a preprocessor, was employed to design the model, which was then translated into the model datasets. In addition, ARC/INFO GIS was used to digitise the model boundaries and the river course. All the contour maps including the interpretation of the model results have been drawn using a SURFER kriging interpolation option to minimize data uncertainties (GS, 1995).

3.2 Conceptual Model and Model Setup

The conceptual model of the study area is relatively simple, consisting of two hydrostratigraphical units: upper alluvium (layer 1) and lower (layer 2), separated by a aquitard, averaging 0.5 m thickness at a depth of around 7 m below the ground level. The alluvium is underlain by the Old Red Sandstone (Figure 5.2). A quasi three-dimensional model was formulated, with layer 1 representing a unconfined condition and layer 2 a leaky confined condition. The aquitard was introduced into the model through a leakage term for the confining silt layer.

The limit of the alluvium conforms with the western and eastern boundaries of the modelled area. There is a distinct topographic break along the limit of alluvium corresponding to outcrops of Old Red Sandstone (Anon, 1983). The northern and southern boundaries of the modelled area were assigned constant hydraulic heads, which were derived from the observed water table data for both layers (Figure 5.3). Natural boundary conditions are also illustrated. These include no-flow boundaries along the limit of alluvium for both model layers and the bottom of the layer 2 below which the Old Red Sandstone is present. Fixed heads were specified for the river nodes and a recharge boundary was applied to the top of layer 1.

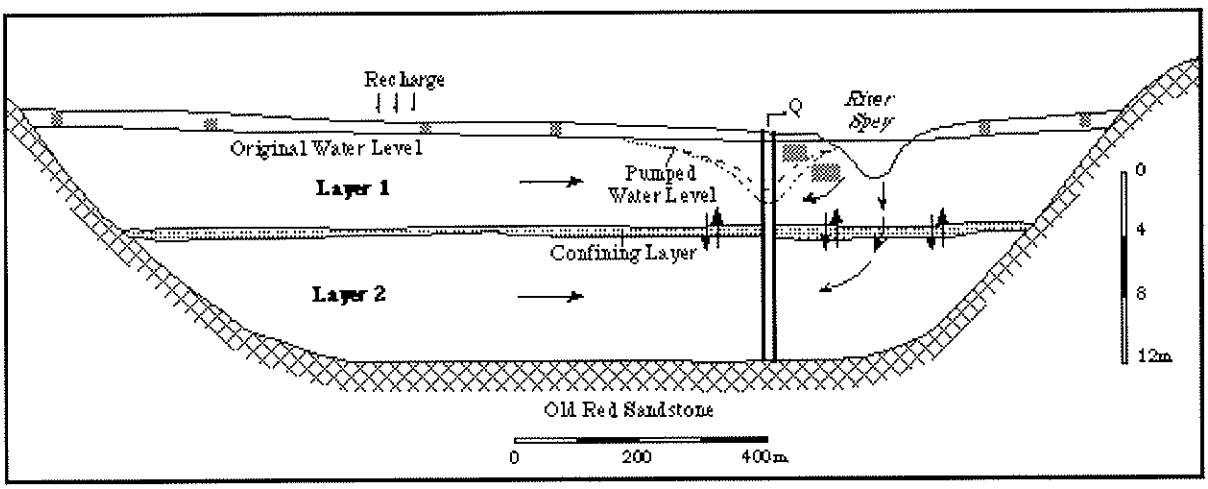


Figure 5.2 *Conceptual model of river-aquifer interactions at the Spey Abstraction Scheme showing potential effect of abstract on water levels*

Under natural conditions, groundwater generally flows from the southwest to northeast in the alluvium, with a hydraulic gradient of approximately 0.003. It appears to be discharged predominantly into the river at the northern end of the site. The effective recharge is through the upper alluvium, where the groundwater table is normally between 1 and 2 metres below the ground surface. There are considerable interactions between layer 1 and the river. However the extent of the interactions between layer 2 and river are not well established.

The modelled area was discretised using a variably spaced block-centered finite-difference grid of 60 rows and 32 columns; giving a total of 2548 active cells including 102 river and 68 constant cells. There are also 1292 inactive cells due to the irregular shape of the model area;

these have no effect on the model solution. The grid was oriented subparallel to the limit of the alluvium as well as the general hydraulic gradient. A finer grid was specifically designed for the wellfield and along the river to allow for a more accurate representation of hydraulic heads and input parameters (Figure 5.3). Detailed model calibration and sensitivity analysis have been presented elsewhere (Chen *et al.*, 1996). The result of model calibration shows a good match between model produced and observed water levels for layer 1 (Figure 5.4).

3.3 Simulation Results

Three steady-state scenarios were simulated using the calibrated model: pre-development, current pumping rate (16000 m^3/day) and projected maximum pumping rate (27000 m^3/day).

Under the stressed conditions, 32 out of 36 production boreholes were selected, each pumping at a averaged value of the total specified abstraction rate depending on the scenario chosen. Because of the boreholes penetrating both the model layers, the pumping rate for each borehole was then apportioned between the two model layers according to the relative transmissivity of each layer (Anderson and Woessner, 1992).

3.3.1 Pre-development

The pre-development simulation indicated that the calibrated model has successfully reproduced the water table contour map for layer 1 (Figure 5.4). The hydraulic gradient, as shown in the water table contour map of layer 1, is slightly higher in the central part of the modelled area. Groundwater generally flows from the southwest to northeast and is mainly discharged into the river. The potentiometric surface of layer 2 is similar in character to that in layer 1, however a vertical hydraulic gradient exists between the two model layers. The water level difference between the model layers is the highest in the region adjacent to the river, and ranges from 0.2 to 0.6 m, becoming negligible towards the western edge of the floodplain.

The pre-development water budget indicates that the river captures 94% of total groundwater inflow, which includes the recharge contribution (1680 m^3/day), boundary inflow from the constant heads (6545 m^3/day) and the small amount of river leakage into the groundwater (198 m^3/day) (Table 5.1). Boundary outflow therefore only represents 6% of the total outflow. Subregional water budgets suggest a significant upward water movement (5685 m^3/day) from the confined lower layer 2 to layer 1. This is eventually discharged into the river under the predominantly vertical hydraulic gradient (Figure 5.5).

3.3.2 Current pumping rate (16000 m^3/day)

Significant changes in relation to the pre-development simulation include the marked increase of induced river leakage into the aquifer, from 198 m^3/day to 11366 m^3/day, and the reduced groundwater discharge into the river, from 7914 m^3/day to 3381 m^3/day (Table 5.1). The water drawn from the river accounts for 69% of the total abstraction rate, and the more detailed breakdown suggests an equal contribution from each individual layer. River water enters layer 2 through the aquitard, as reflected in the increased leakage for layer 1, from 234 m^3/day to 6346 m^3/day. The water transfer from layer 2 to layer 1 has been considerably reduced (Figure 5.5).

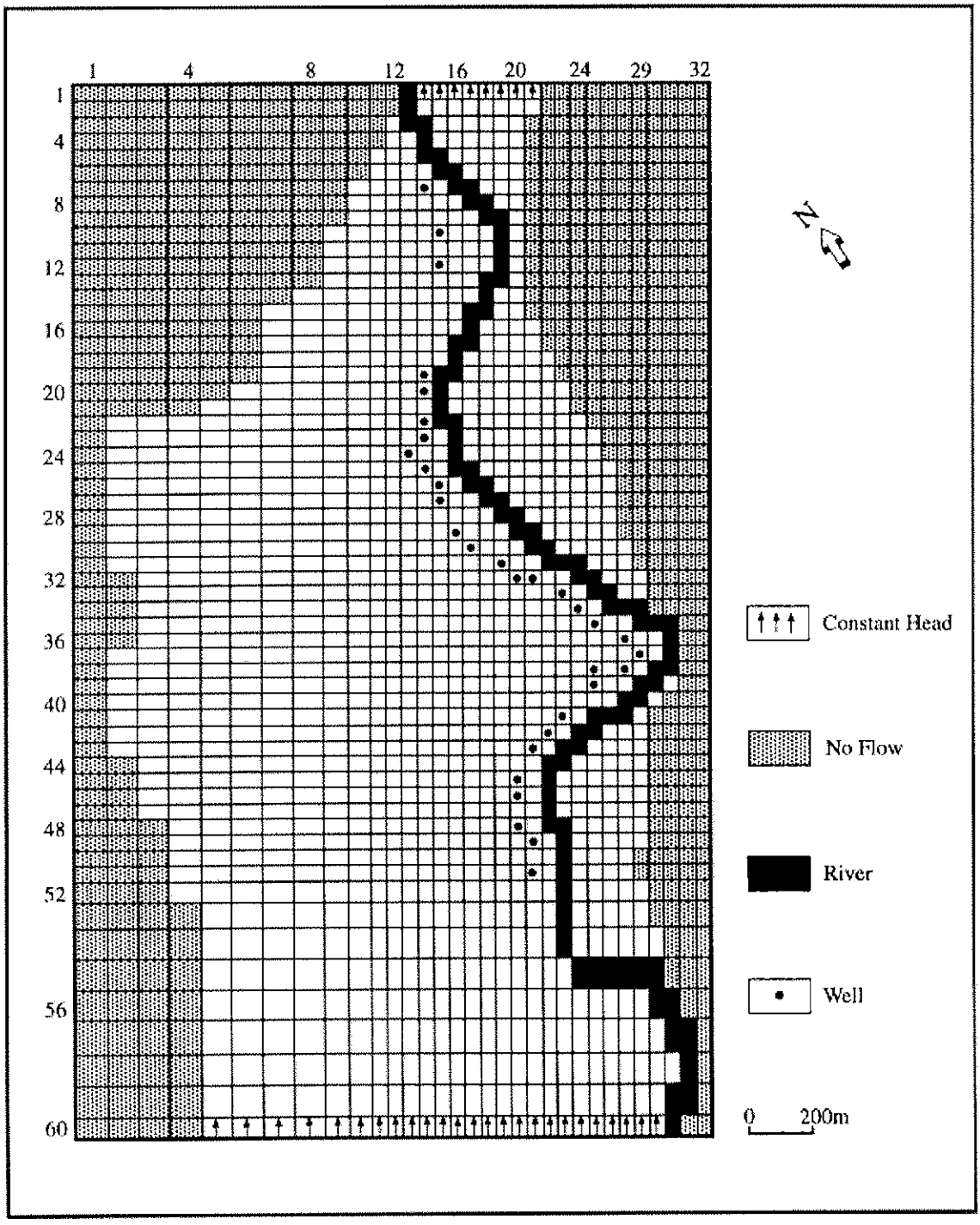


Figure 5.3 *Model grid and boundary conditions of layer 1. Note: boundary conditions for layer 2 are similiar to those of layer1 except no river nodes*

The results of the volumetric water budget show that the river loses water to the wellfield. The amount of water lost is not considered to be of any significance, as the present pumping rate only represents 1.7% of the recorded minimum river flow of 9.31 cumecs (Anon, 1988).

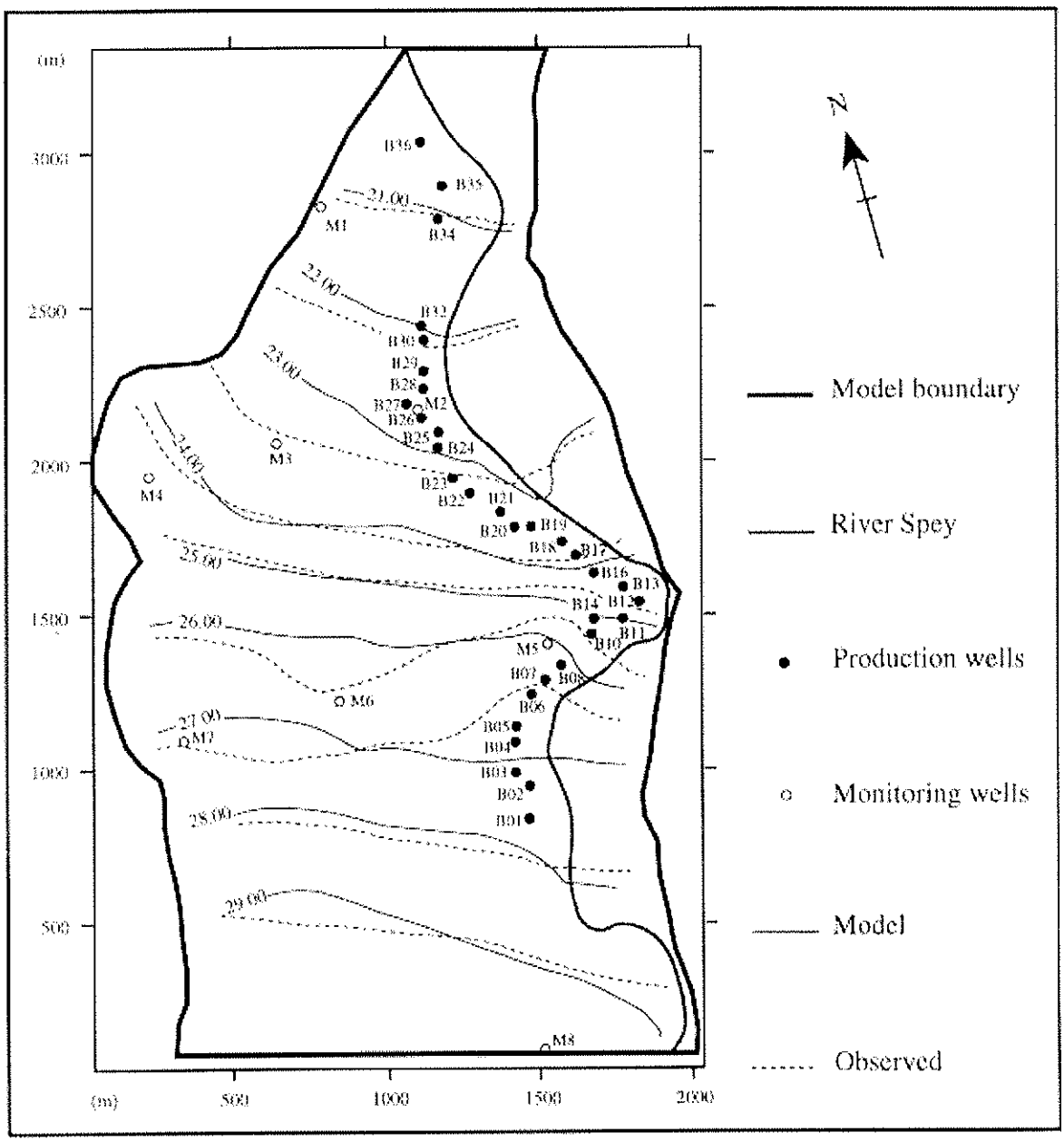


Figure 5.4 Simulated and observed potentiometric surface of layer 1 during the pre-development stage

3.3.3 Projected Pumping Rate (27000 m^3/day)

The predictive simulation run was carried out under the projected maximum pumping rate of 27000 m^3/day, envisaged to meet demands in the year of 2011. Compared with the previous simulation, the wellfield abstraction at the projected pumpage shows a further increase in the river seepage into the aquifer, to 20094 m^3/day, and decrease in the groundwater discharge into the river, to 2409 m^3/day. There is a corresponding increase in the percentage of water drawn from the river, accounting for 74% of the total abstraction rate, comprising 76% and 73% for layer 1 and layer 2 respectively (Table 5.1). Water transfer from layer 2 to layer 1 is

further decreased to 2860 m^3/day and the leakage from layer 1 to layer 2 is increased to 10516 m^3/day (Figure 5.5).

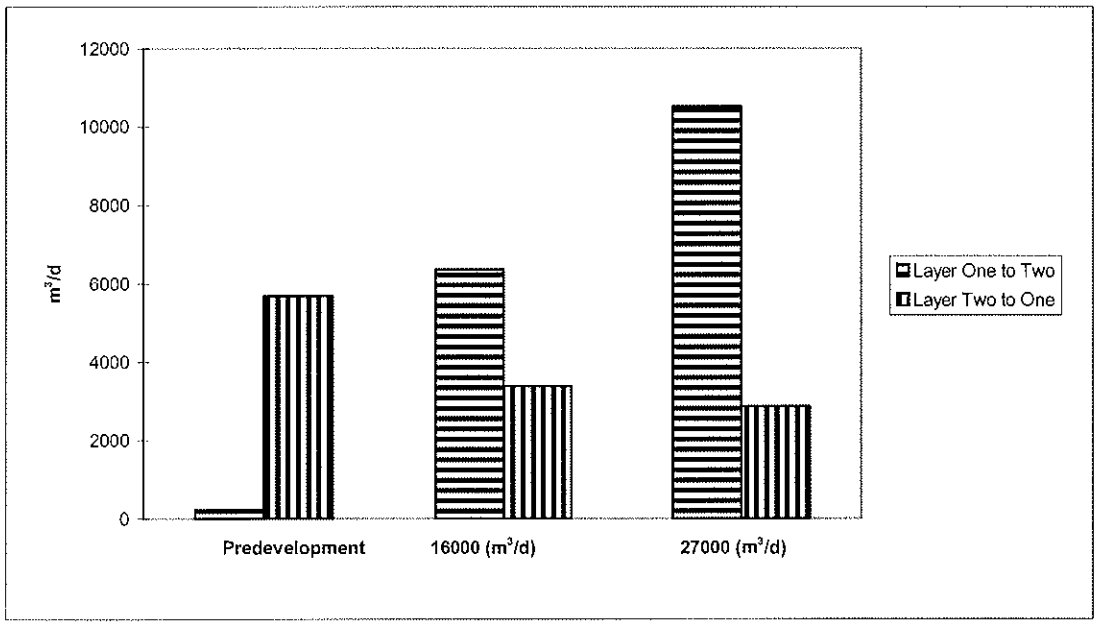


Figure 5.5 *Water transfer between the model layers in three simulated steady-state scenarios*

4. WELLFIELD PROTECTION ZONES (WPZ)

4.1 Capture Zone Definition

Groundwater protection schemes are normally carried out by delineating a number of travel time related capture zones (or wellhead protection areas) around a borehole or the wellfield from a steady-state groundwater model. Certain potentially polluting activities are banned or regulated within such zones. The Environment Agency (EA) in England and Wales has defined wellhead protection zones, based on the 50-day (*Zone 1*) and 400-day (*Zone 2*) travel times and the whole catchment source (*Zone 3*) as part of its Groundwater Protection Policy (EA, 1992). A similar approach has been advocated in the more recent development of a Groundwater Protection Strategy for Scotland (ADRIS, 1995). These areas are delineated using numerical modelling techniques, and this approach for the definition of the wellhead protection zones is adopted here.

After groundwater model formulation and model simulation, particle tracking techniques, using MODPATH (Pollock, 1989), were applied to compute flow paths and delineate the travel time-related capture zones at the projected maximum pumping rate of 27000 m^3/day. These are based on average linear velocities and hydrodynamic dispersion was not considered. An effective porosity of 0.40 was adopted to calculate the average linear velocity fields from the simulated head distribution.

a) Pre-development

Sources and Discharges	Flow (m^3/day)	Percentage of total	*River-Aquifer Interaction
Sources:			
Recharge	1680	20	
Boundary Inflow	6545	78	Dominated by groundwater contribution to river
Seepage from river	198	2	
TOTAL	8423	100	
Discharges:			
Seepage to river	7914	94	
Boundary Outflow	506	6	
TOTAL	8420	100	

b) Wellfield Abstraction (16Ml/d)

Sources and Discharges	Flow (m^3/day)	Percentage of total	*River-Aquifer Interaction
Sources:			
Recharge	1680	8	
Boundary Inflow	7196	36	
Seepage from river	11366	56	
TOTAL	20242	100	69%
Discharges:			
Seepage to river	3381	17	
Boundary Outflow	395	2	
Wellfield Abstraction	16470	81	
TOTAL	20246	100	

c) Wellfield Abstraction (27Ml/d)

Sources and Discharges	Flow (m^3/day)	Percentage of total	*River-Aquifer Interaction
Sources:			
Recharge	1680	6	
Boundary Inflow	7941	27	
Seepage from river	20094	67	
TOTAL	29715	100	74%
Discharges:			
Seepage to river	2409	8	
Boundary Outflow	367	1	
Wellfield Abstraction	27000	91	
TOTAL	29716	100	

Table 5.1 *Simulated volumetric water budget of the Spey river-aquifer system. Note: river-aquifer interaction is represented by the percentage of water from river divided by total wellfield abstraction*

Travel time-related capture zones were computed by placing a series of particles in a small circle surrounding each production borehole and tracking their reverse flowpaths for a specific period of time. The loci of flowpath endpoints encompasses the capture area of the wellfield for the specified time period. Three capture zones (or wellhead protection zones) were then defined using the 50-day and 400-day travel isochrons for layer 1. The size and shape of each zone are determined mainly by the hydrogeological characteristics of the river-aquifer system and the direction of groundwater flow.

Zone 1 lies within the 50-day travel isochron, which implies that the potential contaminants below the water table in the region would be captured by the wellfield within 50 days or less; *zone 2*, between the 50-day and 400-day travel isochron, within which the potential contaminants would reach the wellfield within 400 days or less, and *zone 3*, which covers the rest of the modelled catchment beyond the 400-day travel isochron. The 5-year capture zone within *zone 3* was also delineated in order to understand the general travel time characteristics of the modelled catchment. Forward particle tracking analysis was performed to calculate the time needed for a potential contaminant to travel from the M1-M8 monitoring wells to the wellfield for the unconfined layer 1, and was used to test the efficiency of these monitoring wells.

4.2 Capture Zone Characteristics

4.2. 1 50-day capture zone (Zone 1)

The 50-day capture zone is based on the time necessary for biological contaminants to decay and is designed to protect against the effects of human activities that are immediately adjacent to the groundwater source (EA, 1992). The 50-day capture zones in both model layers are nearly identical in geometry except that the Eastern limit in layer 1 is bounded by the river itself. Because of the high water-transmitting properties of the alluvium and the complex hydrogeological systems that the model represents, the 50-day capture zones take highly irregular shapes. These consist of several discrete regions, which are attributed mainly to the distance and the pumping rates of two neighbouring wells. The extent of this zone is generally situated within 200 m of the river and is centered on the wellfield (Figure 5.6). The cumulative size of the 50-day capture zones is small for both model layers, being approximately 0.5 km^2, or one-twelfth of the modelled area.

The reverse particle tracking analysis indicated that the majority of the imaginary contaminant particles in layer 1 terminated in the river nodes within 10-40 days. In other words, the river would be the primary potential polluting source. Given the high hydraulic conductivities and marked hydraulic gradients it is not surprising that the shortest time for particles to travel from the river to the wellfield is just under a day. It is worth noting, in particular, that the production boreholes from B6 to B18 may draw water in layer 1 entirely from the river according to the particle starting and ending locations. This can be attributed to the higher hydraulic gradients between the river and these boreholes, and it suggests that river-aquifer interactions in this area are at maximum (Figure 5.6). A similar inference can be drawn for the boreholes B1-B5 and B19-29 which abstract significant amounts of groundwater from the alluvium.

4.2.2 400-day capture zone (Zone 2)

The 400-day capture zone is defined by the time required to provide delay and attenuation of slowly degrading contaminants (EA, 1992). It would also allow sufficient time to take any necessary remedial measures once the contaminants are detected.

Like the 50-day capture zones, the 400-day capture zones (*zone* 2) exhibit highly irregular geometry around the wellfield. They extend further westward for both the model layers and eastward for the confined alluvium. The eastern limit of the 400-day capture zone in the layer 1 is bounded by the river (Figure 5.6). *Zone 2* of layer 1 covers approximately 0.75 km^2.

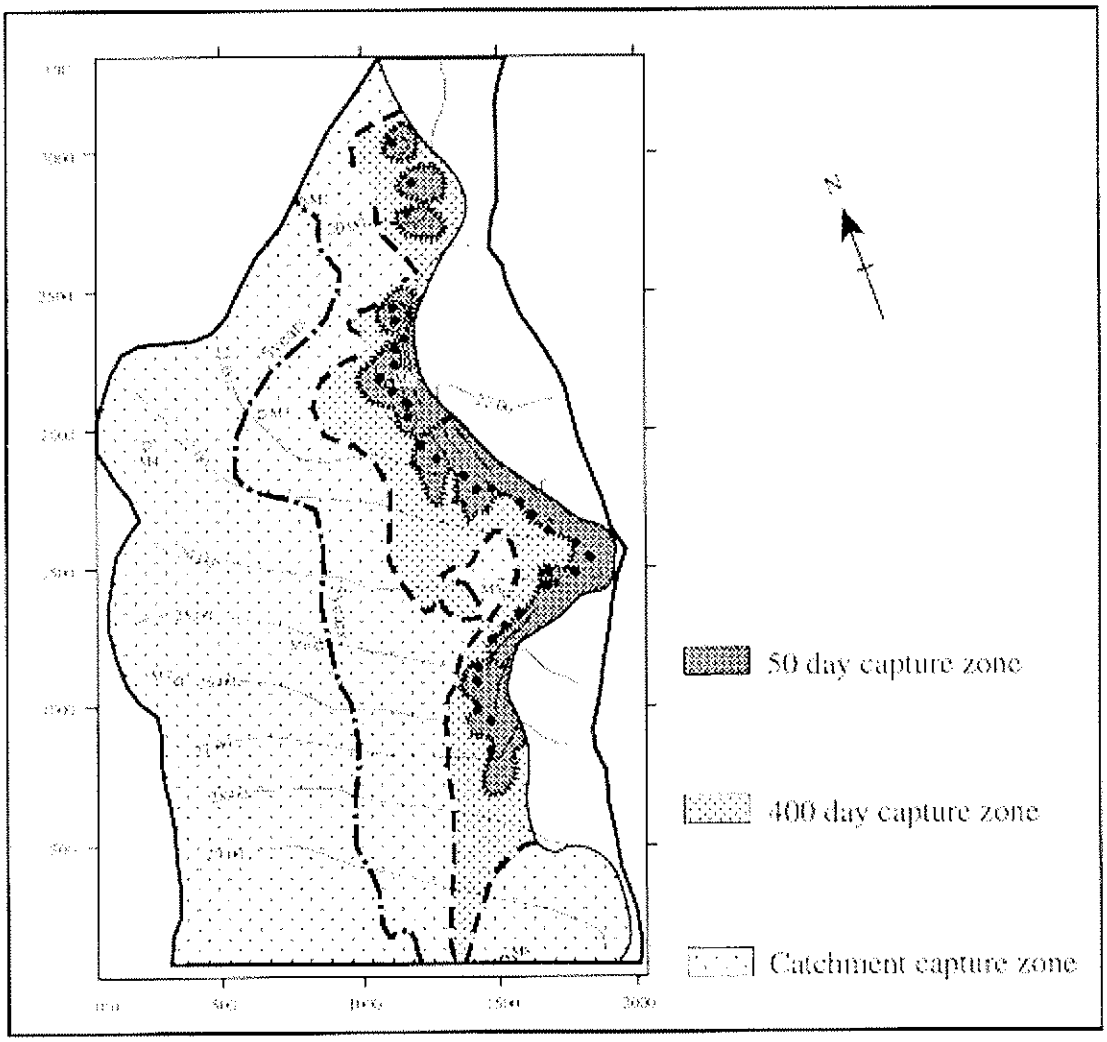


Figure 5.6 Simulated potentiometric surface and capture zones of layer 1 under the projected pumping rate of 27000 m^3/day(also see Figure 5.4 for legend)

4.2.3 Catchment Source Zone (Zone 3)

Zone 3 covers the rest of the modelled catchment beyond the 400-day travel isochron and any contaminant emanating from *zone 3* would eventually discharge into the wellfield with the varying time scales all exceeding 400 days. The time required for contaminants to reach the wellfield depends on many factors, such as their initial positions, hydrogeological properties of the alluvium and the distance to the pumping wells. It can be seen that the 5-year capture zones cover more than 33% of the modelled area for layer 1 (Figure 5.6).

The forward tracking analysis indicated that contaminants detected from the monitoring wells M6, M3 and M1 would be captured by the wellfield within approximately 7, 3 and 4 years respectively. It would take a considerable time for contaminants in monitoring wells M4 (19 years) and M7 (27 years) to reach the wellfield. The longer durations are attributed to the low hydraulic conductivities along the western boundary and the long distance to the wellfield. It would take only 24 days for contaminants from the monitoring well M2, and about 2 years from M5 and M8 to reach the wellfield (Figure 5.6).

5. AQUIFER MANAGEMENT

This study of river-aquifer interactions and the delineation of wellfield protection zones demonstrates the potential of numerical groundwater models as management tools in groundwater protection.

The modelling work has confirmed earlier suggestions that the primary potential source of pollution for the wellfield is the river Spey itself. However, the modelling also indicated that significant potential threats to groundwater integrity could come from pollution sources within the 50-day (*Zone 1*) and 400-day (*Zone 2*) capture zones. Thus, there is a need to carefully control land use and other activities in these two zones in accordance with the Groundwater Protection Strategy for Scotland (ADRIS, 1995). The critical components for a comprehensive monitoring programme for groundwater protection are a network of monitoring wells around the perimeter of wellhead protection zones and a continuous pollution monitor in the river upstream. The purpose of the these monitoring measures is to allow the early detection of possible groundwater and surface water contamination and to take any remedial action, such as the pump shutdown and backflushing the wellfield during any period of river pollution (Anon, 1990).

This modelling study suggests that the current plan for water quality monitoring perhaps needs to be enhanced. First, the planned pollution monitoring at the Boat O'Brig, some 6 km upstream of the wellfield (Figure 5.1a) should be installed as soon as possible and indeed this work is currently underway (Anon, 1990). Secondly, the present groundwater monitoring network in the modelled area could usefully be extended because most of the monitoring piezometers are located within the wellfield inside the 50-day capture zone and would give very short lead times to respond to pollution detection. Moreover, all the permanent monitoring wells, with the exception of M2, fall outside the 50 and 400-day capture zones with very long travel times. It would therefore be advantageous to install further monitoring wells along the perimeter of the 50-day and 400-day capture zones, and perhaps the 5-year capture zone.

For the purpose of land-use control, the Scheme operators have purchased the two farms within which the wellfield is situated, and have already imposed restrictions on potentially polluting farm practices. An irrigation system has also been introduced to replenish soil moisture deficits during droughts which may be exacerbated by the drawdown resulting from wellfield pumping. However, current and simulated drawdown indicate that the magnitude and extent of the drawdown caused by pumping more than 20% of the water from the alluvium itself may previously have been underestimated (Watt *et al.*, 1986). This, together with strict restrictions in farm practices (eg limiting fertilizer applications) could reduce crop production. At present, the restrictions on farm practices have been imposed over a larger area than the capture zones indicate is necessary. However, this strategy may be considered favourable as it adopts a precautionary approach to groundwater protection. Clearly, economic estimates of the costs of land-use restrictions and irrigation supplies should be evaluated in relation to the benefits of groundwater protection if the operating costs of the scheme are to be properly appreciated.

6. CONCLUSIONS

The pre-development water budget indicates that 94% of total groundwater inflow is discharged into the river. In contrast, the budgets for stressed conditions give the percentage of water abstracted from the river as 69% and 74% for pumping rates of 16000 m^3/day and 27000 m^3/day respectively. Significant differences in simulated river-aquifer interactions between the pre-development and stressed scenarios include: (1) induced river seepage; (2) reduced groundwater discharge to the river and (3) increased leakage from the river to the confined lower layer 2. Most significantly, the projected pumping rate will not produce a noticeable reduction in the river flow.

It is recommended that rigorous programs for monitoring water quality both in the river upstream, and along the perimeter of *zones 1* and *2* within the modelled catchment are required to protect the Spey Abstraction Scheme. Water quality monitoring strategy would include the routine sampling and analyses of (1) the river water at the Boat O'Brig, (2) the production boreholes and (3) the monitoring wells installed along the perimeter of the capture zones.

Acknowledgements

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6

The effect of the hydrology of a Thames flood meadow on its vegetation pattern

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Abstract

Water-table depth is perhaps the most important environmental factor to be considered when studying the vegetation of floodplain grasslands. In order to manage the hydrology of these habitats effectively, the tolerance of different vegetation types to water table regimes needs to be known. Hydrological modelling can be used to deduce these tolerances by studying hydrologically stable sites, which display spatial variation within them. Cricklade North Meadow, a National Nature Reserve adjacent to the River Thames, is used as an example. The output of the validated model is analysed by a peak-over-threshold technique known as Sum Exceedence Values, which are then used to explain the spatial pattern of vegetation types.

The approach illustrates the need to consider the stresses imposed on the vegetation by waterlogging separately from those imposed by drought later in the year. The hydrological study of a site with ecological interest, should identify the time of the year when interspecific competition within the vegetation is most intense, because the water-table behaviour at these critical periods has the greatest impact on the plant community composition.

1. INTRODUCTION

In wet grassland habitats, the soil water-table regime is the main environmental factor determining the relative competitive abilities of plant species. The water-table regime not only regulates water supply to the plant, but also has a major influence on nutrient supply and in some instances grazing intensity. Thus, in order to understand the distribution patterns of either individual plant species or whole plant communities within this type of habitat, the spatial variation in the water regime has first to be known. Such knowledge can be used to guide the management of the site in the interests of ecological conservation.

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This paper describes a case study in which hydrological modelling is used to define the water-table regime of a species-rich wet grassland in quantitative terms. The study is part of a larger programme of work which aims to describe the water-regime tolerances of native grassland species (Gowing and Spoors in press; Spoor *et al.*, 1996). The site here is Cricklade North Meadow, a National Nature Reserve, renowned for its large population of Snakeshead Fritillary (*Fritillaria meleagris* L.). The meadow is some 50 ha in extent and contains at least three distinct grassland communities as defined by the National Vegetation Classification (NVC; Rodwell, 1992). The paper sets out to describe how the apparently complex distribution of the three communities can be understood from a relatively simple analysis of the water-table regime. The results are discussed in terms of the meadow's hydrological management that can be used to influence the relative competitive abilities of the different vegetation types.

2. HYDROLOGY AND SITE MANAGEMENT

The meadow is bounded, as illustrated in Figure 6.1 by two rivers, the Thames and the Churn, whose stage-level behaviour dominates its water regime, which is unusual for a site of this size. Lateral seepage from water-courses in most situations only influences the water regime for a distance up to about 50 m or so, yet in this instance the rivers are almost 1 km apart at some places. The reason for this difference is the superficial geology of the area (Figure 6.2).

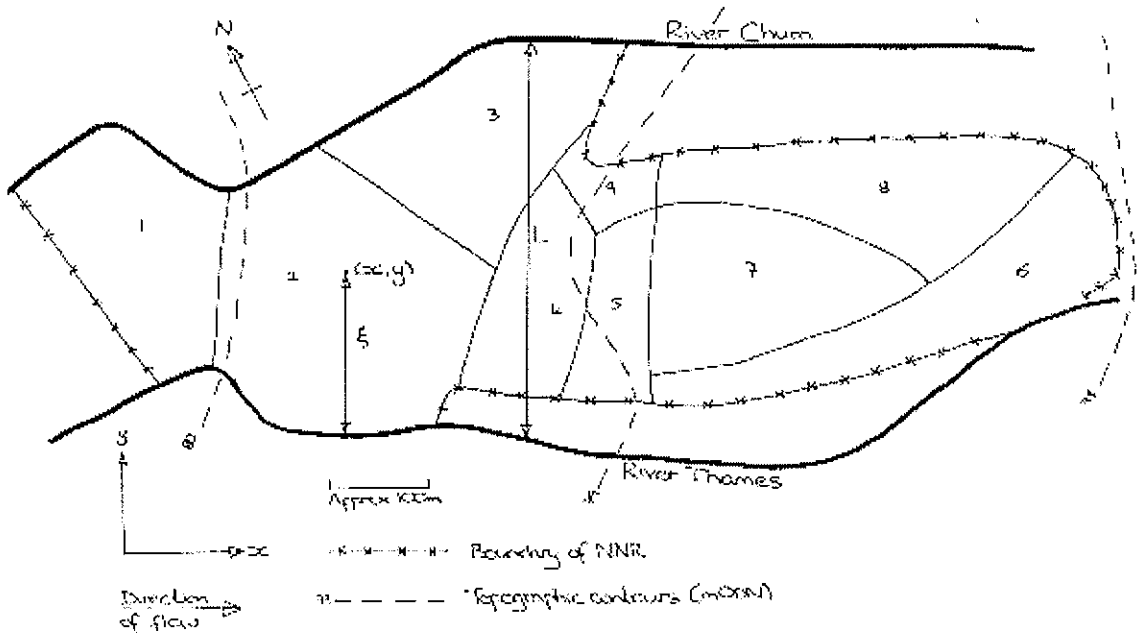


Figure 6.1 *A sketch map of the meadow indicating the relative positions of the two rivers and some of the spatial variables used in the hydrological analysis. Numbers refer to the nine compartments used in the treatment of surface flooding*

The whole area is underlain by the major limestone aquifer of the Cotswolds, but this is confined by the overlying deposit of slowly permeable Oxford clay. Sitting atop the clay are river-terrace deposits of mainly coarse sand and gravel which are very permeable and are in

good hydraulic connection with the two rivers. It is this layer which transmits the hydraulic head of the rivers right across the site. Finally, finer-textured alluvium lying over this layer of sand and gravel gives rise to soils of the Thames and Kelmscott series (Payne, 1987).

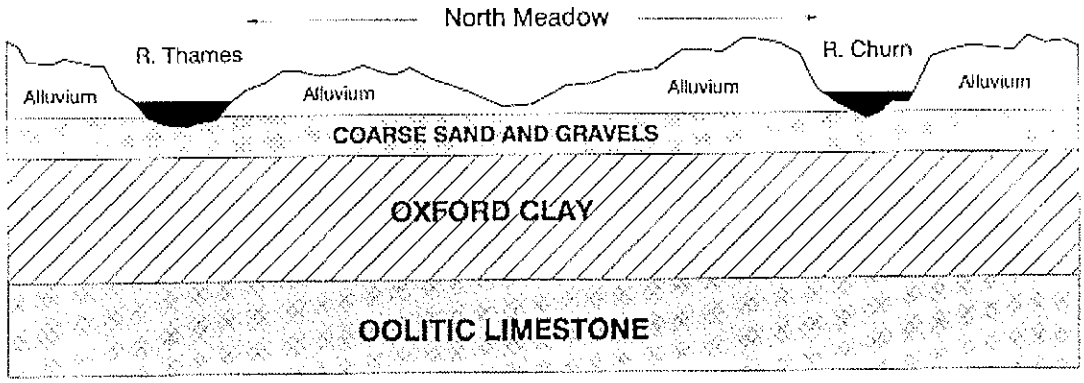


Figure 6.2 A simplified geological profile of Cricklade North Meadow

The rivers regularly over-flow their banks during winter and the meadow is completely submerged for a few days on average each year. There has been no under-drainage of the site and no agricultural intensification because of the peculiar laid-tenure arrangements of a lammas meadow, which give the townsfolk of Cricklade commoners' rights. The combination of the flood meadow hydrology and the sympathetic historical management has created a classic example of the vegetation type defined as MG4 *Alopecurus pratensis - Sanguisorba officinalis* grassland by the NVC. It is believed that the meadow contains 1.5 million plants of Snakeshead Fritillary which accounts for some 80% of the British population of this species. The conservation of the meadow in its present form is therefore of high priority and hydrological management is central to this.

3. HYDROLOGICAL MODELLING

A detailed historical data set exists for the meadow's hydrological behaviour, which has allowed a calibration and validation of a model specifically designed for the site. The stage-levels of both rivers are recorded daily by the Environment Agency (Figure 6.3) and seven dipwells within the meadow have been monitored on approximately a monthly basis by English Nature since 1979 (Figure 6.4). Climate data have been supplied by the Meteorological Office. The hydraulic conductivity of the saturated surface alluvium and its drainable porosity were measured *in situ*.

It can be assumed that the competitive ability of a plant species responds to the behaviour of the water table depth below the soil surface. In order to model this depth with time, it was assumed that :

(a) both rivers are in good connection with the minor aquifer of the sand and gravel above the Oxford clay;

(b) no loss of water occurs by deep seepage through the Oxford clay bedrock; and

(c) the net surface flux due to rainfall and evaporation is uniform across the site.

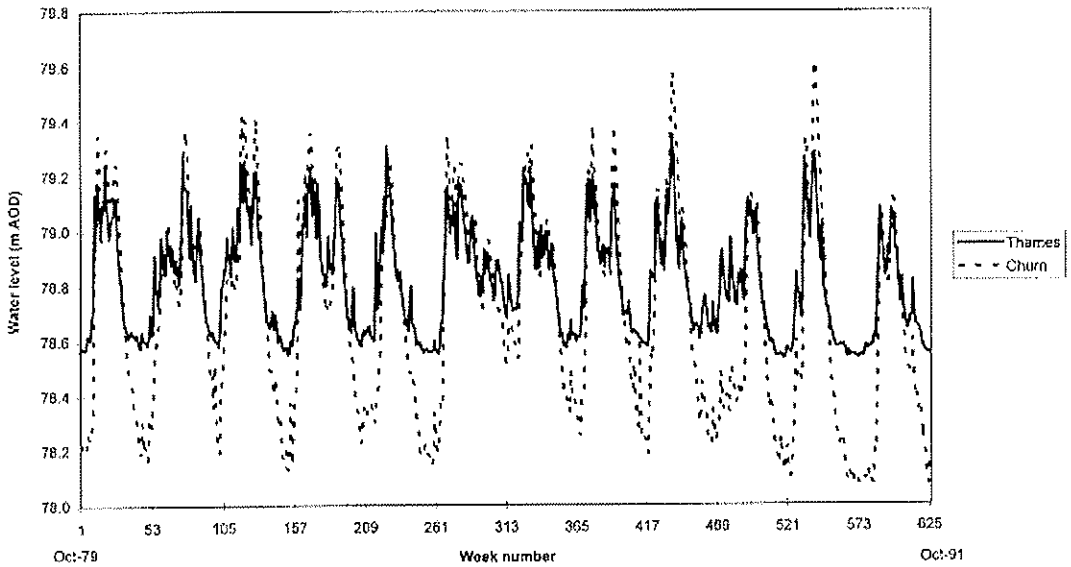


Figure 6.3 *River stage levels at Cricklade North Meadow (derived from data supplied by courtesy of the Environment Agency)*

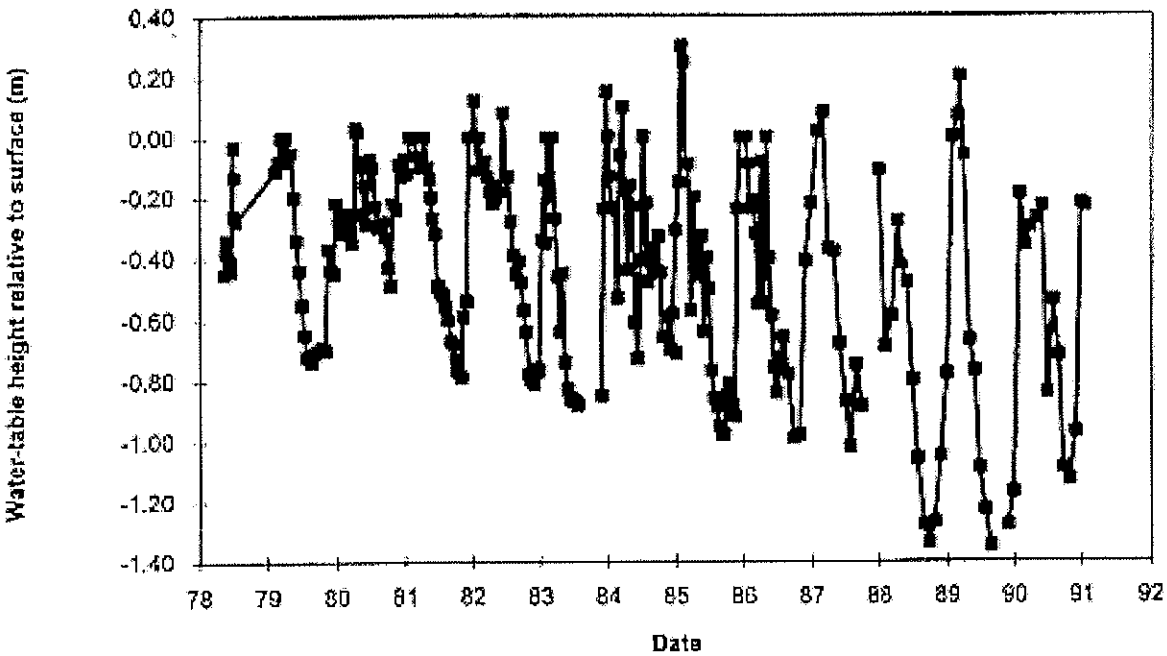


Figure 6.4 *A sample data set of dipwell readings from a single position in Cricklade North Meadow (data supplied by courtesy of English Nature)*

In order to obtain sufficient information to form a link between species distribution and water regime, approximately 600 sample points were taken at random across the meadow. At each

of these points, co-ordinates (x,y) with the x-direction in the general direction of the river flow and the y-direction normal to the river flow, a complete species list was made for a $1m^2$ quadrat. At each point the spacing L_x between the rivers was found and the depth $s_{x,y}$ of the clay alluvium overlying the sand/gravel aquifer and the spot height $d_{x,y}$ relative to ordnance datum recorded.

Three hydrological scenarios had to be considered:

3.1 When flooding occurs. The meadow was divided into 9 compartments, as shown in Fig. 1, based on a general topographic survey. For each compartment, threshold levels for the inflow and outflow of flood water from each river were estimated. The water depth then was simply set by the difference between river level and spot height. Generally, the stage level in the Thames was higher than that of the Churn, so considering the Thames in flood, we write the water depth $w_{x,y}$, measured relative to the soil surface at (x,y), as

$$w_{x,y} = d_{x,y} - h_{T,x} \tag{1}$$

where $h_{T,x}$ is the stage level of the Thames at x.

3.2 when the water table is within the clay alluvium. With the flow through the gravel and sand layer considered to be steady and horizontal from the rivers, the hydraulic head $h_{x,y}$ in the minor aquifer at (x,y) can be calculated as

$$h_{x,y} = h_{T,x} - (h_{T,x} - h_{C,x})\frac{\xi_x}{L_x} - \frac{V'}{2T_x}(L_x\xi_x - \xi_x^2) \tag{2}$$

where ξ_x is the normal distance from the Thames, $h_{T,x}$ and $h_{C,x}$ are stage levels in the Thames and Churn respectively; V' is the vertical flux measured positive upwards into the clay from the minor aquifer, and T_x is the transmissivity of the minor aquifer at that point.

In the clay soil the flow is assumed to be vertical. The water table position is modelled assuming the non-steady state approximates to a succession of steady states with a vertical flux given by the average flux over a chosen increment of time. The flux V' is given by

$$V' = V - S\frac{\mathrm{d}w_{x,y}}{\mathrm{d}t} \tag{3}$$

where V is the net surface flux given by the evaporation minus the rainfall rate and $w_{x,y}$ is the depth of the water table below the soil at (x,y) at time t. Applying Darcy's law, for the flow between the water table and the base of the clay soil where it adjoins the sand and gravel minor aquifer, we have

$$h_{x,y} = d_{x,y} - w_{x,y} + (s_{x,y} - w_{x,y})\left(\frac{V}{K_s} - \frac{S}{K_s}\frac{\mathrm{d}w_{x,y}}{\mathrm{d}t}\right) \tag{4}$$

where K_s is the hydraulic conductivity of the saturated clay soil and S is its specific yield. Combining Eqns. (2) and (4), gives;

$$\frac{dw_{x,y}}{dt} = \frac{1}{S}\left[V - \frac{h_{T,x} - (h_{T,x} - h_{C,x})\xi_{x,y} / L_x - (d_{x,y} - w_{x,y})}{(s_{x,y} - w_{x,y}) / K_s + (L_x\xi_{x,y} - \xi_{x,y}^2) / 2T}\right] \qquad (5)$$

which can be solved numerically to estimate the depth $w_{x,y}$ to the water table as a function of time t.

3.3 When the water table is within the sand and gravel layer. A similar approach is taken to that described in section 3.2 above with the transmissivity of the aquifer reduced as a function of its degree of saturation and a different specific yield to reflect the greater porosity of the aquifer.

$h_{T,x}$, $h_{C,x}$ and V were available from historic data sets and K_s and S were measured in the field. The transmissivity T could not be measured directly due to the disturbance to the vegetation which would have been involved. The value for T in each compartment of the meadow was instead optimised on the dipwell record over a two-year period, and validated against observations for a third year (Figure 6.5). In this way the water table behaviour for each of the 600 sampled points was modelled on a weekly basis over a 12-year period.

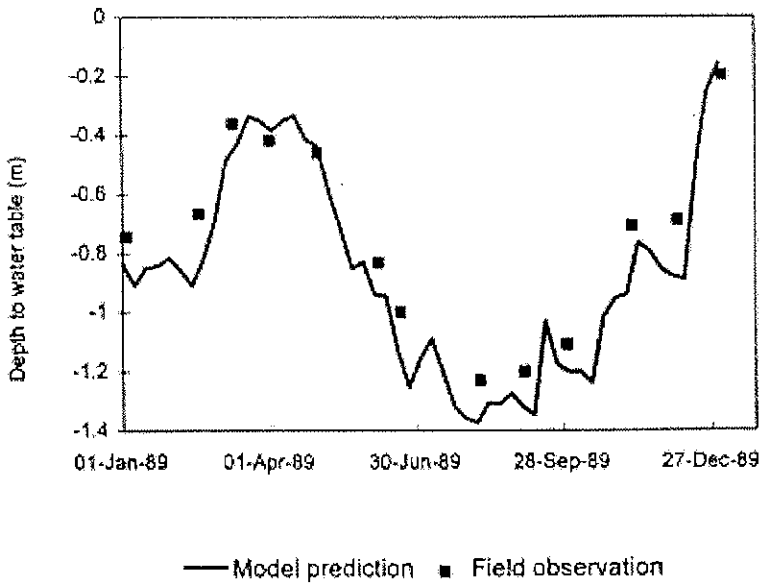


Figure 6.5 *Validation of the hydrological model against dipwell observations in Cricklade North Meadow*

4. ANALYSIS OF THE WATER REGIME

It is necessary to interpret the raw hydrological data, generated as water-table depths, in a manner relevant to plant competition. The simplest parameter to take would be the mean

water-table depth for a given point and relate this to the vegetation. This was found not to be very helpful, however, as plant competition is determined by the occurrence of stressful episodes caused by very high water tables (aeration stress) or very low water tables (drought stress). Taking a simple mean would result in the loss of this information. The preferred method was a "peak over threshold" analysis, first described by Sieben (1965), using Sum Exceedence Values (SEVs).

Figure 6.6 illustrates how SEVs can be derived from a plot of water-table depth. The SEV for aeration stress is a measure of the time period and extent to which the water table is shallower than a threshold depth during the growing season, when there is a high demand for oxygen in the root zone. The threshold is set using the moisture release characteristic to estimate the point at which the air-filled porosity of the surface layer would fall below 10% and therefore limit the free diffusion of oxygen from the atmosphere into the soil (Wesseling and Van Wijk, 1975). The SEV is defined as the area under the water-table depth plot but above this critical threshold during the period of March to September.

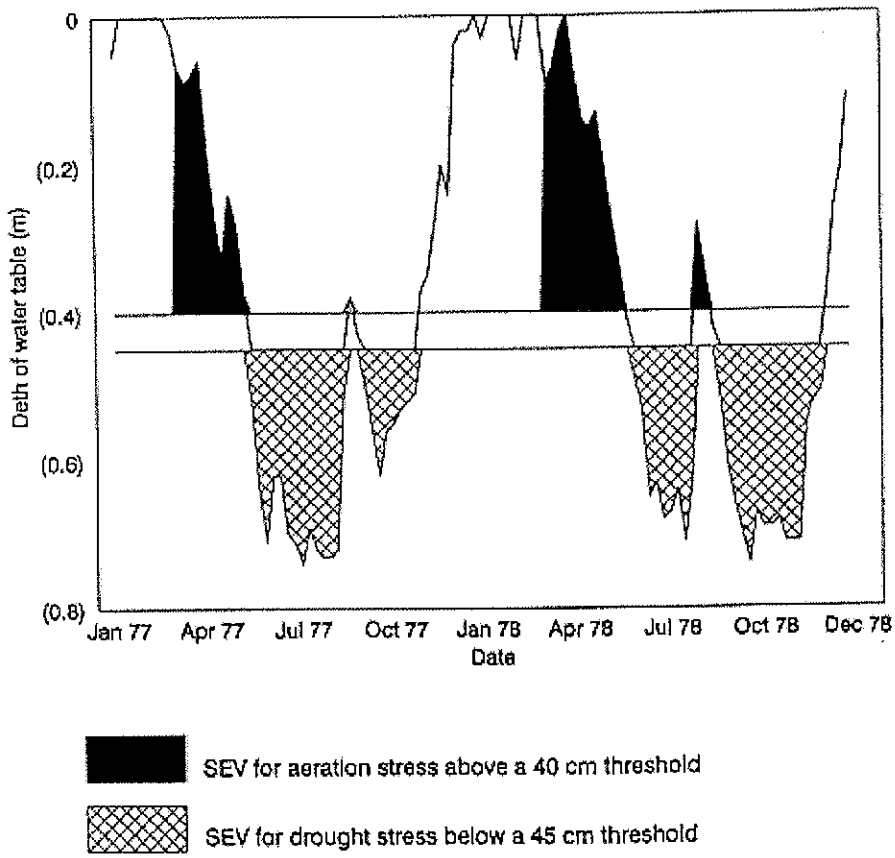


Figure 6.6 Diagrammatic illustration of the calculation of Sum Exceedence Values

Conversely the SEV for drought stress is calculated as the area of the plot where water tables are deeper than a drought threshold, which reflects the depth at which water supply from the

water table to the surface would be limited by the soil's unsaturated conductivity and therefore the evaporation rate could potentially fail to meet peak demand.

Figure 6.7(a)

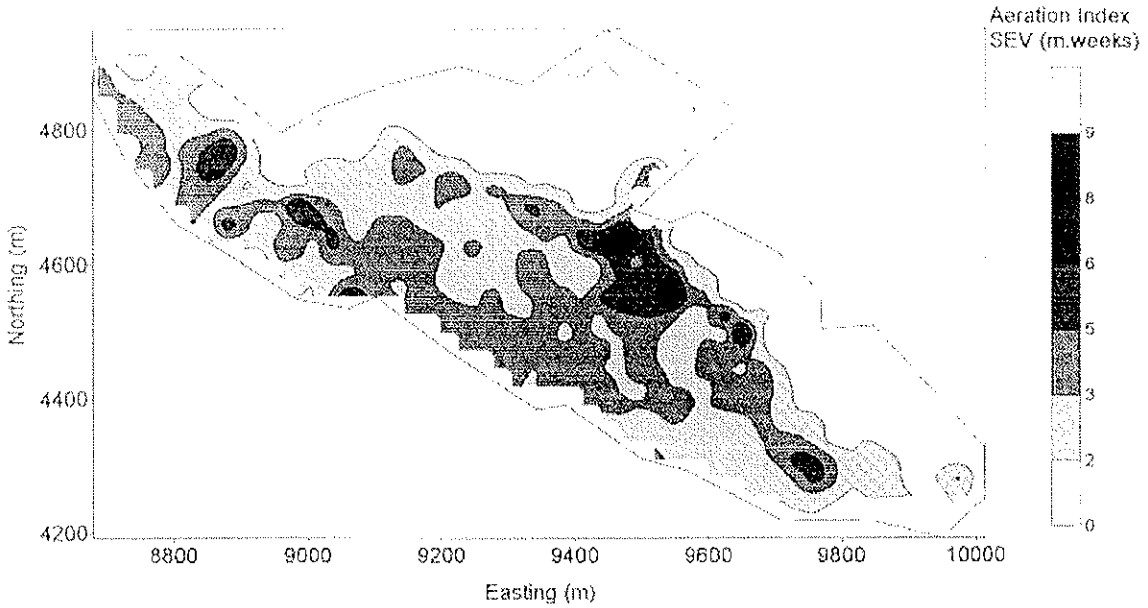


Figure 6.7(b)

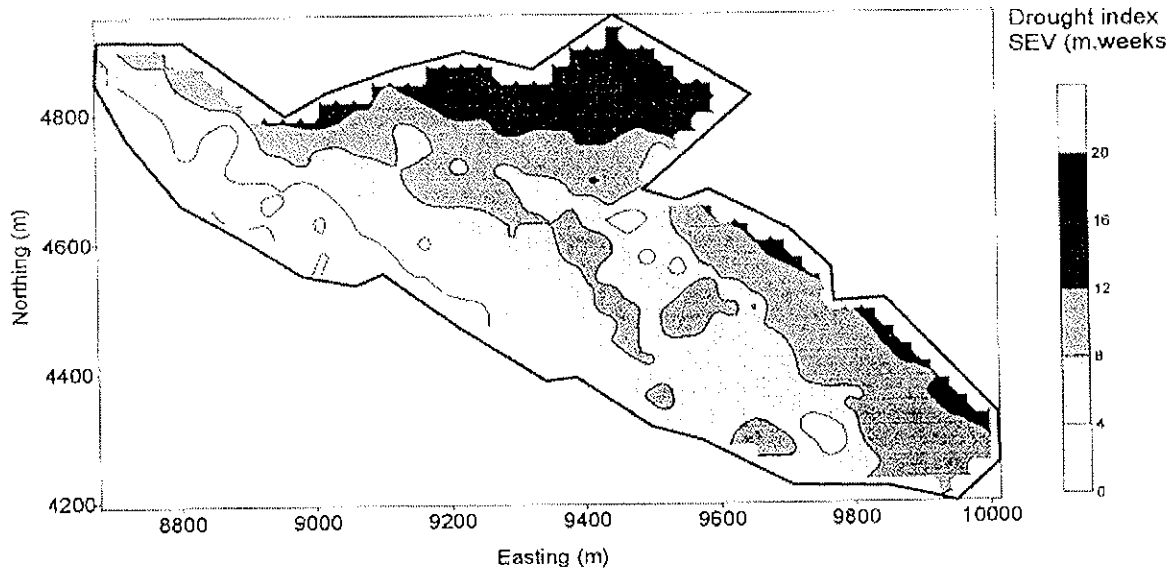


Figure 6.7 *The degree of potential stress to which vegetation may be exposed due to(a) waterlogging or (b) drought. Darker shades represent higher degrees of stress as estimated by SEVs*

These two parameters were calculated for each of the 600 sampled points and the results are presented as two contour maps (Figures 6.7a and 6.7b). The degree of aeration stress is largely dominated by those areas which pond water in the spring following flood events. The contours of Figure 6.7a pick out an old river channel running through the centre of the meadow which tends to hold water after a flood or pond it following heavy rain.

The degree of drought stress is mainly a function of relative distances from the rivers. Those points close to the Churn are more susceptible to drought since they are better drained in summer due to the lower stage level in that river compared to that of the Thames (*cf.* Figure 6.2). The depth of soil over the aquifer also plays a significant role.

The findings from our current research indicate that the extent of these two stresses largely determine plant community distribution in wet hay meadows.

5. PLANT COMMUNITY DISTRIBUTION

The greater part of the meadow is classified as MG4 grassland. The sampled points were often very close to the "classic" community as defined by the NVC (Figure 6.8). Those areas of the site which differed from this type tended towards one of two other grassland communities, namely MG5 *Cynosurus cristatus - Centaurea nigra* grassland and MG13 *Agrostis stolonifera - Alopecurus geniculatus* grassland.

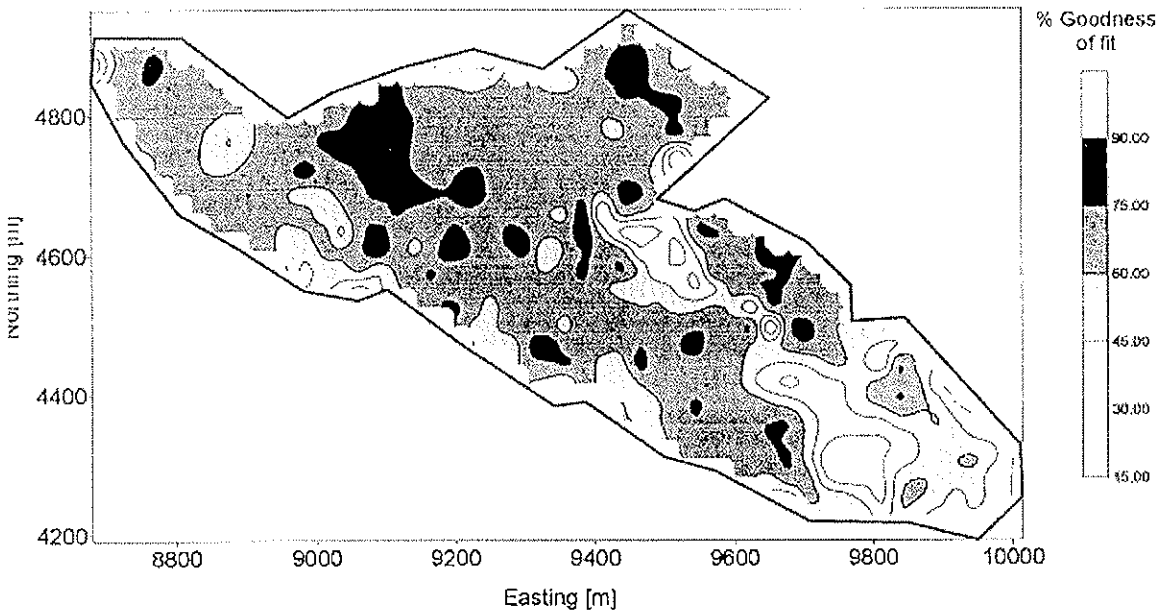


Figure 6.8 *The distribution of the Flood Meadow (MG4) type of vegetation across Cricklade North Meadow. The percentage "goodness of fit" refers to the output of TABLEFIT software (Hill, 1989) and estimates the similarity of the sample to the archetypal species list published by Rodwell (1992)*

Comparison of community distributions with the water regime parameters show the aeration stress SEV to have a strong relationship with the vegetation pattern. Figure 6.9a is a plot of the frequency of the three communities against aeration stress - it emphasises that when

aeration stress (duration of waterlogged soils in spring) is low then MG5 is favoured, MG4 dominates the mid-range and MG13 becomes almost exclusive in the areas where waterlogging is most prevalent.

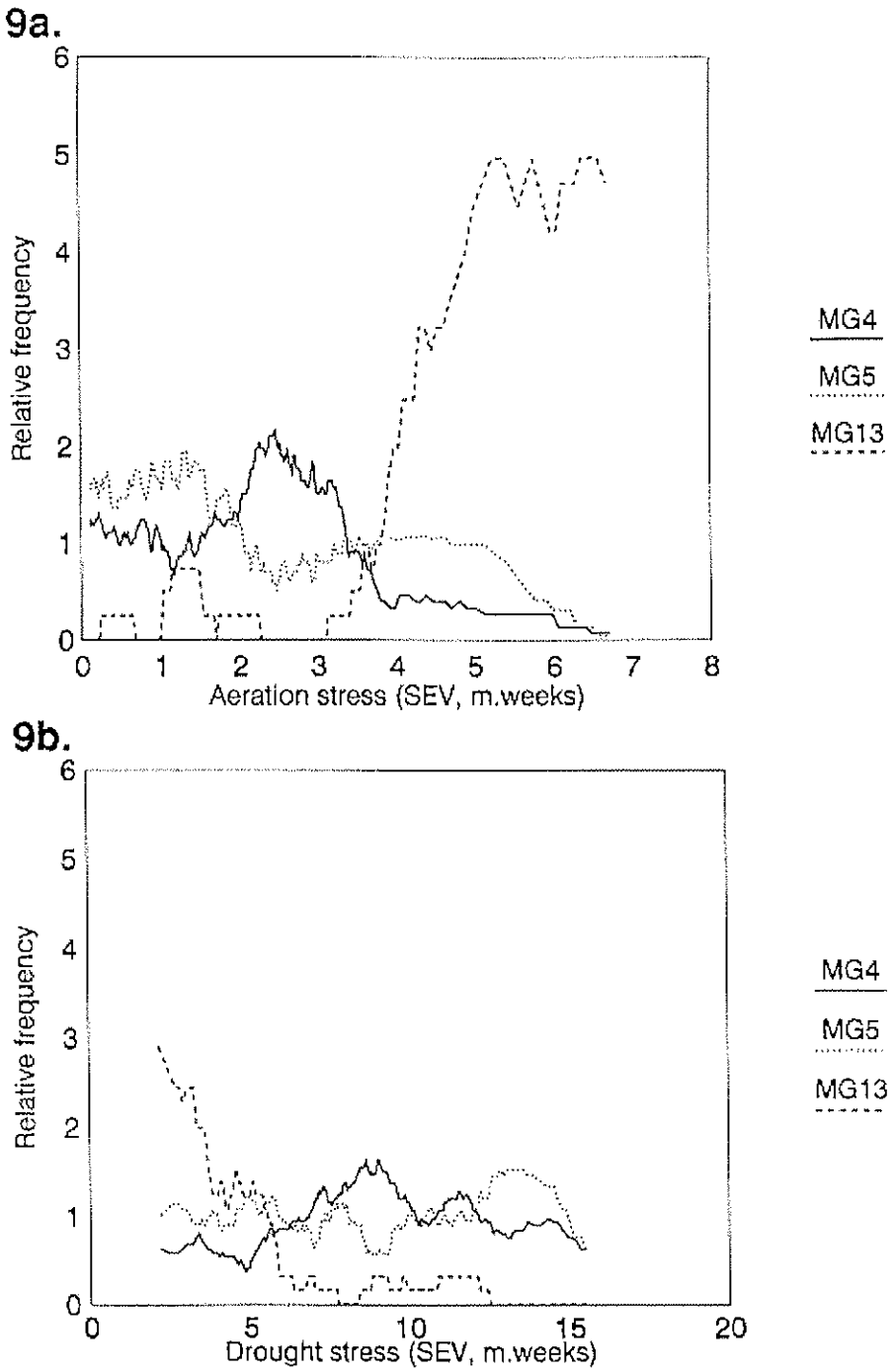


Figure 6.9 *The relative abundance of the three principal plant communities on Cricklade North Meadow with respect to water regime*

The community pattern shows less response to potential drought stress (Figure 6.9b) although the most stressed areas tend to favour MG5 over MG4. The value of the drought stress parameter is highly influenced by the low water-table positions of late summer. The fact that this parameter has less impact may be explained by considering the critical time of year for interspecific competition in a hay-meadow. One would expect this to occur in the April - June period prior to the hay-cut, when competition for light is intense. This period coincides with a high likelihood of waterlogging whilst later in the year when drought may be expected to be the main controlling factor, the competition within the sward is much less intense. The two parameters are of course not independent since positions which pond water in spring are less likely to dry out in summer. It would be expected, therefore, that one plot would show the inverse pattern of the other to some extent.

The conclusion which can be drawn from the analysis, in terms of hydrological management, is that the greatest threat to the MG4 sward and to the Fritillaries which occur in greatest numbers within this vegetation type, is an increase in spring waterlogging which will favour the competitiveness of MG13 species. The priority management action, therefore, is to maintain the drainage outlets of the meadow to prevent increased ponding of water following floods. At the same time the results demonstrate that MG4 requires high water-tables in spring if the community is to sustain itself rather than drift toward an MG5 community, which is regarded as a less threatened type.

5. CONCLUSIONS

This case study illustrates the feasibility of using a quantitative approach to understanding the water-regime requirements of semi-natural vegetation. The results can be used to guide the hydrological management of a site for the benefit of biodiversity. The approach also allows insights into the mechanisms controlling competition between species. In the case studied here the importance of the extent of soil waterlogging in spring has been highlighted. In other cases, such as the flood pasture communities of the Somerset Levels, the importance of summer drought is brought to the fore.

In terms of site management, once the requirements of communities can be quantitatively defined, then the scope for active management to maintain the appropriate level is increased.

Acknowledgements

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7

Floodplain Rivers and Water Level Management Plans

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Abstract

The purpose of this project was to develop Water Level Management Plans (WLMPs) at eight of the key wetland Sites of Special Scientific Interest in the Anglian Region. WLMPs are management tools which summarise the water level management practices and objectives of an area, fully taking into account the objectives of all interested parties. Through their implementation it is intended that sustainable hydrological management can be maintained in important ecologically sensitive areas. A case study of Blo'Norton and Thelnetham Fens is provided which highlights the need to tailor WLMPs to each specific site and in particular the management information available. A summary of this particular WLMP indicates that setting target water levels is inappropriate where data is sparse. Instead, the initial role of a WLMP should be to summarise the objectives of the relevant parties, set out present understanding of the site and define the monitoring necessary to make substantiated assessment of target water levels. WLMPs are shown to be working documents subject to regular review and refinement and that in many cases, early versions of WLMPs will not achieve their objectives in terms of management prescriptions.

1. INTRODUCTION

1.1 Background

Water Level Management Plans (WLMPs) provide a means by which the water level requirements for a range of activities in a particular area can be balanced and integrated. A Plan is a written statement which sets out the objectives for the area and the means by which these objectives may be achieved (MAFF, 1994). The principal of the WLMP is

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therefore to summarise the existing water level management practices at a site and put forward agreed management objectives based upon consultation with all relevant parties to maintain enhance or restore wetland habitats.

The 'Conservation Guidelines for Drainage Authorities' (MAFF *et al.*, 1991) state that WLMPs should be produced for areas where water levels are managed, with priority given first to internationally important areas such as Special Areas of Conservation (SACs), Special Protection Areas (SPAs), Ramsar sites or World Heritage Sites, then to other Sites of Special Scientific Interest (SSSIs) and other nationally important sites. Furthermore, sites should be prioritised and selected where water levels are thought to be controllable; i.e. where structures such as sluices locks or weirs exist on surface watercourses.

Water Level Management Plans (WLMPs) originate from the Ministry for Fisheries Agriculture and Food (MAFF), and the Welsh Office where appropriate. The procedure proposed for the effective preparation of WLMPs is set out in the document '*Procedural Guide for Operating Authorities*' (MAFF, 1994), produced in partnership with English Nature, the former National Rivers Authority and the Association of Drainage Authorities (ADA).

The Procedural Guide is a valuable tool for operating authorities (or their consultants) in outlining the key aspects of WLMP preparation, however this study indicates that early versions of WLMPs at some sites will fall short of the objectives set out in the guide primarily due to the lack of management information available.

1.2 Why are Water Level Management Plans Required?

Much of the most productive agricultural activity in England and Wales takes place in low lying areas, which, originally would have been characterised by large tracts of poorly drained bogs and fens. Historically, the hydrology of such areas has been carefully managed through improved drainage and isolation of rivers from their floodplains to create conditions suitable for agriculture. As a consequence, the rich and varied natural habitats and plant and animal species associated with natural wetlands has become increasingly sparse as poorly drained areas have been 'improved'. The fragments of fen which have survived this process are now under increased pressure as a result of the hydrological manipulation taking place around them as well as a result of the demands placed upon the groundwater supplies below them. Thus the water requirements of conservation and agriculture (and in some cases water resources) in the former wetlands and lowlands have become, in general, conflicting. In the past the opposing hydrological requirements of agriculture and nature conservation has created often intractable problems. This dichotomy combined with a history of river dredging and the pressing needs of flood defence has led to the continued loss of many areas of wetland and conservation interest.

1.3 Key Strengths

WLMPs seek to disentangle the complex and contradictory water level requirements of the three principal activities which dictate practices within an area; conservation, agriculture and land drainage. Therefore, whilst WLMPs are centred upon sites of conservation value, their key strength is the requirement for all parties whose interests may be affected by water level management to agree to the objectives set out within each plan. Where possible, these objectives will be crystallised as target water levels. This not only ensures that the conservation objectives of the SSSI in question will be fully addressed, but also guarantees full consideration of the implications of such objectives upon nearby farmers, local inhabitants as well as on the statutory functions of conservation bodies and the Environment Agency.

WLMPs are considered analogous to Catchment Management Plans (CMPs) and they will ultimately be considered within the CMP framework. They should also fit into the new Local Environment Action Plans (LEAPs) operated by the Environment Agency. In this way, wetland management considerations will be considered in the broader context of catchment management. This is particularly valuable where suecessful management of wetland SSSIs relies on specific water management beyond their boundaries or where conflicting management objectives arise.

1.4 Sites Studied

The eight sites studied in this project are summarised in Table 7.1

Site Name	Area (ha)	Watercourse
Blo'Norton & Thelnetham Fens	21.0	Little Ouse River
Cavenham & Icklingham Heaths	398.5	River Lark
Fowlmere Watercress Beds	38.9	River Shep
Great Cressingham Fen	13.7	River Wissey
Swangey Fen	82.3	River Thet
Thriplow Meadows	3.3	-
Upware North Pit	1.1	River Cam
Wicken Fen	247.2	Wicken Lode

Table 7.1: Summary information for WLMP Sites

These sites were prioritised as the key SSSI sites in the Anglian Region (Central Area), together with the large Ouse Washes SSSI wetland site on the basis of the factors described in Section 1.1. While, as the information in Table 7.1 indicates, they vary in

size, they also vary significantly in general form and hydrology, management systems and issues. The implications of these variations is discussed below.

WLMPs are to be completed for a total of 35 sites in the Anglian Region (Central Area) by the final deadline of March 1998. Here some of the key lessons that have been learnt from this first tranché of sites studies are highlighted and the implications for future WLMPs assessed.

2. DEVELOPMENT OF A WLMP

2.1 Consultation

Once an appreciation of the site has been gained, in terms of its general layout, topography, hydrology and key conservation interests, it is necessary to identify all parties with an interest in the area. This will include the landowner(s), the party or parties that manages the site (a Wildlife Trust for example) and since all sites are SSSIs, English Nature (or, in Wales, the Countryside Council for Wales). Where, as in this study, the plans are being prepared by consultants, it is important that all relevant functions of the operating authority (generally the Environment Agency or Internal Drainage Board) are identified. Other parties who may be affected by water management at the site, such as nearby farmers and property owners also need to be identified at this stage. Finally, relevant staff from the appropriate Borough and County Council need to be identified.

This is a crucial stage in the development of a WLMP. It will be fairly straightforward at smaller sites such as Great Cressingham Fen, where an individual owns and manages the whole SSSI, or at sites where management is well established and supported. However at large sites where there are numerous landowners or tenants and multiple management organisations consultation can be a difficult and lengthy process. Although this study focused on eight relatively small sites, in the context of wetlands such as the Somerset Levels or coastal wetlands, experience indicates that consultation is simplified wherever site managers or operating authorities have clear and unambiguous mandates and where their activities are generally supported by local landowners and residents. This is undoubtedly the case at Wicken Fen, which has been a National Trust reserve for 100 years (and, as such, is the oldest in the country).

Once the full list is assembled, it is necessary to consult all parties in order to determine their aims and assess how their objectives for water level management at the site relate to each other and to existing practice. A vital part of this stage of the WLMP preparation process is the identification of conflicts between the objectives of various consultees or the existing management practices on site. Again, as the number of consultees increases, so do the variety of objectives. Generally though, in spite of this, conflicts may be easily identifiable and relatively foreseeable - for example the archetypal agricultural/conservation discord. Despite this there are often more subtle opposing objectives that can be as much of a hindrance to sustainable management as the well-

documented, more polarised views. It likely that these would not have come to light outside the framework of the WLMP, and in this sense these Plans can bring numerous and often diverse objectives of consultees together in one document.

2.2 Hydrological Assessment and Data Availability

Wetland hydrology is often complex; there are many sources and sinks of water, and water levels in fenland habitats are generally dependent upon more than one controlling factor. For example in the eight sites studied in this project, seven were influenced in some way by floodplain rivers whilst water levels in five were also dependent upon spring flows or seepages. At sites where water level is controlled by a number of factors, an understanding of the ecological implications of variation in water quality from different sources is also important. An understanding of the hydrology of a given site will also require an assessment of artificial influences upon water level since lowland hydrology will often be subject to some human intervention.

At this point it is necessary to list some common factors between sites which enabled the eight sites to be grouped on the basis of general observed and recorded hydrological systems. Although this classification was useful in clarifying certain types of management issues appropriate to different general types of site, it does not define those management issues or seek to simplify or idealise site hydrology.

Site Groups	**Site List**
Shallow valleys, important interaction between surface and groundwater	1 *Blo'Norton & Thelnetham Fens* 2 *Swangey Fen* 3 *Fowlmere Watercress Beds*
Sites where surface water is only controlling factor	4 *Wicken Fen* 5 *Floodplain areas of Cavenham & Icklingham Heaths* 6 *(Upware North Pit)*
Sites where groundwater is only controlling factor	7 *Thriplow Meadows* 8 *Spring-fed areas of Cavenham & Icklingham Heaths* 9 *Great Cressingham Fen* 10 *(Upware North Pit)*

Table 7.2 Water level controls at eight WLMP Sites. Bracketed site names indicate uncertainty about site hydrology and key controlling factors

Table 7.2 summarises the typical hydrological systems encountered in this study, and indicates that different controls are prevalent in different areas of the same site and that hydrological controls are uncertain at other sites, even at this conceptual level. WLMPs must be prepared with this uncertainty in mind. The inter-relationship between the various controlling factors and the extent to which artificial management exerts control upon the site in question needs to be fully understood, in order to suitably determine the means by which the water level management objectives of all interested parties can be satisfied. Any management strategy built without such knowledge will inevitably fall short of some objectives defined within the Plan. The hydrological assessment of each site is therefore central to the development of its WLMP. Without data which adequately describes the hydrology of a site and effectively dispels uncertainties about the relative value of hydrological inputs, it is impossible to draw up management prescriptions (such as target water levels).

3. CASE STUDY: BLO'NORTON AND THELNETHAM FEN

3.1 Introduction

Blo'Norton and Thelnetham Fen SSSI (Figure 7.1) provides a case study which illustrates well the type of issues and conflicts of interest encountered during development of WLMPs. It is a valley fen SSSI which is characteristic of five of the eight SSSI sites outlined in Table 7.1. Here the ecological concerns of the site were relatively well established, but the key hydrological and water level issues had not been clearly identified. The SSSI, covering just over 20 hectares, is situated on the Norfolk-Suffolk border close to the source of the Little Ouse River (NGR TM 017 789). The site is primarily notified for its surviving areas of species rich calcareous valley fen vegetation. This vegetation includes typical elements of East Anglian Fen such as Black Bog Rush (*Schoenus nigricans*), Saw Sedge (*Cladium mariscus*), Marsh Orchid *(Dactylorchis praetermissa)* and Long-stalked Yellow Sedge *(Carex lepidocarpa).* These areas of open fen are however extremely restricted in size and are almost exclusively found on the parts of Thelnetham Fen which are still actively managed by the Suffolk Wildlife Trust. They are mainly associated with the remaining areas of 'Schwingmoor'; floating mats of peat and vegetation. The great majority of the SSSI now supports marshy grassland, Alder and Willow carr and drier Oak and Ash woodland.

Over the past 30 years the fen has been observed to have deteriorated from a position in the late 1950s when calcareous fen and the 'Schwingmor' dominated the site (Bellamy and Rose, undated) to the present situation where large areas of Old Fen (Figure 7.1) are dominated by relatively mature oak and ash. Within that time, the fen has dried out considerably and although part of the proposed Waveney and Little Ouse Special Area of Conservation it is considered to be in a continued state of decline. Only the management efforts of the Suffolk Wildlife Trust, concentrated mostly on Middle Fen, are responsible for retaining the interest which is left, however hydrological management would appear to be a key element in the future management of the SSSI.

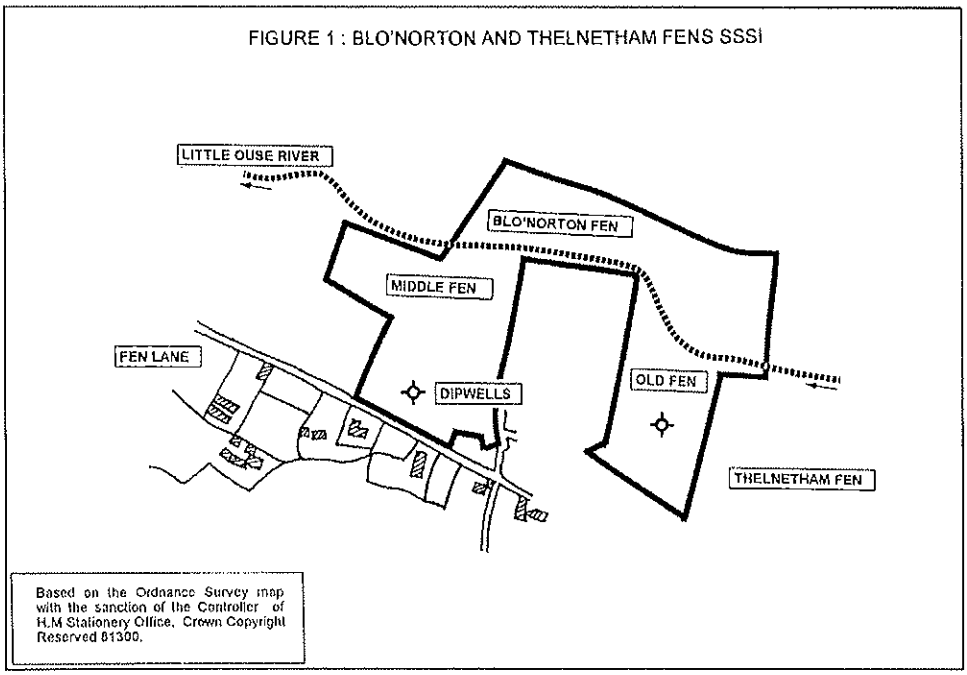


Figure 7.1 Blo'norton and Thelnetham Fens SSSI

3.2 Hydrology and Management Implications

Having established the historical and ecological significance of the site, the WLMP then has to address the key water level issues affecting the SSSI. Blo'Norton and Thelnetham Fen is affected by two principal hydrological components, as the fen lies both on the floodplain of the Little Ouse and over the Upper Chalk aquifer. Historically the Little Ouse would have been responsible for maintaining the water table in surface layers close to the surface of the fen. It would also have contributed water during flood events and, being only 3 km from the spring fed source of the river, these flood waters would also have been base rich. Although only 3 kilometres from the source of the river, the catchment area to the western (furthest downstream) boundary of the SSSI is approximately 46 km^2, whilst Thelnetham Fen itself has a surface water catchment of approximately 2.5 km^2.

The general geology of the region comprises the Upper Chalk (which is a major aquifer and an important source of water for public supply) overlain by alluvium, sands and gravels within the Little Ouse valley, where the SSSI lies. Calcareous groundwater from the Chalk aquifer upwell in springs and seepages within the fen and is the main base rich input. With a high water table supported by the Little Ouse, these base rich surface flows remain in the surface layers of the fen directly influencing the vegetation of the fen and encouraging a calcicole flora. A third hydrological influence on the fen is the ditch system within and around the site. Although currently neglected, this undoubtedly has some impact on the wetness of the fen and if restored and managed correctly, could possibly be used to manage water levels in the fen in the future.

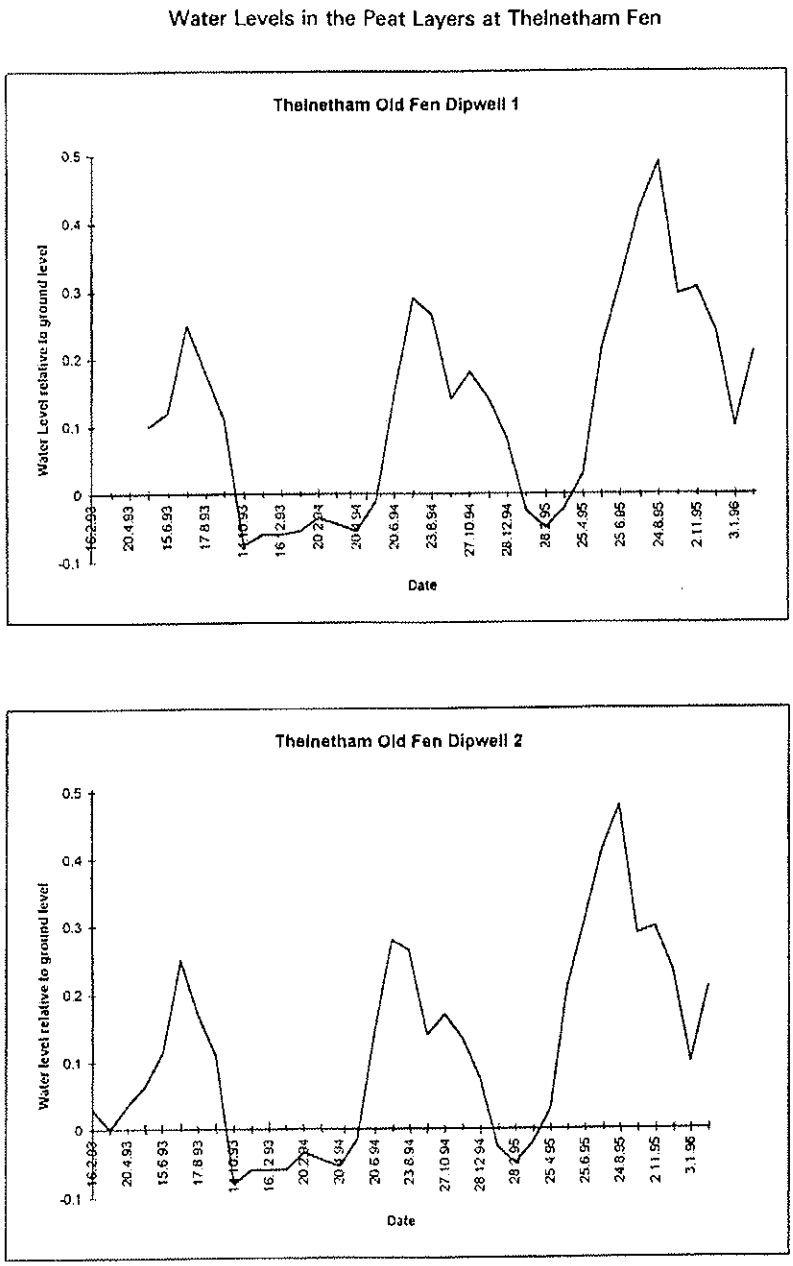


Figure 7.2 *Water level in the peat layers at Thelnetham Fen as detwermined from Dipwells 1 and 2*

3.3 Possible Causes of Degradation

Anecdotal evidence from the Suffolk Wildlife Trust suggested that a deterioration in the overall quality of the fen occurred soon after the Little Ouse was dredged in the 1950s and 1960s. Deep dredging at that time would certainly have had the effect of lowering the head of water in the river and would have caused, or increased a hydraulic gradient toward the river. Despite this, a review of cross-sectional drawings of the river in the

reach in question did not reveal significant changes in river bed level and there is no indication that the influence of dredging is still experienced (the river has not been re-dredged for at least 25 years). The fen lies within an area of intense agricultural activity with a large number of groundwater abstractions for irrigation purposes. Table 7.3 lists groundwater abstractions in the vicinity of the SSSI. This information demonstrates that the Redgrave borehole is by far the largest abstraction in the area, and constitutes 95 % of all abstractions, based on daily licensed volume. The abstraction (from the chalk aquifer) is hydraulically upgradient of the site and may therefore have an effect on groundwater levels in the chalk beneath the Fens, lowering the level of the water table. Should this be the case, it is possible that downward seepage of water from the unconsolidated deposits above the chalk will occur.

NGR	Licensed Volumes or Condition
TM 003 792	830 m^3yr^{-1}
TM 017 787	2.27 m^3day^{-1} and 827.3 m^3yr^{-1}
TM 026 784	9.09 m^3day^{-1} and 3300 m^3yr^{-1}
TM 021 789	Observation borehole in sand and gravel
TM 046 792	3637 m^3day^{-1} Public water supply abstraction
TM 026 783	Observation borehole - chalk
TM 025 783	Observation borehole - chalk

Table 7.3 Summary of abstractions in the vicinity of Blo'norton and Thelnetham Fens SSSI

Groundwater level data from borehole ref. TM 07/166 (Figure 7.1), as illustrated in Figure 7.2, indicate that water level in the sand and gravel below the Fen fell below ground level (23.35 m AOD) from March to October 1993, July 1994 to January 1995 and from April 1995 to the end of the record. Seepage losses from the Fen are possible during these periods, however the data from dipwells installed on Thelnetham Middle Fen (Figure 7.3) indicate that water level on the Fen is at a minimum when groundwater levels are recovering, and therefore do not entirely support the seepage theory. The discrepancy in the two sets of groundwater level data requires further investigation.

Redgrave and Lopham Fen 3 km to the east of Blo'Norton and Thelnetham Fen has suffered considerably from abstraction at the public water supply borehole on its boundary and consequently the borehole is likely to be relocated approximately 6 km east of the site. This may reduce the problems associated with depressed groundwater levels

at Blo'norton and Thelnetham since the new borehole is in a different groundwater catchment.

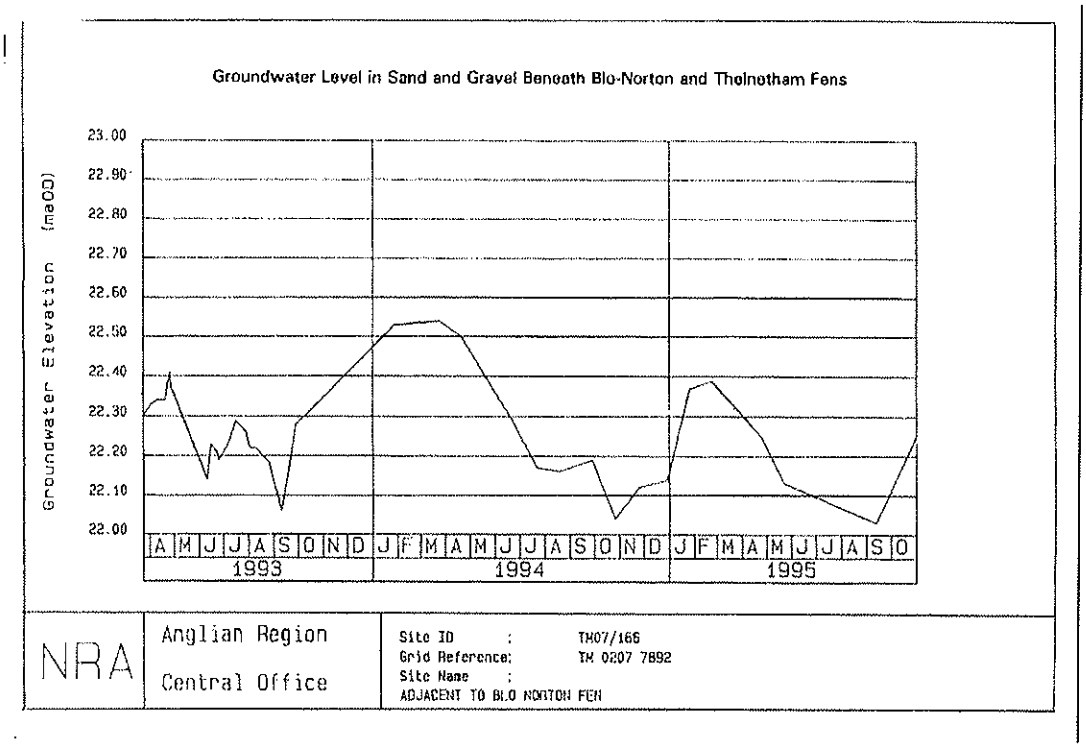


Figure 7.3 *Groundwater levels in the sand and gravel beneath Blo'norton and Thelnetham Fens for the period 1995 to 1995 inclusive. Data courtesy of the former NRA Anglian Region (now the Environment Agency)*

3.4 The Consultation Process

A number of consultations were undertaken for the WLMP, interested parties including:

- Environment Agency
- English Nature
- MAFF
- Suffolk Wildlife Trust
- Local Poors' Trusts (who own the majority of the SSSI), and
- Local residents

The objectives and concerns of the various consultees for water level management within and around the SSSI varied considerably, but were polarised at the extremes between the nature conservation bodies who wanted to see a reversing of the drying out of the fen and the Poors Trusts who regard the colonising woodland as a more valuable resource than the open fen. Whilst local residents were in general supportive of the broad nature

conservation objectives, they were extremely concerned that land drainage and flood defence would be compromised. The Environment Agency, with its dual responsibilities for flood defence and nature conservation identified both objectives as key concerns, however their primary responsibility was to ensure no derogation to flood defence.

The consultation process identified that no current water level management practices occur on the site. The only appropriate water level monitoring refers to two dipwells on the SSSI which are monitored by the Suffolk Wildlife Trust and observation boreholes which monitor water levels in the aquifer. No river level monitoring occurs on the Little Ouse in the vicinity of the fen, although there is a gauging station at Knettishall approximately seven kilometres downstream.

3.5 Summary

The inadequacy of historical water level monitoring for the site restricts the progress that the WLMP can make. There is no clear appreciation of why the fen has so rapidly dried and although the pressures of land drainage, river management and groundwater abstractions are all suspects, the key hydrological impact is not currently identifiable. Without this basic information the assignment of target water levels and the implementation of remedial cost effective hydrological management is not possible.

The WLMP recommended six key actions which are required in the elucidation of the sites hydrology and in setting the baseline for future management:

1. Continue dipwell and borehole monitoring.

2. Undertake investigations into dipwell stability and level to Ordnance Datum.

3. Review the effect of relocating the Redgrave abstraction upon dipwell and borehole data and assess the need for further water level improvements on the fen.

4. Review the possibilities of ditch improvements to alleviate winter flooding, whilst ensuring no derogation to fen water levels at other times of year.

5. In the light of the above, assess the need to increase river water levels.

6. If river level improvements are considered necessary, a thorough study should be undertaken to assess the viable river level which would satisfy the needs of flood defence, agriculture and conservation.

4. CONCLUSIONS

Water Level Management Plans offer a powerful tool to operating authorities in the operational management of wetland SSSI sites where water level control is central to

conservation. In particular, they provide an arena in which the conflicting objectives of all interested parties, both within and beyond the confines of the SSSI boundary, can be put forward and addressed.

Successful WLMPs should ultimately propose target water levels which have been reached through consultation and with the consensus of all parties. However it is crucial to note that WLMPs are still in their infancy, and this ultimate goal cannot be achieved at all sites straight away. Indeed, within Anglian Region (Central Area) there are 35 WLMPs to be prepared by March 1998. If this target can be achieved, the resource implications of many of the recommendations is likely to mean that the realisation of target water levels, if achievable at all, will not be for some years.

Of the eight sites studied in this project this final objective is achievable at all of them, however in this initial form, preliminary target water levels could only be set at two sites. At the other sites there was a need to either undertake a monitoring programme to fully determine site hydrology or collate existing data. Although this strategy may disappoint a number of organisations, the need to undertake hydrological monitoring and modelling where necessary is considered paramount to the successful completion of any WLMP.

There is a need for the major partners - English Nature, Environment Agency, MAFF, ADA in addition to key nation-wide consultees to discuss best practices and agree a common philosophy and policy which can realise the management potential of WLMPs. The lessons learnt from the first tranché of WLMPs, such as those described above, needs to be incorporated into this process if realistic objectives are to be set.

Acknowledgements

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8

Urban Watercourses: Ecological Sustainability and Restoration

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Abstract

Sustainable river management in urban catchments requires that the ecological impacts of stormwater runoff discharges be minimised and that permanent, diverse and self-regulating habitats are established. The application of patch dynamics disturbance concepts to the identification of critical threshold levels for organism removal are described. Synergistic, multi-parameter procedures based on a combination of bed shear stress, toxic emission concentrations and in-stream population loss are developed to provide ecological sustainability criteria for urban rivers dominated by stochastic, episodic discharge events.

1. INTRODUCTION

The principles of urban river management are dominated by water and pollutant fluxes and the engineering of acceptable alternatives to natural systems. Implicit in these principles is the notion of a self-sustaining and self-regulating river system with infrequent chaos over-ride. In the United Kingdom, central government has identified a number of guiding strategic principles for sustainable development (DoE, 1994). Local government however, has taken a leading role in taking forward the 27 principles of the 1992 UN Rio Declaration on Environment and Development with the Environment Agency (former National Rivers Authority) providing guidance on water issues to local planning authorities for the preparation of land use development plans (NRA, 1994). Advice on sustainable development has been incorporated into Regional Planning Guidance (RPG) and much of this is directly relevant to urban drainage.

The emergence of AGENDA 21 as a local action planning basis for strategic and integrated approaches has been an important political and institutional driver for multi-functional catchment management planning. The recent consultation draft produced by NRA Thames Region seeks to identify key catchment planning issues so that they can be addressed in local authority development plans (NRA, 1995). One key objective is stated to be the introduction

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and refinement of techniques to control urban surface water runoff at or near source (and in-channel) as a means of minimising downstream flood and pollution risks. In addition, urban catchment management planning must also consider ecological conservation and recreational opportunities. In this context, the understanding and managing of channel and riparian zones is crucial to both pollutant cycling and biodiversity and therefore to wider issues of river restoration and recovery. However, it must be recognised that planning in the long term for the control of very short term and potentially highly damaging perturbations is far from being an easy concept.

Planning for an 'average' or steady state condition is much less exposed to uncertainty and lack of knowledge than is planning for the infrequent event. Whilst most urban stormwater outfalls (SWOs) and combined sewer overflows (CSOs) may be overdesigned in terms of the average condition, it is accepted in the initial set-point design that they will be subject to operational failure. Little attention to date has been paid to encouraging research into accelerated means and measures for post-failure recovery.

Is it possible to establish and measure those levels of anthropogenic impact which can be considered to be ecologically tolerable? What are the key features of an urban channel which determine its ecological sustainability and which are also amenable to restoration and subsequent management? Given the random, but continual, pollutant perturbations and hydraulic disturbance of habitats in urban reaches, what is the long term ecological significance of episodic variations in flow quantity and quality? SWOs and CSOs contribute to receiving water pollution in both acute and chronic, accumulative terms. The question therefore arises as to whether there are characteristic temporal suites of urban channel biotopes, definable by a limited range of hydraulic, morphological and ecological indices and which might form an appropriate basis for restoration and rehabilitation strategies to support sustainable runoff management.

2. URBAN STORMWATER DISCHARGES

2.1 Ecological Impact Assessment

It is now widely recognised that urban runoff is sufficient to provide the critical limiting factor for receiving water ecology and often implies a lower quality classification than that derived from conventional chemical sampling (House *et al.*, 1993). Even single discharge events from CSOs have been identified to have significant long term impacts on receiving water habitats. Because high magnitude, low frequency storm events (and which are typical of urban runoff) shape and modify the physical habitat, what is needed is a method which predicts the effects of such pulsed discharges on in-stream habitat conditions. The metabolic effects on the organisms of urban rivers resulting from toxic intermittent stormwater discharges will depend on the local hydraulic and morphological characteristics and some of the critical controlling parameters are identified in Table 8.1.

Acute, short term and delayed effects of urban stormwater discharges would appear to be particularly related to high stress flow parameters occasionally combined with elevated flush-spill concentrations of critical toxics. This would imply that sustainability criteria for impact assessment and biotope characterisation should reflect the synergistic effects of multi-parameter interactions. Policy Implementation Guidance Notes (PIGNs) are currently being

formulated by the Environment Agency to developed consenting procedures recommended in the Urban Pollution Management Manual for intermittent CSO discharges which are based on concentration-frequency-duration principles (FWR, 1994). Thus short term and delayed impacts of urban runoff are considered to be the result of distinctly separate but interacting hydraulic and chemical factors. In the UK performance-based procedure, the former physical parameters are definable by a frequency-duration and/or mass flow term whilst the latter are normally specified by dissolved oxygen and/or unionised ammonia threshold levels determined from laboratory LC50 organism test data.

Timescale	Controlling Parameter	Discharge Parameter
Acute (hours)	**Hydraulic** • 0.6 flow velocity • bedshear stress **Physico-Chemical** • dissolved toxics (especially NH_3-N) • instantaneous oxygen depletion • suspended solids flux • faecal bacteria flux including pathogenic concentrations	Water Volumes specified by the individual discharge or single flow event
Delayed (hours-days)	**Physico-Chemical** • delayed oxygen demands and SOD (caused by benthal disturbance and oxidation of organic carbon and NH_4-N) • dissolved and loosely bound toxics [NH_3-N, NO2-N, metals (Cd, Zn) hydrocarbons (PAHs)] • suspended solids balance • micro-organisms and pathogens especially those associated with sediments	Pollutant concentrations and loads specified by the individual discharge or single flow event
Long Term (months-years)	**Physico-Chemical** • chronic organic substances including hydrocarbons, pesticides • solid associated metals • formation of toxic inorganic and organic benthal sediments • eutrophic materials	Accumulative loads resulting from numerous discharges/overflows and specified by annual average statistic

Table 1 Potential metabolic hazards of urban runoff

There is evidence for synergistic effects at low oxygen and enhanced ammonia concentrations leading to increased mortality and drift of benthic invertebrates in urban channels (Gammeter

and Frutiger, 1989). In experimental flumes, Borchardt and Statzner (1990) have also provided evidence of synergistic effects since exposure of *Gammarus* to high flow and sewage effluent caused higher population loss than when exposed to either high flow or sewage alone. However, flush spillages of pollutants from urban sewers are often characterised by high levels of several parameters reaching simultaneous critical values. The net effect of such coincidence upon the receiving water ecology still remains somewhat speculative nevertheless, although the depressed biotic community status and diversity occurring downstream of urban outfalls is now well documented (Ellis, 1995). The chronic benthos effects reflect a biological community in constant flux and an ecosystem lacking essential stability.

2.2 Emission-Oriented Approaches

In contrast to the essentially engineering parameterisation of CSO consenting procedures adopted by the UK Urban Pollution Management Manual, other EU member states have attempted to develop more in-stream ecologically based procedures. The introduction of more rigorous 'Advanced Requirements' for CSO discharges in Germany under their 'generally applied tax rules' (or GART tax system), has generated a screening evaluation procedure to identify critical limits of ecological tolerance in urban receiving waters (ATV, 1989). The limits are specified in terms of suspended solids, oxygen and NH_3-N for stated limit ranges of receiving water velocity, water depth and pH for mean low water flow (dry weather flow) conditions. These are considered to be the controlling physical and chemical parameters of ecological relevance to the watercourse with for example, biologically-affecting, instantaneous critical mean flow velocities ranging between 0.1 to 2.4 m/s depending on the organism.

A threshold index (or a-value) determined as the ratio between the population equivalent of the catchment and the mean low water flow of the receiving water (PE/MLF), is then specified for each set of critical parameter listings. Where the ratio is exceeded, 'Advanced Measures' which usually demand the installation or extension of stormwater retention tanks and/or additional biological treatment, will then be required under the amended ATV standards of the Federal Water Act. Such approaches to establish emission-oriented advanced (or even minimum) requirements are however difficult and complicated, and it remains to be seen whether they will survive in practice.

3. AN ECOLOGICAL EVALUATION FRAMEWORK

3.1 Organism Drift and Patch Dynamics

The generic ecological characteristics of an urban receiving water habitat are instability and ecotoxicity resulting from random episodic perturbation of the community by both hydraulic and chemical stressors. The urban watercourse is dominated by taxa that can tolerate successive erosional-depositional sequences and transient, low quality food sources with shorter retention time for organic matter. The inherent variability in the composition, concentrations as well as loading rates and magnitudes of toxic pollutants also prevents lotic communities from acclimating. Thus a key element for the sustainable organisation of urban water ecosystems is the higher intrinsic temporal and spatial variability of abiotic factors in comparison to other aquatic ecosystem locations.

Patch dynamics concepts attempt to unify these variable factors and to scale the organisation of species communities in terms of evaluative strategies, controlling factors and species richness (Townsend, 1989). Figure 8.1 provides a habitat template defining this patch dynamics concept in terms of temporal and spatial variability and the likely stream ecology outcomes. Crucial to this concept of patch dynamics is the element of ecological disturbance, defined here as any discrete event in time that dislodges organisms from their habitat and opens up space which can be re-colonised by individuals of the same or different species.

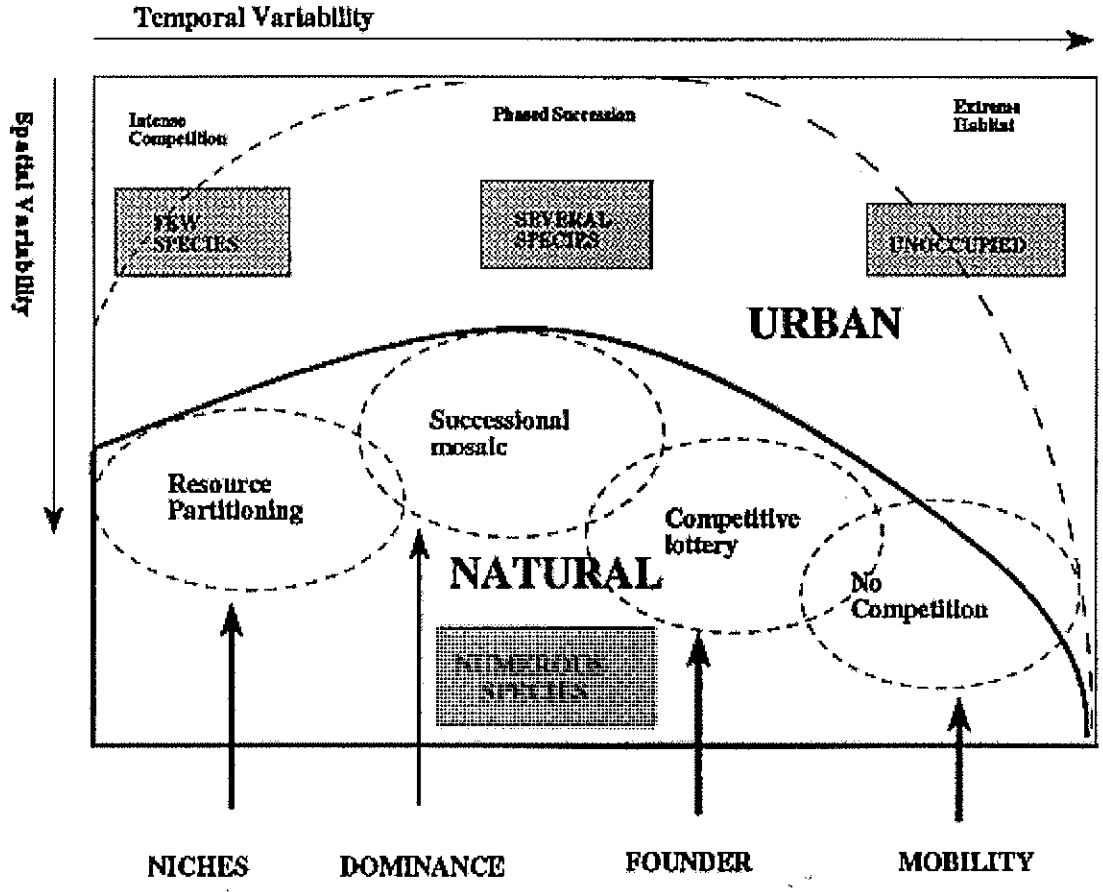


Figure 8.1 *Channel habitat template defining the patch dynamics concept in terms of temporal and spatial variability*

In this context, organism drift is a key mechanism for the dynamics of lotic populations and downstream transport by 'drift' mechanisms can be considered to be either constant, behavioural or catastrophic (Water, 1972). The latter drift mode is characteristic of urban rivers subject to episodic discharge events and will result in significant decreases in benthic densities over short time periods. Such catastrophic drift events have been widely observed in macroinvertebrate communities impacted by intermittent urban runoff discharges and by acute flush events from CSOs (Aalderink *et al.*, 1990). The existence of downstream weirs and inclined drops in regulated urban channels also prevents post-storm recolonisation and recovery thus leading to permanent community deficits.

3.2 Bed Stability

One controlling parameter on organism drift will be the higher flow velocities induced during wet weather discharges which will exert immediate hydraulic stress, causing washout and scouring from both water and sediment phases. In addition, prolonged turbidity will reduce primary productivity with high suspended solids concentrations having "sandblasting" effects as well as infilling and blocking interstitial voids when the flood event recedes. The critical shear stress and interstitial porosity of the river bed are thus of considerable influence on the potential drift rate of benthal organisms. If the interstitial porosity is sufficient, the organisms can shelter from the imposed stress of the CSO discharge wave. The overall population loss appears to be very dependent on the availability of such refugial space; if the benthal gravel interstices become silted up, the loss becomes substantial. Only when there remains sufficient interstitial porosity, will the critical shear stress for organisms be identical to the critical shear stress for the river bed structure.

Sediments discharged from SWO and CSO sewers possess strong cohesive characteristics although this cohesion primarily arises from agglutination due to grease and tars, chemical cementation and biological processes occurring in-sewer, rather than the classical concepts of electrostatic cohesion which are associated with marine or estuarine sediments. Hence, sewer sediments which accumulate downstream of the outfall exhibit rheological properties which are similar to those present in mixed cohesive materials and typically have an apparent yield stress or bed shear strength in the order of 0.7-2.5N/m^2. Field inspection also shows the sediment to be typically stratified in density and thus also varied in strength. The erosion of such benthal sediment deposits has been described as continuous mass erosion by the sudden removal of large sections of the bed similar to the turbulent bursting noted in estuarine deposits (Parchure and Mehta, 1985).

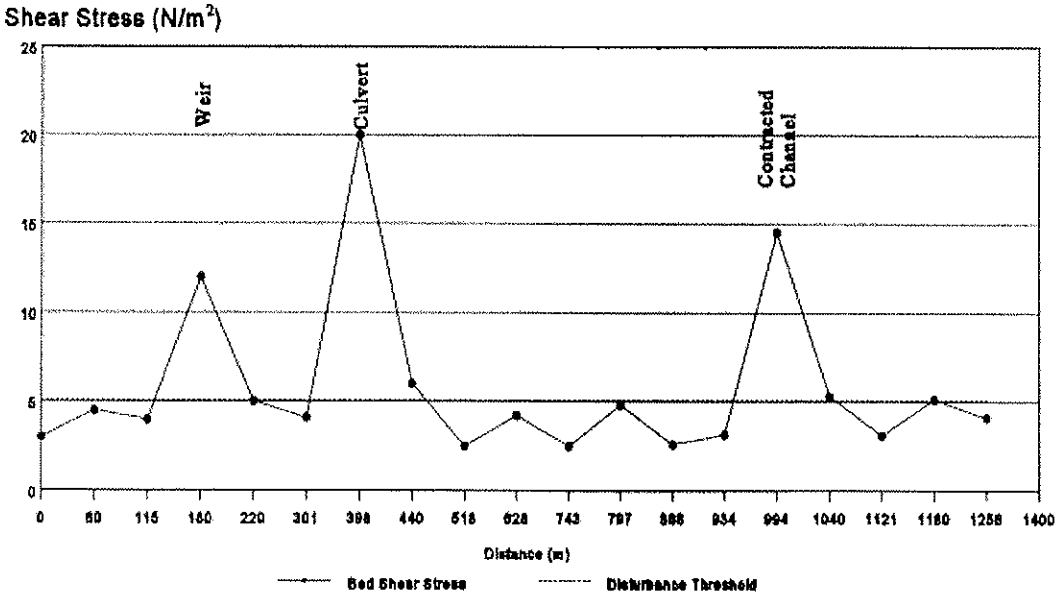


Figure 8.2 *Longitudinal profile of bed shear stress showing disturbance threshold for* Gammarus pulex

During stormflow conditions and under high CSO/SWO discharge rates, bed shear stresses in the immediate vicinity of the outfall can be 3-5 N/m^2 and this can lead to shear erosion of complete upper sediment layers with consequent removal of all contained biota. Thus bed characteristics of the receiving water (especially bed stability and refugial space) play a controlling role in the potential impact of urban stormwater discharges in addition to limitations exerted by toxicity and food supply factors. Figure 8.2 shows the spatial variability of bed shear stress recorded along a short urban river reach in the N. London region affected by a two year return period CSO discharge event. It has been suggested that to maintain the necessary development cycle of important higher-order aquatic organisms, critical bed shear stress values must not be exceeded every second year (Osborne and Herricks, 1989) and the disturbance threshold in respect of *Gammarus pulex* is indicated in Figure 8.2. In a similar manner, the time based, critical disturbance level for non-ionised ammonia has been plotted in Figure 8.3 for the reach immediately below the CSO mixing zone. Both these plots are of significance to the patch dynamics disturbance concept and also provide an appropriate basis for the ecological evaluation of acute and delayed impacts of intermittent stormwater discharges.

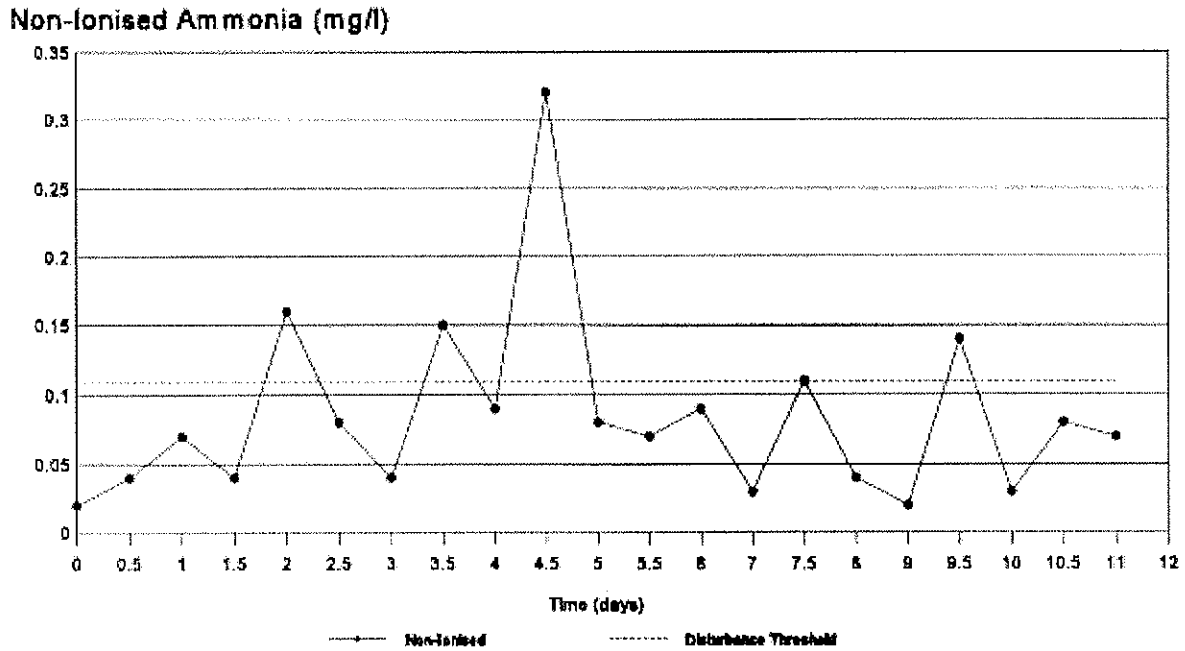


Figure 8.3 *Temporal variability in non-ionised Ammonia for the reach immediately below the CSO mixing zone*

3.3 A Synergistic Approach

The synergistic effects of these combined hydraulic and chemical parameters on in-situ population loss by drift is evident from Table 8.2 which reinforces the significance of interactions and interference between single critical parameters. The drift loss of *Gammarus pulex* from a river bed location having minimal refugial space for this species can be directly related to flow force and toxicity. A simple multiple regression model has been developed for the numerical estimation of this combined impact. Such approaches will inevitably be site-specific but nevertheless do offer the basis for parameter comparisons when considering

alternative management options for minimizing receiving water impacts of urban runoff discharges. The model can run on 'what-if scenarios' such as reductions in the frequency and/or magnitude of SWO and CSO discharge rates and volumes, end-of-pipe treatment or discharge dosing, side-channel storage (riparian horseshoe wetlands), on-line detention etc., to evaluate the resultant effect on receiving water ecology.

3.4 Non-structural Approaches

At SWO and CSO locations where it is not possible to introduce in-sewer or end-of-pipe controls, it may still be possible to reduce the discharge impact on and local scouring of downstream receiving water habitats by implementing in-channel measures targeted at benthic organism retention. These measures could include:

- increasing the bed porosity by introducing cobble, gravel and crushed rock material and forming the bed such that it exceeds the critical two year yield stress level.
- introduction of artificial side bars/groynes using logs and fixed vegetation to prevent bed erosion during wet weather discharges and to induce sinusoidal flow within the channel as well as varying habitat availability in the channel section.
- shadowing the river bed through riparian tree and shrub planting (overhanging willow trees) to provide a rich root structure reaching out below water level to diversify available habitats.
- re-design the flood profile above the specific dry weather flow profile to minimise hydraulic stress effects.
- removal or modification of downstream weirs and drop structures which prevent organism repopulation after flood erosion.
- introduction of marginal 'horseshoe' forebays and wetlands at the point of overflow or outfall to enhance sedimentation and minimise in-channel bed stress. Design detail for the introduction of such features are given in Hall *et al.*, 1993.

There is also a need to develop designs which tie the waterway into the adjacent riparian river corridor to provide an integrated treatment-train approach for urban river management. Thus source control measures such as grassed swales (as relief channels or as distributor channels for incoming impermeable surface flows), small on-line retention ponds built into the floodway, lined infiltration trenches as well as low flow inverts cut into the channel, will all support a wider range of potential flows, habitats and user interests (Ellis and House, 1994). Rehabilitation schemes should also consider the potential advantages of replacing the single channel path line with a multi-thread network having in-built wetland and swale systems. Such engineered 'greenways' will stabilise surfaces and retard flow velocities as well as enhance pollutant interception and increase open-space, landscape values.

The intensive application of these various non-structural measures will help to reduce the acute and delayed impacts of SWO and CSO discharges as effectively as enhanced biological treatment of the effluent. However, the performance of these measures have not been quantified to give any reliable indication of their long term restoration efficiencies. One must therefore ask whether such non-structural or ecological engineering approaches in the long term will be more or less reliable than the conventional "hard" engineering solutions we currently possess.

Shear stress (N/m^{-2})	Non-ionised Ammonia (*100 µg/l)	Population loss (%/30 mins)
1.7	1.67	7
1.7	3.33	9
1.7	4.33	7
1.7	7.33	7
1.7	10	12
2.28	14.28	20
9	0.33	12
9	1.67	16
9	2.66	18
9	6.00	21
9	7.16	21
9	8.33	29
24	0	32
23.5	1.33	38
23	3.33	45
23	4.33	43
24	7	50
24	8	72
23	12.57	60
23	12.92	70

Table 8.2. Physico-chemical controls on population drift.

4. CONCLUSIONS

Engineers, hydrologists and ecologists involved in urban river management have to scale the temporal and spatial variability of the hydraulic and chemical factors influenced by stormwater runoff and which lead to organism disturbance. This requires quantification and mitigation of ecological impacts such that existing regulated channels having poor water quality and depressed habitats with low specific retention capacities (urban position on Figure 8.1), can be restored or re-created to achieve intermediate specific capacities with phased successions closer to natural conditions. The use of patch dynamics concepts based on the quantification of key controlling parameters for community loss provides a planning level evaluation procedure for comparing the impacts of alternative urban runoff management measures. In addition, it can be used to assess likely recovery rates following rehabilitation and upgrading schemes. However, there are difficult inherent management issues relating to how the urban aquatic ecosystem has evolved in response to continual perturbation. It could be argued that perpetual disequilibrium and disturbance of the macroinvertebrate community is the 'normal' condition for urban channels. If this argument is accepted, then the goal of sustainable runoff management becomes restoration of the entire spectrum of low/high frequency perturbations and indeed this has been advocated by some workers (Niemczynowicz, 1994). In addition restoration and rehabilitation might well make the renovated system appear to be much more vulnerable to episodic pulse disturbance. Therefore techniques and measures supporting post-failure recovery become all the more important; recovery analysis is essential to the integrity and success of sustainable urban runoff management.

The patch dynamics approach can help the definition of functional relations between habitat characteristics, flow and chemical states for the urban channel biotope, identifying disturbance and risk thresholds of significance to differing species and biotopes. In this respect, it can support habitat management strategies within the Catchment Management Planning (CMP) process and could link into national EA river habitat survey (RHS) methodologies which in turn are intended to inform sustainable development strategies and management practice. It remains a paradox that whilst many of the key problems in ecology refer to large scale processes in space and time, much of the ecological research effort has been focussed on mechanisms that operate on small, short-term scales. The challenge is to link processes at the level of the individual local population or sampling area to outcomes at the regional or catchment scale. This includes processes that influence species recruitment migration and distribution as well as the impact and interaction of pollutants at the ecosystem level.

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9

Geomorphological basis of river restoration

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Abstract

Most river restoration projects in Europe have been designed to improve landscape and conservation value often with little regard for channel stability. To recreate a sustainable natural channel it is necessary to (i) determine the stability, morphology and geotechnical characteristics of the river, (ii) develop a soft engineering design based on the survey data, and (iii) evaluate the stability of the design. Two schemes are outlined to illustrate the application of these design principles; one on an upland river which actively transports gravel and the other on a lowland river with an immobile gravel-bed.

1. INTRODUCTION

European rivers have, for at least five thousand years, been physically degraded as a result of anthropogenic activity. This can be classified into indirect and direct effects. The former refers to changes in the flow and sediment transport regime of the river resulting either from land use change, for example deforestation and urbanisation, which can affect whole river systems, or from the construction of water mills, dams and certain types of flood alleviation works or from the operation of water transfer schemes which have a more local impact. Such changes can destabilise rivers and precipitate alternating periods of valley incision and extension and flood plain construction and terrace development (Brookes, 1988; Petts *et al.*, 1989). However, provided the rivers are not artificially constrained, they develop naturally towards a new regime condition. In contrast direct management of rivers for flood alleviation and land drainage and for river stabilisation and training can be more intrusive as the river is canalised by dredging, widening or straightening and by the use of heavy engineering works to protect the banks and stabilise the bed. This prevents the re-establishment of a natural equilibrium. In addition, any failure to preserve the sediment budget through the engineered reach can trigger instability. As a result heavy maintenance, an euphemism for dredging and bank protection, is then required to maintain the engineered reach in an unnatural state and stabilise adjacent reaches.

Canalisation totally destroys habitat variety by removing meanders, riffles, pools, steep banks, dead zones and tree cover and destroying the substrate. Consequently the river becomes a sterile, uniform canal and the conservation, fisheries and amenity value of the river is severely degraded.

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Many European rivers have been canalised, particularly over the last 200 years, principally for flood alleviation and land drainage but also for river stabilisation in upland areas. Within England and Wales between 12.3% and 41% of main rivers have been affected during the period 1930-1980 as part of capital works or major improvement schemes (Brookes *et al.*, 1983). This represents an average density of 0.06 km per km^2, compared with 0.03 in the US (Leopold, 1977) and 0.9 in Denmark where 97.8% of all rivers have been straightened (Brookes, 1987). This reflects the intensity of land use in Denmark and similar densities are likely in Holland and northern Belgium for the same reason. Switzerland is similarly affected as virtually all major rivers were regulated during the 18th and 19th centuries to control flooding, drain mosquito infested wetlands, and reclaim land (Vischer, 1989). In Germany all the major rivers, Rhine, Elbe, Mosselle, Wesser, Main and Danube, have been totally modified (Kern, 1992), as have virtually all the main rivers in France, Italy, Spain and Portugal. One exception, the River Loire in France, recently escaped the same fate and it remains the last large and relatively wild river in western Europe.

Public concern in the US in the 1960s and 1970s regarding the environmental impact of conventional river engineering works spread to Europe in the following decade. This concern, coupled with the introduction of European Union legislation on environmental impact assessment in the 1980s, has resulted in the development of the more sympathetic management procedures, as for example in the UK and Germany (Gardiner, 1991; Kern, 1994). This requires a more holistic and interdisciplinary approach to river management. Although the adoption of these more enlightened procedures will, hopefully, prevent future canalisation projects, there remains a legacy of existing works which require restoration.

2. RIVER RESTORATION PROJECTS

A number of restoration projects have been carried out in Europe, particularly in Denmark, Germany and the UK, and more are planned. Most have been implemented on lowland rivers, namely those where bed material transport is negligible, rather than steep upland rivers that transport significant amounts of bed material load. This probably reflects the predominance of canalisation works on low gradient rivers.

Many of these schemes have been designed to maximise habitat variety, often by introducing exotic features, to meet ecological and aesthetic objectives with little concern for sustainability or for the natural functioning of river systems. This approach fails to recognise that rivers are physically determined as their features are dependent on flow and sediment transport processes and the nature of the alluvial material through which they flow. Consequently, as rivers in particular environments have certain characteristic features, it is totally inappropriate to impose an unnatural condition upon them as this will affect their sediment transport balance and stability. Although lowland gravel-bed rivers will generally respond less rapidly than upland rivers to such changes, due to lower bed material transport rates, any systematic aggradation or degradation can destroy the habitat features that were created, indicating that they are not enduring.

While there is no question that restoration should reflect ecological and aesthetic objectives, the basis for engineering design must be a fundamental understanding of the processes controlling natural channel shape and dimensions. Such designs will recreate habitats appropriate to the type of river being restored which can then be recolonised by macrophytes, invertebrates and

fisheries. Additional habitat features aimed solely at enhancing species richness should only be incorporated provided they are sustainable and that they do not require any subsequent management to prevent any particular species becoming dominant.

General guidelines have been published in many European countries which aim to assist the design process (Eiseltová and Biggs, 1995; Nielsen, 1992; Tanago and Jalon, 1993; RSPB/NRA/RSNC, 1994). These mainly review the physical and biological characteristics of rivers and provide background information regarding the range of possible in-channel and bank engineering works, both non-structural and structural, for restoration and rehabilitation. Some also incorporate case studies which outline the objectives of the scheme, type of river, approach and outcome (Kern *et al.*, 1992; RSPB/NRA/RSNC, 1994). Significantly most of these refer to low gradient rivers. This information, although valuable, is, nonetheless, descriptive rather than prescriptive since few details are given regarding the design of the schemes and, more significantly, no limits are given to their range of application. In order to successfully develop more natural approaches for river management and restoration it is imperative that these softer procedures are tested to the limit. Indeed, failures are often more enlightening than successes, provided they are recorded, since mistakes can then be prevented and over-design avoided.

3. RIVER RESTORATION DESIGN PROCEDURES

More specific design guidance is provided in a National Rivers Authority (UK) report on restoring and rehabilitating canalised rivers (Hey and Heritage 1993; Hey 1994). This distinguished between *restoration*, where all artificial constraints on the river are removed and pools, riffles and meanders re-instated, namely non-structural methods, and *rehabilitation* where it may be necessary to retain some heavier engineering works, such as masonry walls and weirs, but there is opportunity for some naturalisation and the creation of habitat features using instream or bankside structures or through bed re-profiling. This paper focuses on restoration design.

Full restoration involves the design of a natural channel to replace the canalised one. This may not exactly replicate an earlier natural channel since control conditions over the intervening period may have changed. Instead it aims to establish a river with a natural range of instream and bankside features which will be enduring under present river conditions. It may also be necessary to maintain the original engineering objectives in terms of flood capacity or water table levels. The simplest approach to restoration would be to remove the artificial constraints on the river and let nature take its course. The danger would be that the associated erosion and deposition could significantly destabilise adjacent reaches, particularly on upland rivers. In contrast, on lowland gravel-bed rivers, the response time could be extremely slow, upwards of thirty years, which may be unacceptably long. Intervention is required to artificially recreate a natural type channel to avoid these problems.

There are three stages to the design process. The first requirement is to establish the geomorphological characteristics of the river not only within the engineered reach but also adjacent sections. This provides the basic data for designing the scheme and also for assessing its engineering performance.

3.1 Geomorphological Assessment

3.1.1 Channel stability

Upland rivers are generally more unstable than lowland ones as evidence by incision and bank failures and the development of bars and braided channels. Characteristically eroding and depositing reaches alternate along a river and these features migrate over time. Downstream migration results from local changes in sediment supply, while upstream movement is in response to local changes in transport capacity. River response to natural or man-induced changes can be identified in general terms using Lane's (1955) proportionality index:

$SQ \alpha Q_s D$

where S is the channel slope
Q the discharge
Q_s the sediment load
D the bed material size.

Figure 9.1 illustrates the changes that can occur, including those resulting from canalisation, and identifies the importance of identifying other potential destabilising influences within the catchment as they could migrate over time and jeopardise the integrity of the restoration works. The rapidity and degree of change depends on the sensitivity of the river to erosion and deposition and the severity of the trigger mechanism. A new equilibrium or regime state would eventually result if the river is trained in an attempt to stabilise it as, for example, in the DEC watersheds in northern Mississippi. While catchment wide assessments can identify potential destabilising influences, the current local condition needs to be evaluated. This can be achieved by field, flow and historical survey data (Table 9.1), and they enable changes to be monitored over time. Should evidence or forecasts indicate that a scheme may be adversely affected by channel instability, then remedial or preventative measures need to be taken to control it.

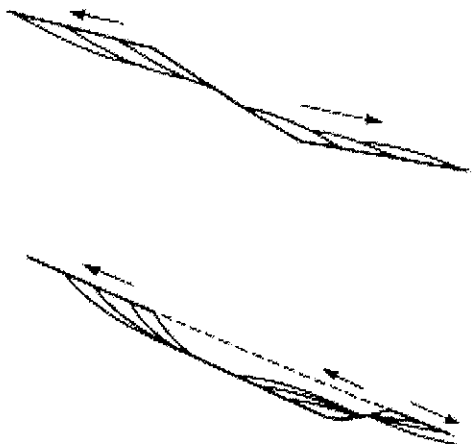
3.1.2 Geomorphological survey

Topographic surveys should be carried out along the engineered reach and for a minimum of seven times channel width upstream and downstream in order to define the approach and exit conditions. Cross-sections should be surveyed at pool, riffle and intermediate sections, to define morphological variability, and a contour plan produced. The plan should then be used to map key habitat features including pools, riffles, runs, glides, dead zones, bar forms, steep banks, berms, tree cover, type and location of bank protection works, fish weirs, bridge piers and abutments, fallen trees, areas of eroding bank and their mode of failure.

3.1.3 Geotechnical survey

Information needs to be obtained to characterise the bed and bank material along the reach. For gravel bed rivers surface bed material size-frequency distributions are required for calculating discharge capacities and for evaluating spawning potential, and this can be determined for pools and riffles using a grid by number sampling procedure supplemented by wax and clay areal samples should it contain material finer than 10 mm (Fripp and Diplas, 1993). Sub-surface samples for calculating bed material transport can be obtained using bulk by mass procedures

(International Organisation for Standardisation, 1992). In sand-bed channels there would be no significant difference between surface and sub-surface fractions and composite bulk samples would suffice.



Channel straightening	$S^{+}Q_{+} \longleftrightarrow Qs_{+}D_{+}$	up
	$S_{+}Q_{-} \longleftrightarrow Qs^{+}D_{-}$	down
Channel widening and dredging	$S^{+}Q_{+} \longleftrightarrow Qs_{+}D_{+}$	up
	$S^{-}Q_{-} \longleftrightarrow Qs_{-}D_{-}$	centre
	$S_{-}Q_{+} \longleftrightarrow Qs^{-}D_{+}$	down

Figure 9.1 *Channel response to straightening and widening and dredging (+ = increase; - = decrease; above line = control; below line = response). From Hey (1994)*

If the restored channel is to be realigned, then it would be necessary to undertake a bore hole survey along the route of the proposed river. This would determine the elevation of the upper surface of the gravel, since it may not conform to the required pool-riffle bed topography, and identify whether any reprofiling was necessary. Second, it is essential that the calibre of the floodplain gravel corresponds to the sub-surface bulk sample from the river bed otherwise erosion or deposition could result in the restored reach. Care would need to be exercised when comparing the two samples since the small size of a borehole sample, relative to that from the river bed, could bias the distribution towards the coarser fractions. If the bed material in the realigned section is dissimilar, then it would be necessary to replace it with appropriately graded material.

Field evidence		Instability tendency
A	**Channel morphology**	
1	Undermined bank protection structures, bridge footings	Incision/faulty design/overdredged
2	Buried structures, contracted bridge openings	Aggradation
3	Erosion of both river banks a) no central bar/island b) with central bar/island	 Incision/or tree removal/under designed Aggradation
4	Channel infilling and lateral contraction with vegetation encroachment - small discharge capacity (relatively shallow, fine bed material, low gradient) - braided	Aggradation
5	Enlarged channel with large discharge capacity (relatively deep, coarse bed material, steep gradient)	Incision and lateral erosion (bedrock - long term) flood alleviation scheme
6	Evidence of increased bank erosion in meander bends and associated unvegetated point bar deposits	Degradation
B	**Floodplain sedimentary sequences**	
1	Buried soils within alluvium	Aggradation/made ground
2	Textural changes in vertical sequences of alluvium - a) coarse sediment (bed material load) overlying fine overbank sediments (suspended load) b) fine sediment overlying terraced coarse within-channel deposits	 Aggradation/made ground Incision or lateral contraction
3	Elevation of channel bars higher than fossil bars exposed in river bank	Aggradation
4	Elevation of channel bars lower than those exposed in river bank	Incision
C	**Floodplain morphology**	
1	Inactive multi-channel system on floodplain	Incision/canalisation
2	Terraces on valley floor	Long term incision/aggradation cycles 10s - 100s years
Flow levels		
Specific Discharge		
1	Increase in stage level for long term mean annual discharge	Aggradation
2	Decrease in stage level for long term mean annual discharge	Incision
Historical evidence		
Survey Information		
1	Changes in cross section	Incision/lateral erosion or aggradation/contraction
2	Increased sinuousity	Incision/lateral erosion
3	Decreased sinuosity (→ braiding)	Aggradation

Table 9.1 Indicators of channel instability (based on Lewin et al., 1988)

The properties of the bank material (particle size, angle of friction, cohesion, shear strength, etc.) and variation with depth should be determined using standard sampling and analytical procedures. Surveys are required along the banks of the river, to check factors of safety on existing banks for failure mechanism corresponding to those observed in the field, and along the banks of the proposed channel. Should bank failure be predicted in the restored section, then some form of bank protection will be required at vulnerable locations on the outside of meander bends and at the infilled sections of channel at each end of the restored reach. The absence of trees and shrubs on the newly created banks could significantly reduce factors of safety with the result that some form of temporary protection against surface erosion and mass failure may be required until vegetation becomes fully established.

3.2 Restoration Design

For full restoration it is necessary to determine the bankfull cross-sectional, longitudinal and plan shape of the river. Average reach dimensions, defined over one meander wavelength as this is the repeating length of the river, are uniquely prescribed by bankfull width (W), mean depth (d), maximum depth (d_m), channel slope (S), sinuosity (p), and meander arc length or channel distance between riffles (z) (Hey, 1978). In order to allow for variations along the reach, pool and riffle dimensions also need to be specified.

Provided that the reaches adjacent to the restored section are natural and stable, then data from the geomorphological survey and old maps and aerial photographs can be used to determine these parameters. The latter enable the original sinuosity of the river to be re-instated and, thereby, channel length and gradient, while the local survey data prescribe the bankfull widths, mean and maximum depths in the pools and riffles and the meander arc lengths. If the meander bends in the restored section have a smaller curvature than those in the adjacent reaches, then maximum scour depths in the meander bends would need to be calculated using an appropriate empirical equation (Apmann, 1972; Thorne and Abt, 1992).

Where the neighbouring reaches are unstable or have been engineered to some degree, then it would not be possible to use local information as a blueprint for restoring the river; neither would it be appropriate to re-instate an earlier meander geometry. In these circumstances regime equations which are appropriate to the local river conditions can be used to predict the regime bankfull width, depth and slope given the discharge, bed material size and, for mobile bed rivers, bed material transport rates (Hey, 1988). Generally the design discharge in these equations is the bankfull flow, since this is considered to be the channel forming flow as it corresponds to the flow that transports most sediment in the longer term (Wolman and Miller; 1960; Andrews, 1980). However, where the reach to be restored is unstable or engineered, the observed bankfull flow is undergoing systematic change or is artificially maintained. In these circumstances an alternative is to use the flood discharge corresponding to the return period of bankfull flow for natural stable channels. This is generally considered to be the 1.5 year flood, annual maximum series, although its value is likely to vary between rivers depending on flow and sediment transport regimes (Hey, 1975).

The sinuosity of the river can be determined from the ratio of the valley slope, prescribed, to the predicted channel slope. This, together with the meander arc length, on average six to seven times channel width, defines the plan shape of the river. Pool-riffle variations in width and depth can be determined from regime equations for gravel bed rivers (Hey and Thorne, 1986),

while maximum scour depth in meander bends can also be estimated (Apmann, 1972; Thorne and Abt, 1992).

Caution has always to be exercised when using regime equations to determine channel dimensions. Although channel width and depth can be predicted with a reasonable degree of precision, estimates of channel slope can be very much in error, and, thereby, channel sinuosity. As the creation of river meanders is a key element in many restoration schemes, there is a danger that an inappropriate plan form may be constructed. One possible solution would be to predict channel width and depth and then use a appropriate bed material transport equation to determine the slope required to transmit the input load.

3.3 Design Evaluation

Before constructing the scheme it is necessary to ensure that its bankfull capacity corresponds to that in adjacent reaches and that it will remain stable. In the absence of gauged data, bankfull flows can be calculated for a number of cross-sections along the river using appropriate flow resistance equations. If necessary, modifications should be made to the design to ensure discharge conformance through the reach.

To maintain the overall stability of the river it is essential to preserve the bed material transport regime. Failure to do so will precipitate erosion and deposition. This can be assessed by calculating the bankfull bed material transport at various cross-sections in the restored reach and at sections immediately upstream and downstream. For stability, it is necessary to ensure that transport rates are comparable at each cross-section. Alternatively, if daily average flow duration curves are available, then the average annual bed material load could be calculated at a number of cross-sections from derived bed material load rating curves. Provided the total input load can just be transmitted through the restored reach and it corresponds to the transport capacity downstream, stability can be maintained. Modifications would have to be made to the design if there is any imbalance in bed material transport between sections or any systematic change along the reach. Finally, the stability of the river banks needs to be assessed since any failures will affect local bed material transport capacities and sediment budgets and, thereby, the stability of the reach.

Should it be necessary to reconnect the restored river prior to vegetation becoming established on the banks, then consideration should be given to the possibility of surface erosion. Maximum shear stresses on the banks, particularly on the outer bank in meander bends (Apmann, 1972; Agostini *et al.*, 1985) would need to be determined for comparison with critical values for erosion of the bank material (Smerdon and Beasley, 1959). If critical shear strengths are exceeded, then some form of soft bank protection may be required until vegetation becomes established (Hemphill and Bramley, 1989; Lachat, 1994; Johnson and Stypula, 1993). Where it is necessary to maintain steeper unvegetated banks in meander bends for nesting kingfishers and sand martins, surface erosion and toe scour is required.

Calculations also need to be carried out to assess factors of safety against shallow, planar and rotational failures in cohesive sediment (Choudhury, 1978; Janbu, 1973) or against beam, shear or tensile failures in composite banks (Thorne and Tovey, 1981) given the geotechnical properties of the bank material and the design height and slope of the bank. As the actual failure surface can never be known in advance, all possible combinations of failure planes/angles and groundwater conditions should be tested to establish the condition with the lowest factor of safety. If the correct failure mechanism is not anticipated, the assumed factor of

safety could be higher than the true value. Observations of bank failures in neighbouring sections will identify the most likely modes of failure. Protection against mass failure is required if the factor of safety is less than unity. If failure is predicted, bioengineering/biodegradable bank protection methods which treat the cause of failure, are preferred to more traditional procedures and they need to be effective until trees become established on the bank (Hemphill and Bramley, 1989; Lachat, 1994; Johnson and Stypula, 1993).

4. APPLICATION

Geomorphological principles have been applied to design two schemes in the UK: the River Blackwater at Reymerston, Norfolk and the River Neath between Aberdulais and Marsgwyn, Glamorgan. Strictly, both should be classified as diversions, but as they involved the conversion of straight or meandering canalised rivers into more natural meandering channels they can be regarded as restoration projects. The former represents a typical lowland river with a relatively immobile gravel bed, while the latter is an upland type river which actively transports gravel.

4.1 River Blackwater, Reymerston, Norfolk

The River Blackwater is a small chalk-fed stream which, prior to land drainage works in the mid-nineteenth century, had a sinuous course. Channel improvements to aid land drainage involved the construction of a straight, deep, trapezoidal channel which decoupled the river from its flood plain. The proposed diversion, to facilitate the extension of a sand and gravel quarry, aimed to maintain the river's flood capacity and land drainage standard, while enhancing the conservation, fisheries and amenity value of the river and creating a functioning flood plain. Six hundred metres of river were affected by the proposal.

Geomorphological, topographic and river corridor surveys were carried out along the existing channel and adjacent upstream and downstream reaches to establish the pre-condition. Essentially the river had a uniform trapezoidal section; bed width 3-4 m, bank top width 9-10 m, and overall depth 1.7-2.1 m. The river followed the course constructed when the drainage scheme was implemented with long straight reaches linked by short, large radius, bends. Along much of the reach, the bed was formed of compacted gravel, although there were sections where this was covered by sand, silt and organic material up to a depth of 0.3 m. Bed macrophytes had colonised some of the silty material. The vegetated banks were relatively steep (between 45-60°) and composed of a variable thickness of sandy silty clay overlying gravel and sand. Given the height of the gravel in the bank relative to that of the bed, it indicated that the bed of the stream had been dredged by approximately 0.8 m. The existing channel had no intrinsic geomorphological value as it lacked the range of features normally found in chalk-fed gravel-bed streams; riffles, pools, gravel bars, and vertical banks. The lack of morphological variety restricts ecological diversity, as indicated by the River Corridor Survey, and the imbricated bed material is unlikely to be colonised by invertebrates. Consequently, this reach had little fisheries value.

Calculations were carried out to estimate the bankfull capacity of the dredged channel using resistance equations applicable to gravel-bed rivers (Hey, 1979). This indicated a capacity of 6.27 m^3 s^{-1}. The mobility of the gravel bed at bankfull was established using the Shields stability criteria. With an entrainment function of 0.06, a value applicable to imbricated gravel,

material up to 4.1 mm could be transported. From the bed material size analysis, this indicated that only 5% of the bed material is potentially mobile.

The required route for the diversion followed the southern flank of the valley. In order to restore a natural type channel, given that the present river is approximately 0.8 m deeper than it was originally, it was necessary to create a new valley about 15-20 m wide and 0.8 m below the existing flood plain and construct the restored river within it. This was formed in backfilled material after the extraction of commercial grade gravel. The bed of the river was relaid with gravel which had a grading comparable to that in adjacent reaches and the upper bank and flood plain constructed out of the stockpiled fine alluvium. A bankfull width of 5.5 m and a mean depth of 1.0 m was chosen for the riffle sections, based on a relatively unaffected reach of river about 1 km upstream. The planform was chosen to recreate the sinuous course of the original channel with meander arc lengths appropriate to the width of the river. Given the fall between the ends of the diversion and the new channel length, the slope of the diversion was prescribed. The capacity of the river together with the 15 m wide low flood plain was estimated to be 8.12 $m^3 s^{-1}$ even when the berm was left unmanaged (Possey, 1967). The additional capacity leaves a margin of safety in the design. Calculations also showed that the bed material would remain immobile even during flood conditions. The detailed designs for the riffles and pools were based on regime equations for gravel-bed rivers (Hey and Thorne, 1986). Riffles had a top width of 5.5 m and a maximum depth generally of up to 1.75 m but deeper where the bend encroached against the valley side. Details of part of the scheme are shown in Figure 9.2.

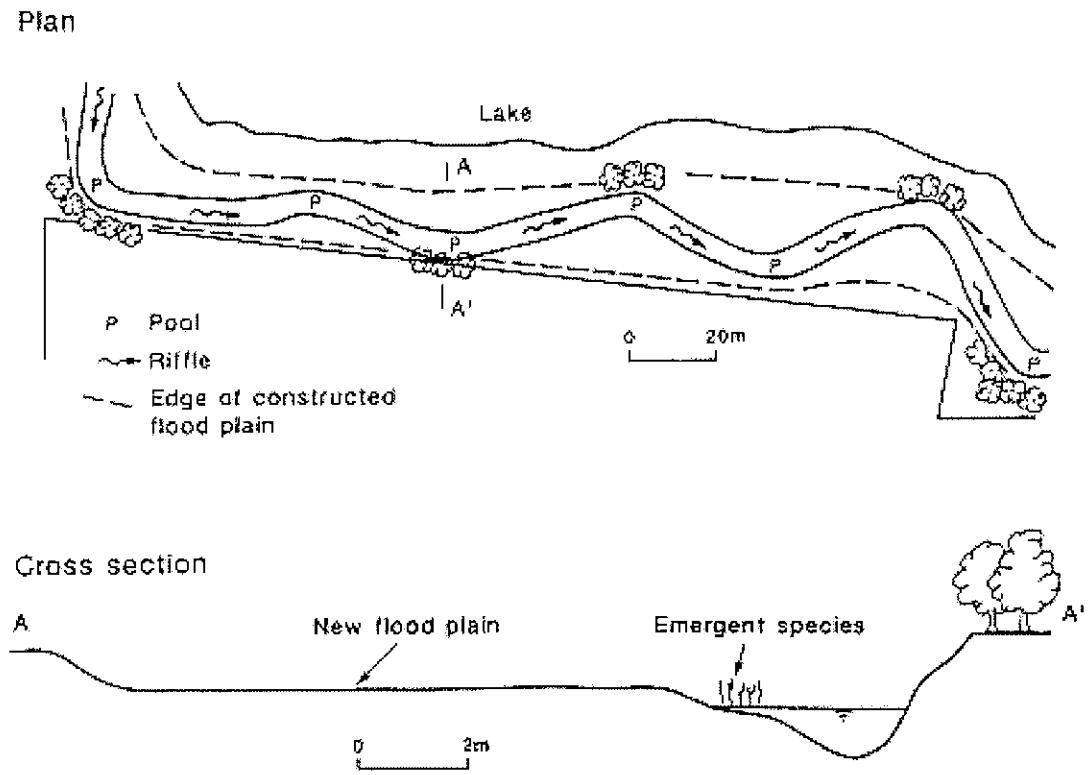


Figure 9.2 Design of Diversion at Reymerston, River Blackwater, United Kingdom

The new channel was constructed in 1991, but flow into it was restricted to allow colonisation with aquatic and marginal organisms. The initial low flows encouraged the rapid establishment of algae and macrophytic vegetation and colonisation by filter feeding fauna which are characteristic of faster-flowing gravel riffles, such as caseless caddis and blackfly larvae, and swimmers and crawlers on vegetated margins such as cased caddis, molluscs and shrimps. As commercial grade gravel was abstracted from beneath the diversion route prior to back filling with appropriately graded gravel and finer upper bank material, this initial period prior to closing off the old channel also enabled the material to consolidate and the flood plain to become vegetated. Following a large flood in October 1993, when the Blackwater broke through into the gravel workings, all flows are now routed through the new channel.

Family name	**Culford Stream at Lackford**	**Blackwater at Reymerston**
Tubificidae (worms	✓	✓
Erpobdellidae (leeches)		✓
Glossiphonidae (leeches)		✓
Limnaeidae (snails)	✓	✓
Planorbidae (snails)	✓	
Hydrobiidae (snails)	✓	✓
Sphaeridae (clams)	✓	✓
Gammaridae (shrimps)	✓	✓
Asellidae (water lice)		✓
Baetidae (mayflies)	✓	✓
Limnephilidae (caddisflies)	✓	✓
Hydropsychidae (caddisflies)	✓	✓
Sialidae (alder flies)	✓	✓
Elmidae (riffles beetles)	✓	✓
Dytiscidae (diving beetles)	✓	✓
Haliplidae (water beetles)	✓	✓
Tipulidae (crane flies)	✓	✓
Chironomidae (midges)	✓	✓
Simulidae (black flies)	✓	✓

Table 9.2 *Comparison of macroinvertebrate composition on restored riffles (Blackwater at Reymerston) two years after construction with riffles on comparable natural river (Culford Stream at Lackford). Samples obtained by kick-netting.*

Although a prolonged period of high flows has subsequently occurred, the restored channel has remained stable and its overall flood capacity, within the two-stage section of the newly created valley, has proved to exceed that in the adjacent reaches. Recolonisation by macro invertebrates would appear to have been completed by 1993 given that kick sample surveys indicated a comparable composition to that in a neighbouring natural channel (Table 9.2).

On this type of river, due to the low gradient and size of the bed material, there is no significant bed material transport through the reach. Consequently, provided that the new channel is designed such that all flows are below bed material transport thresholds, then the river would not erode. Although this allows some scope in choice of design for the restored channel, in

terms of plan shape, gradient and cross section, and also with regard to additional habitat features such as submerged benches, gross overdesign has to be avoided as this would lead to siltation and bank encroachment.

4.2 River Neath, Aberdulais-Marsgwyn

To accommodate the planned A465 trunk road, it was necessary to divert the River Neath at five locations. The river, which has a bankfull flow of 180 $m^3 s^{-1}$, actively transports gravel-bed material. Over the years, the drainage authority has carried out considerable dredging, to remove gravel shoals and riffles, and long lengths of non tree-lined banks have been protected by blockstone revetments to prevent bank erosion and meander migration. Water quality improvements in recent years have led to a dramatic improvement in fisheries, especially salmon. The highway authority originally planned to construct straight uniform diversions. This would have steepened the river by upwards of twenty-five percent and caused serious instability problems. The National Rivers Authority, Welsh Region, the agency consenting the works, required that a more natural solution should be adopted to foster fisheries improvement, maintain the natural stability of the river, and generally enhance the conservation and amenity value of the riverscape.

Geomorphological, topographic and geotechnical surveys were carried out along the sections that were to be diverted and adjacent reaches (Figure 9.3). In view of the river engineering works that had been carried out along the reach, the morphological information could only be used as a guide to the design of the diversions, and regime equations (Hey and Thorne, 1986) were used to establish pool and riffle dimensions given the gauged bankfull discharge (180 $m^3 s^{-1}$), and surface bed material size (D_{50} ranging from 120 mm at Marsgwyn to 38 mm at Aberdulais).

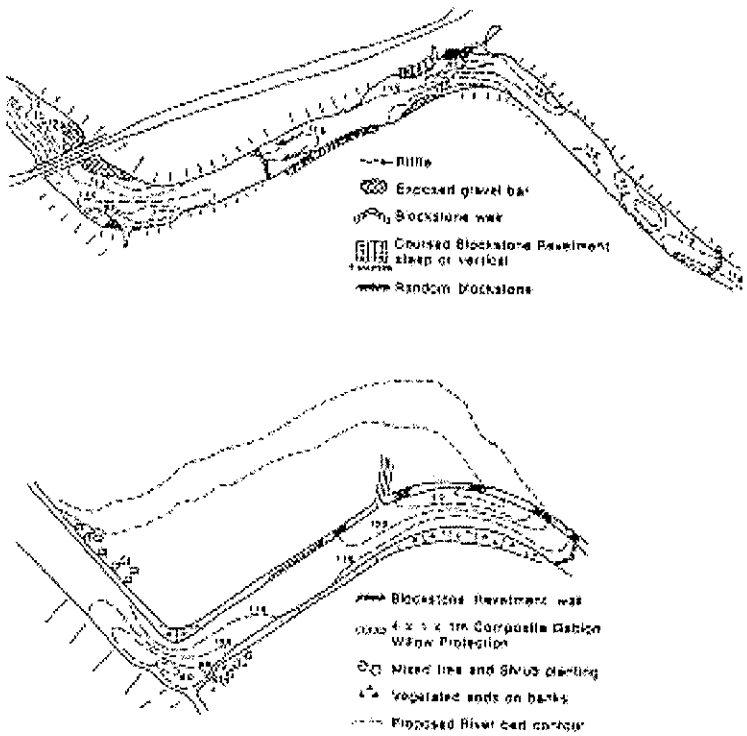


Figure 9.3 Design of Diversion at Ynsbwllog, River Neath, UK

Calculated bankfull widths generally ranged between 28 and 34 m with mean depths between 2.9 and 2.3 m. Pools were designed to have an asymmetric cross-section with maximum depths of up to 4 m depending on the curvature of the bend (Apmann, 1979). At Ynysbwllog, the opportunity was taken to created a 'hammer-head' bend by directing flow at ninety degrees to the valley side. This will generate a large pool, which will act as a holding area for mature salmon, while the reverse flow that is generated immediately upstream from the bend will create a shallow, relatively warm, dead zone which will be an excellent nursery area for salmon fry (Figure 9.3). Channel length was maintained within each diversion and, thereby, the gradient and sinuosity, while the exact course of the river was prescribed by the meander arc length (Figure 9.3).

The geotechnical survey along the river bank and the line of the proposed diversions enabled the stability of the banks of the restored river to be assessed, particularly against rotational failure which had been locally observed and, where necessary, modifications were made to bank height and slope to provide a suitable factor of safety. Where this could not be sensibly achieved, additional protection was prescribed with emphasis on softer bioengineering solutions. The calibre and elevation of the gravel on the diversion route was also established. This showed that the bed material grading approximated that of the gravel underlying the flood plain. Differences can be attributed, in part, to different sampling and analytical techniques and to the spatial variability of the buried gravel. However, material collected in flowing water would be expected to be coarser than material obtained on land due to loss of fines. The elevation of the gravel along the diversion route approximated that required for the bed of the restored river. Finally the bankfull capacity of each diversion was estimated using resistance equations (Hey, 1979), and the associated sediment transport rates calculated using the Meyer-Peter Muller equation to ensure that the sediment budget through each reach was maintained.

5. CONCLUSIONS

When designing restoration schemes on mobile gravel-bed rivers, it is essential to recognise that there is really only one design option since the controls on channel form, discharge, sediment load, bed and bank material and the valley slope, are prescribed. Any attempt to impose an alternative design will result in instability unless heavier engineering approaches are adopted (e.g. bank revetments), and this would defeat the object of the restoration exercise.

Although these particular examples describe diversion schemes, effectively they can be regarded as restoration projects as they provided the opportunity to enhance the conservation, fisheries and amenity value of the two rivers. The methods used to design the schemes are still being developed and it will certainly be necessary to monitor their engineering and environmental performance in order to evaluate and refine the procedures. Currently designs have to be based on local conditions, if the river is natural and stable, or regime equations, if the river is unstable or artificial. The application of more rational design procedures awaits the development of physical-based equations for predicting channel width.

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10

Restoration of the River Skerne and River Cole: Impact on flood hydrology

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Abstract

River Restoration on the River Skerne and River Cole in the UK has been undertaken by the River Restoration Project Ltd (RRP), a company established by a group of individuals interested in and committed to restoring rivers. European *LIFE* funding has enabled restoration work on three demonstration sites, the two in the UK and the River Brede in Denmark.

The restoration has aimed to reintroduce natural habitats and features into damaged rivers, reconnect rivers with their floodplains and demonstrate the benefits of river restoration. Monitoring of the physical, chemical and biological effects of restoration on the rivers has been an integral part of the project. The monitoring has included hydrological measurements both before and after restoration to help to demonstrate the impact of restoration on river hydrology and flood alleviation. Computational hydraulic modelling of the River Cole and River Skerne has predicted the impact of the restoration design on the flood levels and discharges. Data collected from ongoing monitoring of water levels, discharges and flooded outlines will be used to validate the model predictions. This paper concentrates on the impact of the restoration works on the flood hydrology at the two UK demonstration sites, as predicted by the hydraulic model.

1. INTRODUCTION

The River Restoration Project Ltd was established as part of a joint initiative between the United Kingdom and Denmark to encourage the restoration of rivers in Europe. This paper is based in work undertaken with the River Restoration Project on two demonstration sites, the Rivers Cole and Skerne. The impact of river restoration on the flood hydrology at these sites was part of a larger, multidisciplinary investigation into the impacts of river restoration on geomorphology, landscape, water quality and sediments, vegetation, invertebrate ecology, birds and fish. An expected effect of river restoration is amelioration of flood flows.

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HR Wallingford were funded by the Ministry of Agriculture, Fisheries and Food (MAFF), the River Restoration Project Ltd (RRP) and the National Rivers Authority (NRA) Yorkshire and Northumbria region to investigate the existing and design flooding regime on the two UK demonstration projects. Computational, numerical models were built, using the SALMON-F package, of both the Rivers Cole and Skerne to demonstrate existing flooding regimes and predict flooding regimes with the proposed designs. The designs were amended and refined as a result of using the models.

This paper looks at the flood hydrology on the two UK demonstration sites to demonstratethe predicted impact of restoration on the flooding regimes. The work on the flood hydrology has been based on prerestoration data collected and on the results from the computational, hydraulic models. The results presented in this paper are based on the statistical 1 in 2 year up to 1 in 100 year flood conditions. The model predictions given in this paper are currently being validated with field data.

2. BACKGROUND TO THE RIVER RESTORATION PROJECT

The aims of the project were fourfold:

1. To establish three European Demonstration Sites which apply new and state-of-the-art techniques to the restoration of natural habitats in damaged rivers and their floodplains.

2. To demonstrate the benefits of river restoration for Integrated Catchment Management in terms of nature conservation, water quality, river hydrology, flood prevention and amenity by monitoring the physical, chemical and biological effects of restoration.

3. To involve motivate and train those who influence or undertake river management work

4. To widely disseminate information about river restoration using pan-European networks

Three demonstration sites were established; two in the United Kingdom and one in Denmark on the River Brede. This paper will concentrate on the Rivers Cole and Skerne, the UK restoration sites.

3. IMPACT OF RIVER RESTORATION ON FLOOD HYDROLOGY

With the increase in drainage on rural catchments, and the expansion of towns and buildings on the floodplain, the runoff characteristics of many catchments have changed. Due to quicker runoff, the response times of floods have decreased and peak discharges have increased. On many catchments, embankments have been constructed to ensure that houses and agricultural lands remain free from flood water. Channels have been deepened, widened, straightened, and sometimes lined to convey flood water more quickly. These changes to rivers have increased the maintenance commitment with larger channels requiring maintenance to retain the design conveyance capacity. In these rivers, the contact with the floodplain has been lost for all but the very largest floods. The attenuating effect of the water flowing onto the floodplain has often been lost and, in many places, the flooding

problem downstream has increased. One solution to this problem has been to build flood storage ponds in the catchment which artificially attenuate the flood water.

The restoration of rivers can bring the river back into contact with its flood plain. It is hoped that, by undertaking restoration of sections of rivers, the flood water can be attenuated as in a more natural river floodplain system.

The information provided in this paper on the flood hydrographs before and after restoration works on the Rivers Cole and Skerne are those predicted in the model for a particular flood event - usually the 1 in 100 year event.

4. GENERAL HYDROLOGICAL CONDITIONS OF THE SITE

4.1 River Cole

The River Cole rises in chalk which sustains a modest base flow throughout the year. The catchment has a high response to rainfall because more than 55% of the catchment is underlain by clay. The mean annual flood based on the 18 year record from the gauging station at Inglesham, the downstream limit of the catchment is 15.5 m^3/s, rising to 26.3 m^3/s during the highest recorded flood in December 1979. The 1 in 100 year flood discharge is predicted to be 57 m^3/s at Inglesham weir and approximately 60 m^3/s at Coleshill Bridge. Up to 1950, the floodplain was only partly drained and much of it was operated as a water meadow system which encouraged inundation. Downstream of Coleshill Bridge the floodplain was regularly flooded and land use was dominated by permanent pasture. The Land Drainage report of 1935 describes much of the floodplain as water logged and prone to frequent flooding. Overall the hydrology of the catchment has been altered by urbanisation, largescale underdrainage (in the 19th century and more recently) and arterial drainage systems, culminating in the 1974 Cole Stage 1 works which effectively eliminated inundation of the floodplain downstream of Coleshill Bridge.

4.2 River Skerne

The catchment of the River Skerne is 250 km^2 which is approximately twice the size of the River Cole catchment (129 km^2). The mean annual flow of the river is 1.61 m^3/s compared with 1.18 m^3/s on the River Cole. The predicted 1 in 100 year flood has a peak discharge of 55 m^3/s and the Mean Annual Flood has a peak discharge of 23 m^3/s.

The most recent extreme flood event on the River Skerne was in 1979 when the flood that occurred was slightly greater than the 1 in 100 year event. The 1979 flood event was used to calibrate the hydraulic model of the restoration reach. The flood corridor of the River Skerne through the restoration reach is very narrow. The flooded outlines from the results of the hydraulic model show that the flooded outlines of the Mean Annual Flood and the 1 in 100 year flood through the restoration reach are very similar in area although the depths of flooding in the 1 in 100 year event are greater. The flood levels for the predicted 1 in 100 year event would be high enough to cause limited flooding of properties to the north of the restoration site. This shows agreement with the flooding observed in 1979 where some properties on the northern side of the river were flooded.

5. DESCRIPTION OF RESTORATION WORKS

5.1 River Cole

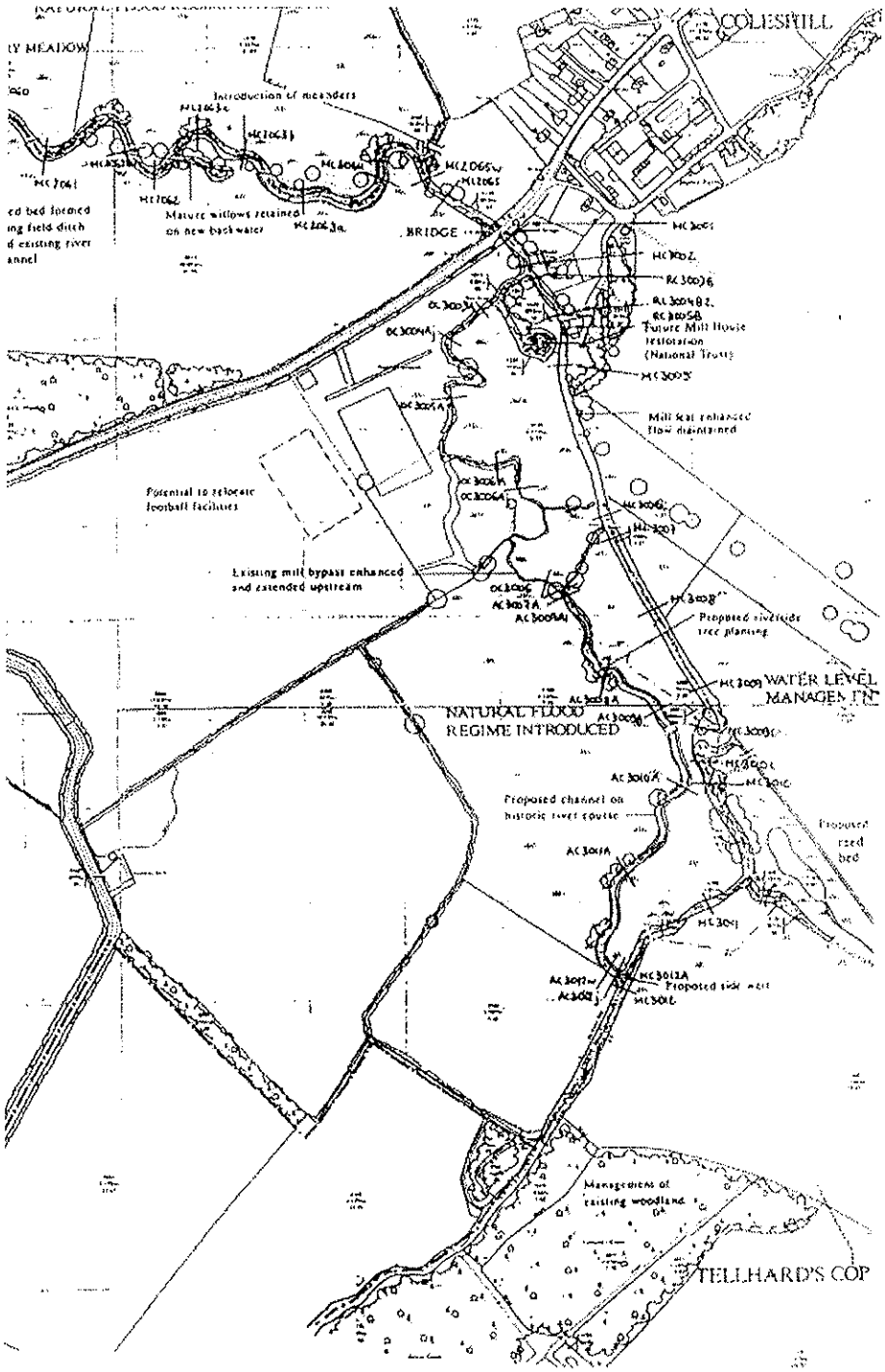


Figure 10.1 General layout of restoration works on the River Cole, Wiltshire

Figure 10.1 shows a sketch plan of the work undertaken on the River Cole, the RRP rural site near Faringdon in Wiltshire. The overall aims of this project were to restore a 2 km stretch of the River Cole which falls within the National Trust boundaries. The restoration involved: hydrological impact of the restoration has been to increase the hydraulic roughness of the channel with the introduction of meanders and vegetation and to change the frequency of flooding and floodplain inundation. The changes in frequency, level and volume of flooding are all discussed below.

6. IMPORTANT ISSUES AND CONSTRAINTS

6.1 River Cole

The proposed changes on the River Cole had to be designed to ensure that the flood levels for a given flood event were no higher than the existing levels for the same flood event. To ensure that the proposed design satisfied this constraint a computational, hydraulic model as built by HR Wallingford, of the River Cole, from Westmill bridge at the upstream boundary and Inglesham weir at the downstream boundary of the model. The model used was SALMON-F.

The flood events used in the model to test the existing and design conditions were from the 1 in 100 year flood to a 1 in 2 year flood. The flood hydrographs were determined using a flood routing model, RIBAMAN. There were a number of strategic positions along the River Cole where property, roads or public amenities would be at risk if flood levels increased.

6.2 River Skerne

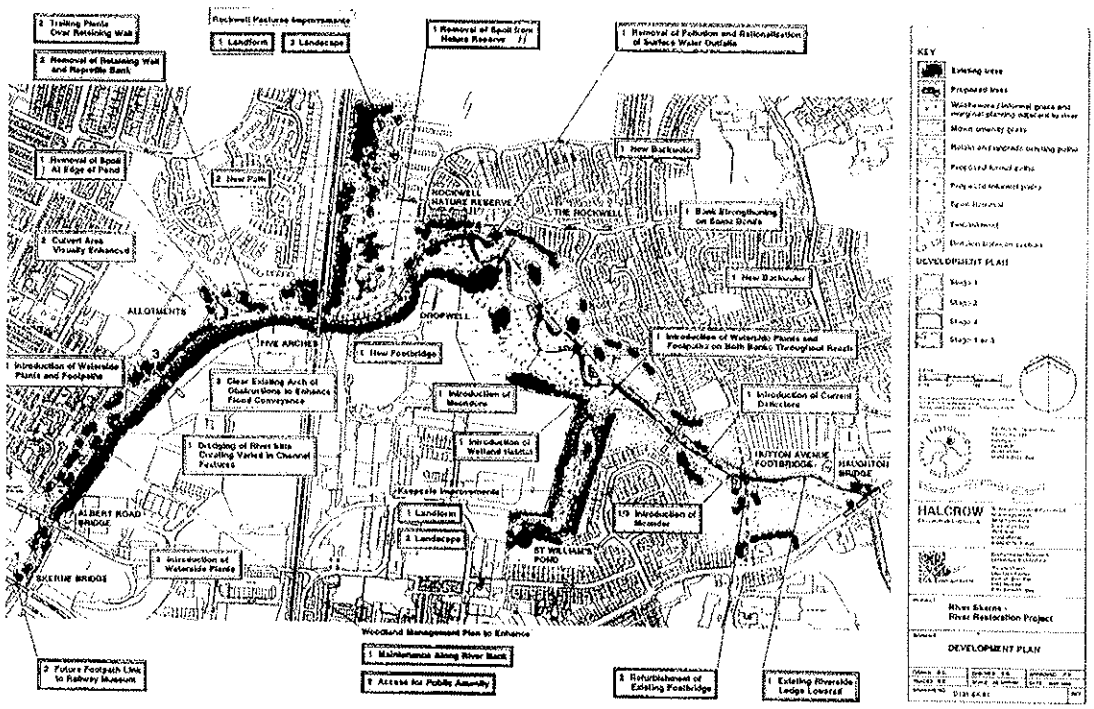


Figure 10.2 General layoutout of restoration works on the River Skerne, Co. Durham

The River Skerne runs through an urban area (Figure 10.2) and although there is open parkland to either side of the river, in the area of the major restoration a gas pipeline runs along the right bank. During restoration, this has restricted the movement of the river on that bank. The meanders which were created and lowering of the floodplain had to be carried out on the left bank. A number of outfalls discharged into the river on the left bank and this further constrained the lateral movement of the river. The River Skerne is crossed by several bridges, rail, foot and road, along the length of restoration and these bridges could not be moved. The restoration plans were designed to accommodate these bridges.

The proposed changes on the River Skerne had to be designed to ensure that the flood levels for a given flood event would be no higher than the existing levels for the same flood event. To ensure that the proposed design satisfied this constraint a computational, hydraulic model was built by HR Wallingford. The model covered the River Skerne from Great Burdon Bridge at the upstream boundary to John Street Bridge at the downstream boundary. All the site constraints restricted the restoration changes which were achievable but were only indicative of any urban watercourse. The resultant changes to the river shape and length were not predicted to be significant in changing the flood hydrographs. The changes made, by lowering the bank levels did, however, change the frequency of water flowing onto and the volume of water on the floodplain.

7. HYDRAULIC MODEL PREDICTIONS

7.1 River Cole

Figure 10.3 shows the flow hydrographs for a 1 in 100 year flood event for pre restoration and post restoration situations at Coleshill Bridge, which is a strategic position in terms of flood defence along the River Cole.

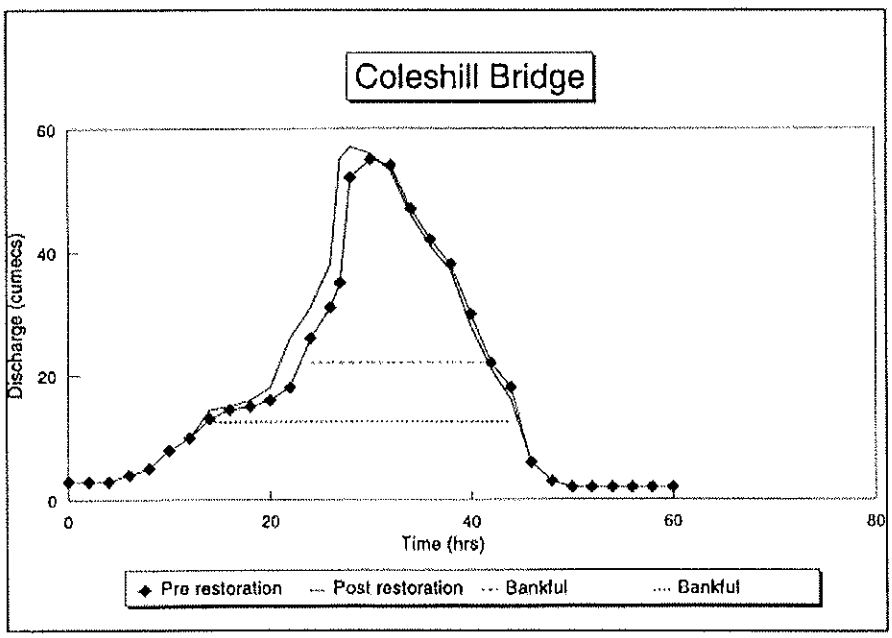


Figure 10.3 Discharge hydrographs at Coleshill Bridge - pre and post-restoration

The peak of the discharge hydrograph in the post restoration situation is actually greater than that in the prerestoration situation. The bankful flow in the post restoration situation is approximately 13 m^3/s compared with 22 m^3/s before restoration. With the lowered banks the water passes onto the floodplain at this position approximately 10 hours sooner than it would have done before restoration and, in a typical 1 in 100 year flood, remains on the floodplain for approximately 32 hours. This can be compared with 19 hours for the same magnitude of flood event before restoration. The increase in the volume of water on the floodplain, during a typical 1 in 100 year flood event, over the whole area considered for restoration is predicted to be 1.6 Mm^3. That is an increase in flood plain water of 70% over the previously floodplain volume of 2.3 Mm^3 predicted during a typical 1 in 100 year flood event.

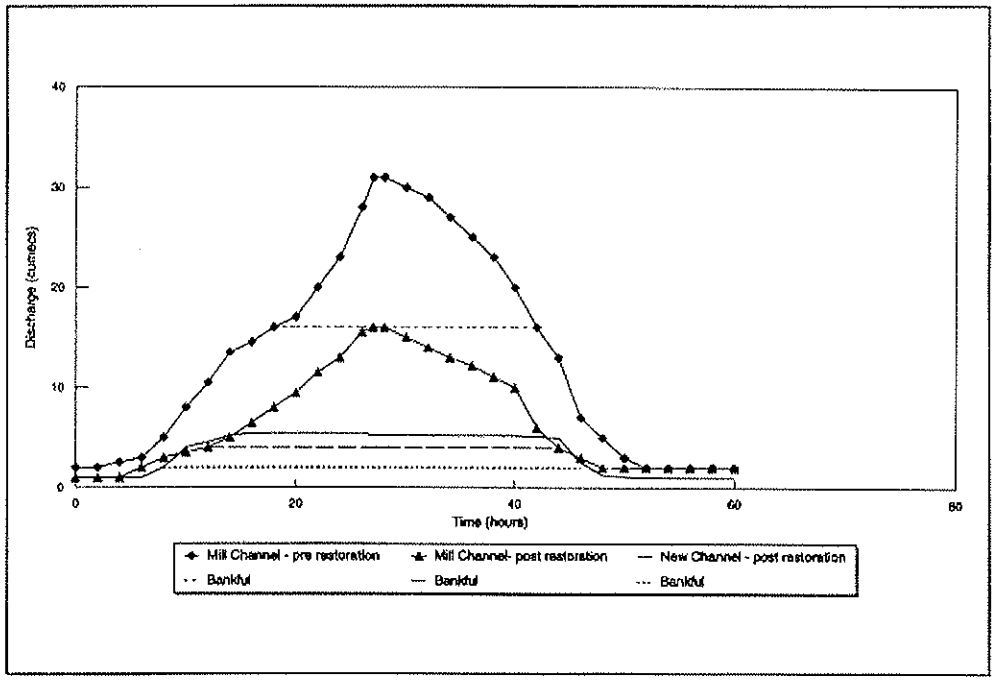


Figure 10.4 Discharge hydrographs along the mill channel and new channel re- and post-restoration

Figure 10.4 shows the discharge hydrographs at a position along the mill channel and new channel. These positions and are representative of the situation on the mill channel, new channel and surrounding floodplain areas. As the flow is split, in the restored river, between the new channel and the mill channel, the flow along the mill channel is reduced. The levels in the mill channel have been maintained by raising the crest of the weir at the mill to a level previously held when the mill was in operation. Figure 10.4 displays the pre restoration situation along the mill channel, showing a peak discharge of 30 m^3/s with the peak discharge being almost halved after restoration. The bank levels for pre and post restoration situations are very different, leading to the predicted bankful flow being reduced from 16 m^3/s to 4 m^3/s as the flood water flows more readily and more quickly onto the surrounding land.

With the lowered banks, it is predicted that water will flow onto the floodplain from the mill channel for 32 hours in a typical 1 in 100 year flood event compared with 24 hours before restoration. The water which does not pass along the mill channel goes into the new channel

via a weir set at a level to control the amount of water passing into the new channel. During a typical 1 in 100 year flood event, the discharge passing into the new channel is predicted to have a peak value of 5 m^3/s. At the position along the new channel considered in Figure 10.4, the predicted, bankful discharge is 2 m^3/s and, during this event, the water would flow onto the flood plain from the new channel for 39 hours in a typical 1 in 100 year event.

Table 10.1 shows the predicted, bankful flow and estimated duration of flooding in one year for several locations along the channel both before and after the restoration. The bankful flow on the mill channel downstream of the bifurcation would be reduced from 15m3/s to 5 m^3/s which equates to the flow being out of bank on average for 6 days in a year compared with, on average, less than one day per year before restoration. Similar situations are shown at the football pitch where the bankful flow would be reduced from 4 m^3/s to 2.7 m^3/s and the average number of days flooding in a year would increase from 1 to 5 days. At the Fritillery field, downstream of Coleshill Bridge, on the right bank, the bankful flow would be reduced by 50% as the bed level of the channel has been raised by over 1m. At this site the duration of flooding over a year would have been from a few hours pre restoration, increasing to one day per year post restoration.

Location	U/stream of bifurcation	D/stream of bifurcation on main channel	New channel just d/stream of bifurcation	New channel	Football pitch	D/stream of Coleshill Bridge	Fritillery Field
Q_{bf} pre restoration (m^3/s)	22	15			4	34	23
Duration of out of bank flow in 1 year	4 hours	8 hours			1 day	~1 hour	2 hours
Q_{bf} post restoration (m^3/s)	22	5	4	1.5	2.7	15.6	12
Duration of out of bank flow in 1 year	4 hours	6 days	1 day	17 days	5 days	5 hours	1 day

Table 10.1 Bankful flow and flooded frequency

Figure 10.5 shows the impact on flood levels for the pre and post restoration situations along the mill channel. The right bank level is the same both before and after restoration but the left bank level has been reduced from 79.8m to 79.45m AOD. The predicted flow along the mill channel has been reduced as described previously and this has an impact on the flood flows, reducing the 1 in 100 year flood level from 80.3m AOD to 79.95m AOD. As the bank levels have been lowered, even though the flood level is reduced, the flood water would be on

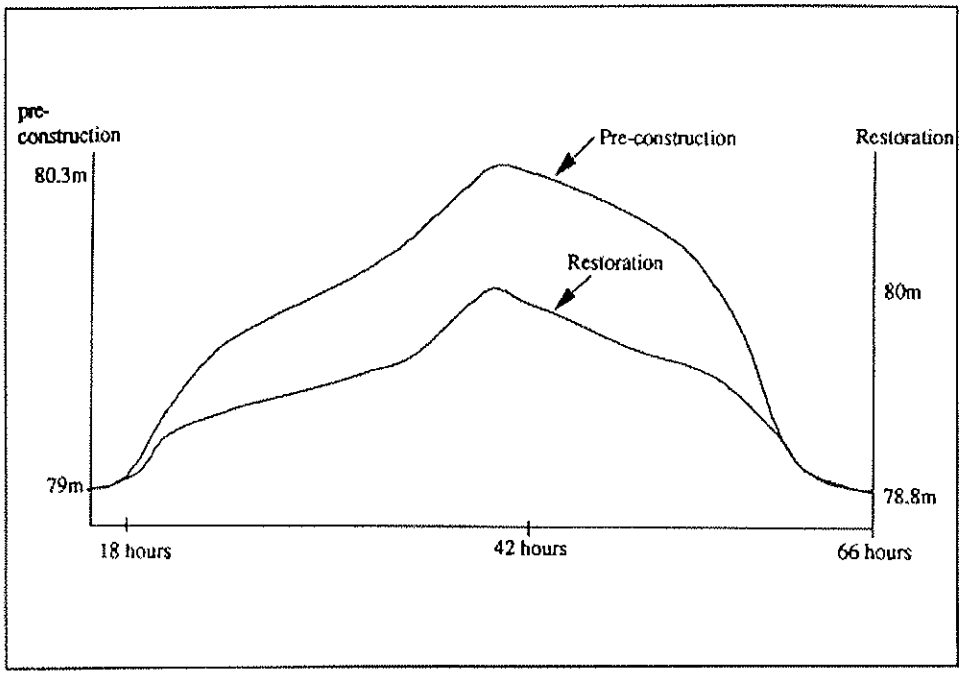


Figure 10.5 Stage hydrographs along the mill channel pre and post restoration

7.2 River Skerne

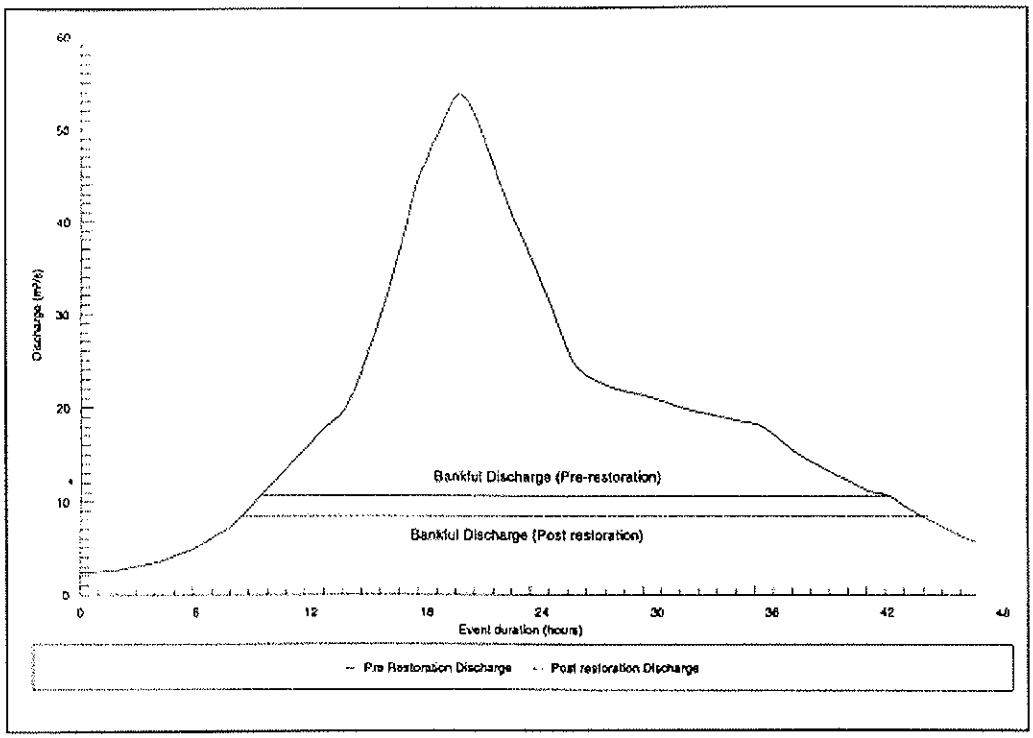


Figure 10.6 Discharge hydrographs within the meanders pre- and post-restoration

the flood plain for longer than in the pre restoration situation: 14 hours compared with 10 hours before restoration. Therefore, at this position along the mill channel, the predicted, peak water level has been reduced by 30% but the total volume of water on the flood plain would be increased by 50%.

The flood hydrographs on the River Skerne are relatively unchanged as the changes to the river have mainly influenced the plan form of the river by the introduction of meanders. The banks and floodplains have been reprofiled so as to get more water onto the floodplain more frequently. Figure 10.6 shows the discharge hydrographs at a location within the meanders before and after restoration with the bankful levels shown. It can be seen that the bankful level has been reduced therefore allowing more water onto the floodplain.

The bank level on this section has been reduced by 0.3m and the predicted, bankful discharge has decreased by 3.5 m^3/s to 8.5 m^3/s, a reduction of 23%. The impact of this is to allow more water onto the floodplain, a predicted increase of almost 1 Mm^3 in a 1 in 100 year flood. The total volume on the floodplain before restoration in a typical 1 in 100 year flood would have been approximately 3.7 Mm^3. The predicted increase in volume of flood water on the floodplain due to the restoration is over 25% for a typieal 1 in 100 year flood event.

Table 10.2 shows the frequeney of flooding along the River Skerne in the area of the restoration. The values given are for post restoration and are based on daily average flow exeedence curves. The winter and summer and yearly flood frequencies are given. The greatest frequency of flooding is predicted to occur around Rockwell Nature Reserve where there will be on average 4.5 days of flooding per year, four days of that flooding occurring in the winter months between October to March.

Location	**Footbridge**	**Meanders**	**Rockwell**	**Downstream of Five Arches Bridge**
Bankful Discharge (m^3/s)	21 m^3/s	12 m^3/s	10 m^3/s	14 m^3/s
Frequency of flooding (all year)	15 hours	3.3 days	4.5 days	1.75 days
Frequency of flooding (Oct-March)	14 hours	2.75 days	4 days	1.5 days
Frequency of flooding (April-Sept)	1 hour	8 hours	0.5 days	0.25 days

Table 10.2 Frequency of flooding - River Skerne

8. CONCLUSIONS

The restoration design of the two demonstration sites on the Rivers Skerne and Cole within the UK have tried to bring the river back into contact with its floodplain. The design the of the restoration works were required to ensure that flood levels were no higher. The design had therefore to meet the flood constraints of ensuring that flood levels were no higher but also to ensure that more flood water was in contact with the flood plain and floodplain inundation was more frequent. It may appear that these two aims are contradictory but the hydraulic model results presented in this paper have shown that the standard of service required for flood defence and allowing more water onto the flood plain can be achieved and may be complementary.

A summary of the predictions of the hydraulic model are given below.

For the River Cole:

- By raising the river bed level at Coleshill Bridge, the bankfull capacity is predicted to be reduced by 50%, increasing the amount of water flowing onto the floodplain in a 1 in 100 year flood by 70%.
- At a position along the original Mill Channel on the River Cole, the peak 1 in 100 year flood level is predicted to be reduced by approximately 30% as the bank has been lowered, but 50% more by volume of water will spill onto the floodplain.
- The floodplain will flood more frequently with lowered banks. Peak water levels at a position just downstream of the new channel on the River Cole are predicted to be reduced, but the total volume of water at that position on the floodplain will be increased by 50%.
- The duration of inundation of floodplain on the River Cole has increased. At the Fritillary Field site, the average length of inundation is predicted to increase from a few hours per annum to one day.

For the River Skerne:

- On the Skerne, the flood hydrograph is relatively unchanged. However the bank levels have been lowered as a result of the restoration works, and the volume of water passing onto the floodplain is predicted to increase by 25% for a typical 1 in 100 year flood.

The results provided in this paper are model predications and, as such, are therefore averaged results based on flood hydrographs which extend for a given length of time. These model predictions are currently being validated with field data.

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