GROUNDWATER – RIVER INTERACTION IN A CHALK CATCHMENT: THE RIVER LAMBOURN, UK

by

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ABSTRACT

Chalk streams are of high ecological value and are dependent upon groundwater discharge to support flows. This study investigates chalk stream - aquifer interaction, focusing on a near-natural catchment; the River Lambourn of the West Berkshire Downs. The topographic catchment of the Lambourn is 234km^2, principally underlain by Upper Chalk. The river has a perennial length of c. 16km, and a 7.5km seasonal section.

Temporal dynamics of the recharge - storage - discharge sequence are investigated using linear regression techniques to identify the lag between recharge and discharge. The effective maximum duration of groundwater flow is 9.1 months, which is used with regional hydraulic gradients to calculate a bulk (interfluve) hydraulic conductivity of 114m/d (using Sy = 1%), suggesting that interfluve permeability has been historically underestimated.

Spatial flow accretion on the Lambourn is defined from 12 reaches (each 1 - 2km long), exhibiting mean accretion rates between -0.019 and 0.211 cumecs/km. The accretion rate profile approximates a sinusoidal pattern (λ=12km), suggesting a catchment scale litho-structural control. However, local topography and lithology also exert influence. High accretion rate reaches are associated with major dry valley intersections and elevated valley floor permeability, whilst the presence of Chalk Rock at shallow depths restricts local accretion.

For my wife, Kaylois Henry,
who put up with so much for so long…

Love is patient, love is kind.

1 Corinthians 13:4
(The Bible, New International Version)

And to my parents, John & Brenda Grapes,
for all their love and support throughout my life.

"Research is formalized curiosity. It is poking and prying with a purpose."

Zora Neale Hurston

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Chapter 1 Introduction

1.1 BACKGROUND

Groundwater – surface water exchange represents a significant, but under researched, flux element of the global hydrological cycle. Although such exchange occurs to a certain degree in all river systems, and acts over a range of spatial and temporal scales, it is most significant in permeable catchments, which are river basins wholly or chiefly underlain by aquifer formations. A glossary of technical terms is given in Appendix 1. The term 'permeable catchment' was apparently first used in this context by Ineson & Downing (1964) in a study of the hydrogeological controls on the flow regimes of six rivers in southern England, whose catchments were underlain by chalk and/or alluvial aquifers.

A significant proportion of the world's population lives in permeable lowland catchments, and effectively relies upon water supplies regulated by groundwater – surface water interaction. However, the importance of this water exchange is belied by the relative paucity of associated research, especially concerning exchanges between regional-scale bedrock aquifers and river systems. This aspect is particularly pertinent from a UK perspective, where the absence of continental-scale rivers (and their associated extensive, permeable, alluvial deposits) results in major water supplies being derived principally from bedrock, rather than alluvial, aquifers. Two such aquifers dominate UK groundwater supply; the Cretaceous Chalk in southern and eastern England and the Permo-Triassic sandstones of the Midlands and north - western England. Although groundwater - river interaction is recognised as an important control on the function of these aquifers, particularly the Chalk, progress to improve understanding has been restricted by limitations within the institutional context of UK research.

Institutionally, the study of groundwater – surface water interaction has tended to be fragmented (NERC, 1998), lying on the periphery of three established disciplines: surface-water hydrology, hydrogeology and ecology (Nawalany *et al.*, 1994; Younger, 1995; Brunke & Gonser, 1997). Of these, surface-water hydrology has been generally associated with research in physical geography and civil engineering, whilst hydrogeological research has generally developed from an earth science background,

but has incorporated a civil engineering aspect in the development and use of numerical groundwater models. Ecological research in this area has developed largely independently and has concentrated specifically on the reach or smaller scales, with similar work also being undertaken by some freshwater biologists. One consequence of this fragmentation in the research context has been a lack of consistent terminology, which can be illustrated by the usage of common terms such as *influent* and *effluent*. For example Sear *et al*. (1999), writing from a hydro-ecological perspective, describe discharge from an aquifer into a river as *influent*. However, in hydrogeological terminology, groundwater discharge to a river is described as *effluent* (Sophocleous, 2002). In the last decade there has been a broad movement to address this type of institutional constraint, with recognition of the need for a more holistic approach to understanding earth systems. This has occurred within a context of promoting sustainable development to reduce widespread environmental degradation, as considered in the 1992 Rio Earth Summit (UNDSD, 1992). Within this broad framework, the need to integrate management of groundwater and surface water systems was recognised, and has become a key facet of the European Union Water Framework Directive. This has been associated with the incorporation of ecological methodology in to the water resource management decision making process (e.g. Rippon & Wyness, 1994; Johnson *et al*., 1995; Strevens, 1999). However, the limited number of effective interdisciplinary studies upon groundwater – surface water interaction demonstrate that there is still some ground to be covered before this institutional limitation is overcome.

The institutional issue has been compounded by logistical constraints, relating to the perceived (and actual) difficulties of monitoring groundwater – surface water exchanges in the field. Such investigation requires the identification and measurement of groundwater seepage from, or to, a surface water body, with the attendant difficulties of accurately quantifying a low, spatially heterogeneous flux which normally forms only a small proportion of the local water balance, and is thus susceptible to significant error margins. No single methodology is appropriate for all interaction scenarios and only through the effective co-ordination of a number of approaches (including various physical and chemical field measurements combined with numerical simulation) can an accurate quantification of a system possibly be achieved.

Using just such a co-ordinated approach, involving surface water, groundwater and meteorological datasets, this study seeks to improve understanding of the temporal and spatial patterns of groundwater – river interaction on the River Lambourn, a chalk stream in southern England, and to identify generic controls that may be applicable to other chalk catchments, to assist in the optimisation of water resource management in such catchments.

1.2 RESEARCH CONTEXT

Over the last five years, there have been a number of reviews relating to aspects of groundwater – river interaction, albeit frequently illustrating different disciplinary perspectives and from varying geographical emphases. Notable reviews include Brunke & Gonser (1997), Winter (1999), Sear *et al.* (1999) and Sophocleous (2002), which provide an indication of the differing research philosophies of various disciplines.

The **ecological** approach is illustrated by Brunke & Gonser (1997) who examined the literature relating to 'direct', ecologically-focused research on groundwater – river interaction, which is dominated by work from the United States and continental Europe. Such 'direct' research is normally undertaken at a local scale and investigates the biological communities residing in the hyporheic zone, where groundwater and river water mix, and also the physico-chemical processes which occur there. In the UK, ecological research on groundwater – river interaction has mainly been of an indirect nature, for example, investigating the freshwater ecology of permeable catchments, with less emphasis on definition of the hyporheic zone and the dynamics of small scale water exchange, which probably reflects the absence of continental scale rivers / alluvial deposits in the UK.

The **surface-water hydrology** perspective is exemplified by Sear *et al.* (1999), who reviewed UK-based literature relating to groundwater – river interaction. They sought to identify a diagnostic signature for groundwater-dominated rivers based upon four criteria, namely flow regime, channel morphology / sedimentology, water quality and instream ecology. Sear *et al*. concluded that no single signature for groundwater dominance could be identified, it being dependent upon aquifer type, and crucially the **scale** of investigation. Much of their diagnostic data were derived from the downstream sections of major UK rivers, whose multi-provenance, anthropogenically-modified discharge and quality regimes effectively concealed any groundwater signature.

However, Sear *et al*. showed that smaller rivers in lowland headwater catchments, which derive their water from a single groundwater source (e.g. chalk or limestone), could display a much more prominent groundwater dominated signature, comprising: a stable discharge regime (e.g. Q95 > 30% of mean flow); mainly low, but variable, drainage density; a stable thermal regime and high water clarity.

Winter (1999) followed a **geomorphological** approach in his review of US research on groundwater – river interaction, which formed part of a broader review of groundwater – surface water interaction. Winter categorised the occurrence of such interactions using five landscape types: mountain terrain; riverine systems; coastal terrain, hummocky terrain and karst terrain. He recognised the dominance of interaction in riverine (alluvial aquifer) settings and emphasized the importance of palaeo-channels as a controlling influence.

Sophocleous (2002) reviewed groundwater – river interaction from a **hydrogeological** perspective, again drawing largely from research undertaken in the USA. He followed Sear *et al*. (1999) in recognising the importance of investigative scale, and especially the hydrogeological **context** for interaction; whether part of a local, intermediate or regional scale groundwater flow system. This point is highly significant to understanding groundwater – river interaction, especially from a water resource management perspective. For example, Rushton (2002) described how simulated reductions in groundwater abstraction from the East Kent Chalk aquifer in the southern UK were associated with only limited increases in the discharge of the upper River Dour. These results arose because the upper section of the river formed part of only a local groundwater flow system (i.e. receiving local scale discharges), whilst the intermediate and regional systems discharged to the sea. In some cases it is these larger scale systems that experience greater modification due to the changes in groundwater abstraction, and thus any effective investigation of river – aquifer interaction must consider both the regional and local hydrological context.

The varying approaches followed by the different disciplines have typically focused upon the research questions considered most important by that discipline, but in so doing they have failed to produce the holistic understanding required for optimal water resource management. At present the principal gap lies in the investigative scale, where ecological research focuses at a patch or sub reach scale but the other disciplines

generally work at a catchment scale. Currently ecological issues are becoming ever more significant in water resource regulation, and thus it is essential that this scale discrepancy be addressed in order to prevent an overly precautionary approach becoming entrenched.

1.3 LEGISLATIVE CONTEXT

The research context outlined above is particularly important in determining the direction of policy initiatives that seek to achieve the goal of sustainable water management. For example, in the UK, the need for integrated management of groundwater and surface water systems is recognised in two pieces of current legislation, the draft Water Bill and the EU (European Union) Water Framework Directive.

One of the preliminary results of the consultation process for the draft Water Bill has been the Environment Agency's CAMS (Catchment Abstraction Management Strategies) process, which seeks to advance integrated management of surface and groundwater resources. This process was initiated following the Government's publication of Taking Water Responsibly (DETR/ The Welsh Office, 1999), which presented post-consultation decisions relating to changes in the UK water abstraction licensing system.

The theme of integrated management of surface water and groundwater resources is also advocated within the European Union Water Framework Directive [2000/60/EC] (Hiscock *et al*., 2001). The aim of the directive is: "*To establish a Community framework for the protection of inland surface waters, transitional waters, coastal waters and groundwater, in order to prevent and reduce pollution, promote sustainable water use, protect the aquatic environment, improve the status of aquatic ecosystems and mitigate the effects of floods and droughts.*" Management of water resources under the directive will encompass both surface water and groundwater elements, and will be undertaken at the river basin (catchment) scale. Thus, the directive strongly promotes integrated catchment management, and inevitably requires an improved understanding of groundwater – surface water interaction for effective implementation.

Together, these two legislative drivers identified the need for detailed research into groundwater – surface water exchange, which is being addressed in the UK through

LOCAR (Lowland Catchment Research), a thematic research programme of the Natural Environment Research Council (NERC). The importance of the legislative drivers to the evolution of the programme is shown in the first of the programmes broader objectives, which states that LOCAR seeks *"To provide an underpinning science base for the requirements of the UK and CEC* for environmental protection within a framework of sustainable and integrated river basin management"* (NERC, 2001). [*Commission of the European Communities]

LOCAR represents the largest integrated programme of research into groundwater – surface water interaction ever undertaken in the UK and results from the programme are likely to provide significant advances in understanding permeable catchment systems. The programme consists of research in three flagship catchments: the Frome/Piddle in Dorset, the Pang/Lambourn in Berkshire, and the Tern in Shropshire. The present study has been undertaken in the context of this developing research programme, but does not represent a formal element associated with it.

1.4 AIMS, OBJECTIVES AND SCOPE

Aims

The specific aim of this study is to investigate river –aquifer interaction in a near-natural chalk stream – aquifer system (the River Lambourn), where the minor anthropogenic modification of the system has not concealed the background temporal and spatial variability in flow exchanges. It is recognised that the flow regimes of many chalk streams have been significantly impacted by groundwater abstraction (Acreman & Adams, 1998) leading to ecological degradation (for example; Strevens, 1999), but attempts to reverse historic environmental degradation and restore more natural flow regimes have been hampered to a degree by a lack of suitable baseline patterns as role models. Using the Lambourn as an analogue for the natural condition of other chalk catchments, this study aims to provide a baseline pattern of flow exchange behaviour that could then be transferred to highly impacted catchments as a means of assessing their degrees of modification.

The focus of the study will be to investigate the temporal and spatial characteristics of the system's river – aquifer exchange fluxes, in order to elucidate generic processes, patterns and controls, particularly the influence of the catchment

storage condition on river discharge and that of valley floor parameters (for example the presence, morphology and lithology of alluvial deposits) on local flow accretion patterns.

As a wider aim, this study seeks to provide information that will assist in improving the integrated management of surface water and groundwater resources in chalk catchments, which is the focus of current and future regulatory approaches that have been discussed previously. To optimise such management requires improved understanding of the timing, location and magnitude of impacts from groundwater abstractions upon river flows, thus indicating the need for investigation of both spatial and temporal aspects of river – aquifer exchange.

Objectives

The aims of the study will be met through undertaking a number of separate, but interlinked objectives. These are:

1. To improve understanding of bulk flow dynamics in chalk catchments by elucidating the temporal characteristics of a near-natural chalk recharge – storage – discharge sequence. This will be undertaken by quantifying temporal elements of catchment scale flow paths, from infiltration at the ground surface, via unsaturated zone migration and saturated flow, to discharge from the catchment.

2. To investigate a technique to estimate catchment discharge from spatially averaged groundwater level data to allow baseline flow regimes to be approximated for impacted catchments, as an element of a rehabilitation strategy.

3. To investigate spatially-based influences on chalk stream - aquifer exchanges by initially defining the longitudinal pattern of groundwater – river interaction in the Lambourn catchment at varying spatial scales and then correlating this pattern with topographic, geological and hydrological variables to identify the principal controls.

4. To assess the applicability of a recognised theoretical approach for calculating river – aquifer exchanges (Darcy's Law) by using field data (comprising

groundwater levels, river stages and river discharges) to estimate values for the hydraulic conductivity of valley floor lithologies.

5. To investigate the influence of bulk aquifer properties on spatial patterns of flow exchange, and the sensitivity of the flow accretion pattern to valley floor parameters, by undertaking numerical modelling of the Lambourn catchment using dedicated field data for calibration and verification.
6. To extend the understanding of chalk catchment flow dynamics by incorporating the results from this study into an enhanced conceptual model of flow paths through the chalk aquifer from recharge to discharge.

Scope of thesis

Following this brief introductory chapter, the current state of knowledge relating to groundwater – river interaction is reviewed in Chapter 2, particularly literature pertaining to chalk catchments. Chapter 3 describes the location and characteristics of the study catchment and outlines the rationale, equipment and methodology used in the investigation. Chapter 4 presents the results of temporally based analyses of the recharge-storage-discharge sequence, culminating in a successful analytical simulation of catchment discharge based upon a four-parameter linear regression equation. Chapter 5 describes the spatial variability of flow exchange along the River Lambourn, with increasing spatial resolution, concluding with a detailed pattern of interaction based upon current meter data from 12 reaches. Potential controls on the spatial pattern of river - aquifer interaction are investigated in Chapter 6, including estimates of valley floor permeability and numerical groundwater modelling to assess the potential morphology of subsurface parameters. The results of the study are discussed in Chapter 7, within the context of the current state of research detailed in Chapter 2. Finally, Chapter 8 presents the conclusions of the study and identifies areas for future research.

Chapter 2 Investigating river – aquifer interaction: past, present and future

2.1 BACKGROUND

Groundwater – river interaction represents a major flux boundary in the global hydrological cycle. However, despite its critical control on the discharge regime of many rivers, there has been relatively little associated research, especially on the interaction between bedrock aquifers and their related river systems. This aspect is particularly significant in the UK, given the importance of water resources in permeable catchments underlain by regional scale **bedrock** aquifers, such as the Chalk and the Permo-Triassic sandstones of lowland England. The situation differs markedly in the USA and continental Europe, where research on river – aquifer interaction has focused on large rivers and their associated **alluvial** aquifers, which at the continental scale are absent from the UK. [NB a glossary of technical terms is given in Appendix 1]

Typically, the research that has been undertaken in the area of groundwater – river interaction is fragmented (Younger, 1995), and includes elements of hydrology, hydrogeology, ecology and freshwater biology. Although the need for truly interdisciplinary studies has been recognised from many quarters (e.g. Valett *et al.*, 1993; Sophocleous, 2002), to date few such studies have been undertaken, which illustrates the difficulty of integrating different investigative approaches.

Particularly significant are the differing spatial scales of investigation that are typical of hydrological and ecological studies. Most hydrological investigations are undertaken at the catchment scale (over tens or hundreds of km^2), whereas ecological research is normally at the patch (m^2) or reach (hundreds of m^2) scale. Reconciling these disparate scales is critical if the results of ecological research are to be appropriately incorporated into the water resource management process.

A robust understanding of groundwater – river interaction is essential in managing the conflicting demands of human requirements for water versus in-channel, ecological needs (recognised as an Ecologically Acceptable Flow Regime by Petts *et al.*, 1999). Such management issues include: the temporal and spatial impacts of groundwater abstraction upon river flows (e.g. Bullock *et al.*, 1995; Kirk & Herbert, 2002); the exchange of poor quality water between rivers and aquifers

(e.g. Younger *et al.*, 1993); the application of catchment hydrological models for integrated control of water resources (e.g. Rushton & Tomlinson, 1999); the effects of regulated river stage on groundwater levels (R. Bradford, pers. comm.); and the design of hydrological and ecological monitoring schemes to provide representative assessments of river flow regimes.

2.2 RIVER – AQUIFER INTERACTION: CONCEPTS AND PROCESSES

2.2.1 Basic concepts

Research on groundwater – river interaction has taken place across a number of disciplines, as discussed previously. Whilst the physical processes involved in the interaction are common to all studies, the context in which they are investigated can differ significantly. The primary distinction lies between the broad hydrological perspective, which focuses upon the interchange of water, and the broad ecological perspective, which focuses upon the ecological significance of the water exchange, and these differences in perspective are explored below.

Hydrological perspective

The conceptual foundation underpinning the study of river – aquifer interaction is based upon the exchange of water between two adjacent, but distinct, hydrological systems, principally differentiated in this context by the nature of the water flow that takes place within them. Rivers are characterised by open channel flow, whilst water movement in aquifers takes place through a subsurface, saturated medium, often (but not exclusively) by intergranular seepage. The differential nature of flow processes in rivers and aquifers is a key facet in understanding the function of interlinked river – aquifer systems, which principally relates to the widely varying flow velocities encountered in the two components. Flow velocities in rivers are generally within the range 1m/s +/- 1 order of magnitude, whilst the equivalent range of groundwater flow velocities (for recognised aquifer formations) is 1×10^{-3} m/s +/- 2 orders of magnitude. These ranges indicate that groundwater flow velocities are normally around 3 orders of magnitude lower than surface water velocities and this discrepancy significantly increases the functional complexity of interlinked systems.

The process of groundwater – river exchange is largely governed by the hydraulic gradient (analogous to a topographic gradient) between the aquifer and the

channel, which is normally recognised as a difference in the elevation of the water surface present in each medium. This understanding has formed the basis for most hydrological conceptual models of river – aquifer exchange, examples of which are explored in Section 2.3.

Ecological perspective

Much ecological-based research on river – aquifer interaction is focused upon characterising the mixing zone where groundwater and river water converge, and two key terms are used in this context. The first is the groundwater – surface water **ecotone**, defined by Triska *et al.* (1993a, b) as a transition zone between adjacent ecological systems that has characteristics which are uniquely defined by its spatial and temporal context, and by the strength of the interaction between the systems. The second term is the **hyporheic zone** (also described as a connecting ecotone; Brunke & Gonser, 1997), which can be defined from various perspectives. For example, Triska *et al.* (1989) define the hyporheic zone as sub-streambed interstitial volume containing > 10% surface water, whilst White (1993) considered that it could be delineated biologically, chemically or hydrologically. This interpretation was supported by Stanford & Ward (1993), who considered the hyporheic zone to be:

- A groundwater zone penetrated by amphibiontic stream organisms (i.e. insects which reside in water during their larval stage);
- A groundwater zone in which microbially-mediated chemical dynamics exert control on material cycles in the active channel and associated riparian vegetation;
- A volume of groundwater that may be hydraulically interactive with the channel hydrograph over short time scales (e.g. hours).

Delineation of these conceptual elements has been the objective of many ecological studies of groundwater – river interaction, and whilst the focus of this research has differed from that of hydrological investigations, the field techniques that have been employed are broadly similar (e.g. Gordon *et al.*, 1992). This overlap is explored in Section 2.4.2.

2.2.2 Fundamental processes

Flow exchange pathways

Interchange of water between a river and aquifer can take place via intergranular seepage or via direct flow. Seepage will be the dominant process where the aquifer itself is dominated by intergranular flow (for example, in a sandstone), or where there are alluvial deposits separating the river channel from the underlying aquifer. This type of exchange will result in relatively subdued interaction that is difficult to identify in the field. Direct interaction occurs where a bedrock aquifer outcrops in the bed and/or banks of a river, exposing fractures or solution-enhanced fissures that allow rapid and high volume exchanges of water. This type of exchange is characteristic of aquifers that display locally sub-karstic behaviour, for example the Corallian limestone aquifer of North Yorkshire, described by Carey & Chadha (1998).

Influence of aquifer storage

The control exerted on an interlinked river – aquifer system by the storage capacity of the underlying aquifer formation is often intimated by the use of the term *permeable catchment,* which appears to have first been expressed in the hydrological literature by Ineson & Downing (1964). The storage capacity provided by the aquifer leads to a time lag being interposed between recharge and discharge events, the lag being proportional to the storage capacity of the aquifer. Sandstone aquifers with high storage respond slowly to imposed stresses (e.g. on a decadal scale), whilst limestone aquifers of lower storage will react to extreme climatic events within the same hydrological year. Such time lags do not occur in impermeable catchments, where the flow regime is highly responsive to rainfall.

In a permeable catchment the aquifer in effect acts as a subsurface reservoir, storing significant quantities of water by utilising the volume of the unsaturated zone, via an increase in groundwater levels. This storage has the effect of smoothing the variability in rainfall and recharge to produce a stable discharge and water quality regime, usually with a well-defined seasonal pattern. Hydrologically, the flow regimes of rivers draining permeable catchments are characterised by high Baseflow Indices, elevated values for Q_{95} / Mean Annual Flow and a low Coefficient of Variation (Sear *et al*., 1999).

2.2.3 Karst systems

Karstic flow systems represent a special case of river – aquifer interaction, being unique in two key respects relative to 'normal' permeable catchments:

a. The difference in velocity between groundwater flow and surface water flow is notably absent, as evidenced by numerous groundwater tracer tests in karstic systems (e.g. Smart & Smith, 1976; Perez, 1996). Groundwater flow is entirely focused within enlarged conduits, each of which is essentially a natural pipe carrying an 'underground river', with little or no interaction with the surrounding bedrock material.

b. The influence of saturated storage is negligible in karst systems, as it has been shown that all effective sub-surface storage occurs in the epikarstic unsaturated zone (Clemens *et al.*, 1999; Perrin *et al.*, 2003; Lee & Krothe, 2003). Hence the buffering capability that is characteristic of permeable catchments is significantly reduced in karstic systems, as the bulk of the aquifer material is effectively impermeable. This results in the non-occurrence of the characteristic stable discharge and water quality regime associated with permeable catchments, as evidenced by Drysdale *et al.* (2001).

Conceptual flow paths in a karstic system are illustrated below in Figure 2.1, which shows the focusing of permeability in occasional discrete features whilst the bulk of the rock mass is effectively impermeable.

Given that the description of groundwater – river interaction in Section 2.2.1 above envisages it to comprise water exchange between *adjacent* but *distinct* hydrological systems, it is debatable whether karstic systems can be considered to display such behaviour. This point was recognised in a study of the karstic Floridan aquifer in the Sante Fe River basin of north central Florida by Kincaid (1998), who concluded that: "The results of this investigation imply that, in regions such as the western Santa Fe River basin, there can be no clear distinction between ground and surface waters". Given the extensive literature on karst systems, and its marginal relevance to the type of groundwater – river interaction being investigated in this study, only highly pertinent karst studies have been included in this review.

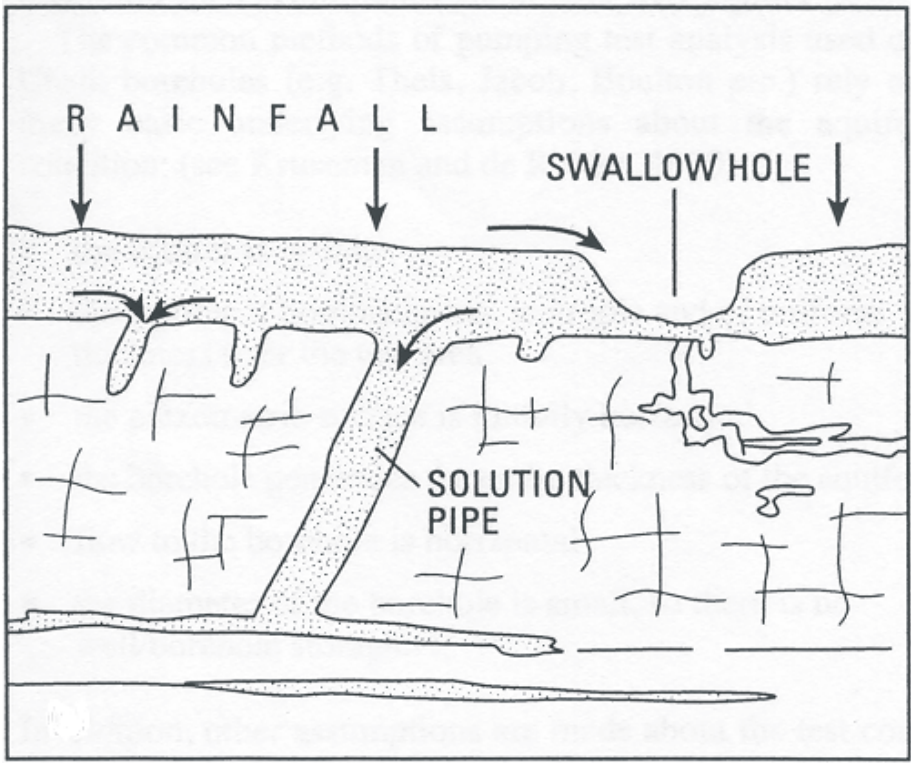


Figure 2.1 Potential recharge flow paths in a karstic system
(from Allen *et al*., 1997)

2.3 HYDROLOGICAL CONCEPTUALISATION OF RIVER – AQUIFER EXCHANGE

2.3.1 Current conceptual models

Conceptual diagrams of river – aquifer exchange are normally based upon a series of valley cross-sections, characterised by different head gradients between the aquifer and river. For example, Rushton & Tomlinson (1979) used four conceptual scenarios, shown in Figure 2.2, to depict their assessment of controls on leakage between rivers and aquifers.

In Figure 2.2, Condition (a) shows groundwater levels higher than the river stage, and this leads to enhanced river flow; Condition (b) shows a situation where groundwater and river levels are equal, so that no interaction occurs; Condition (c) illustrates groundwater levels below river levels, which leads to seepage from the river to the aquifer; while Condition (d) shows a situation where seepage from the river to the aquifer has reached a limiting value such that any further fall in groundwater level has no effect on seepage rates (Rushton & Tomlinson, 1995).

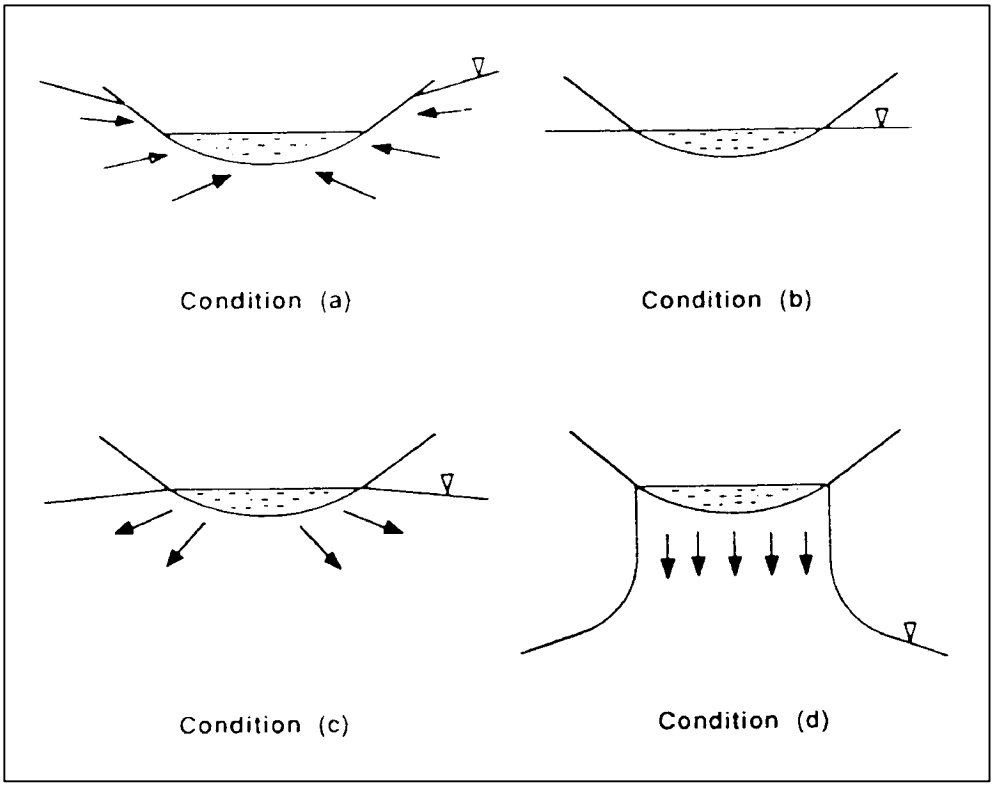


Figure 2.2 Schematic representation of different forms of river - aquifer interaction (after Rushton & Tomlinson, 1979)

A shortcoming with the approach detailed above is that it only recognises the differential head gradient control, and fails to address a number of other key controls on interaction, for example the influence of streambed sediments (Rushton & Tomlinson, 1979).

2.3.2 Limitations of current hydrological conceptual models

The limitations of the simple cross-section conceptual scenarios presented above fall into three categories. Firstly, the suitability of using Darcy's Law in this context; secondly, the significance of valley floor (alluvial) controls; and thirdly, the recognition of differing reaction times of groundwater and surface water components. The importance of each problem is discussed in the following sections.

Using Darcy's Law for calculating river – aquifer exchanges

The conceptual scenarios shown in Figure 2.2 rely upon Darcy's Law to estimate seepage between a river and an adjacent aquifer, which is proportional to the hydraulic gradient between the aquifer and the river. The water flux can be estimated,

given the hydraulic conductivity (permeability) of the intervening sediments and the surface area of the river bed and banks:

$$\mathbf{Q = - K\, i\, A} \qquad \text{Equation 2.1}$$

Where:

Q = exchange flux (e.g. m^3/day)
K = hydraulic conductivity of river bed and banks (m/d)
- i = hydraulic gradient between aquifer and river
A = area of river bed and banks through which exchange occurs (m^2)

However, a number of factors affect practical applications of this relationship, including:

- The anisotropic and heterogeneous nature of river bed and valley floor deposits, allied with poor definition of their permeability
- The presence of steep hydraulic gradients, comprising both horizontal and vertical flow components, which cannot be adequately represented by either Darcy's Law or Dupuit-Forchheimer Theory (e.g. Todd, 1980; p.112, 114)
- The differing reaction times of the river and aquifer system, which make the meaningful estimation of hydraulic gradient problematic

Together, these factors greatly hinder reliable estimation of seepage between aquifers and rivers.

The significance of valley floor controls

The rate and orientation of groundwater flow in valley floor alluvial deposits is intricately linked to their distribution and lithology. The varying sequence of erosion and deposition in fluvial systems can lead to complex patterns of floodplain stratigraphies, examples of which are shown in Figure 2.3.

Figure 2.3(A) shows the stratigraphy of a confined floodplain dominated by coarse grained, high permeability, sediments, which is likely to promote close interaction between the river, the alluvial deposits and the underlying bedrock aquifer. In contrast, (B) illustrates the deposits of a confined sandy floodplain that aggrades through overbank deposition of sand and silt. In this situation, groundwater flow is restricted to the coarse sand and gravel at the base of the floodplain sequence. This

limits interaction between the alluvial deposits and the river, but allows exchange with the bedrock aquifer. Cross-section (C) shows the profile of a cut and fill floodplain where the highly mobile nature of the channel produces a complex distribution of various sediment types. The presence of low permeability layers and lenses throughout the sequence tends to produce high floodplain water levels, but significantly restricts the continuity of groundwater - river interaction.

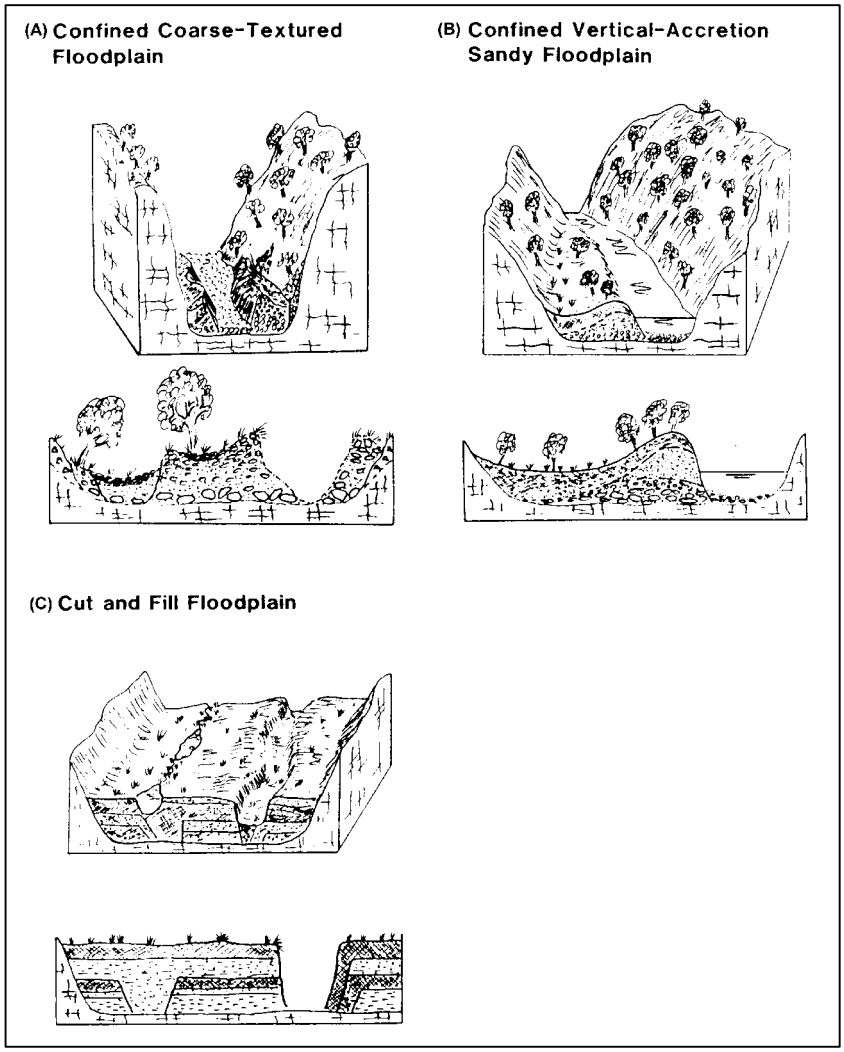


Figure 2.3 Generalised floodplain stratigraphies arising from variations in the sequence of erosion and deposition (from Nanson & Croke, 1992)

For many rivers the situation is complicated by the evolutionary history of the floodplain through the Holocene, reflecting changing water and sediment regimes. Thus, in the UK, many lowland floodplains can be characterised by the stable-bed aggrading-bank (SBAB) model described by Brown *et al.* (1994), which is illustrated in Figure 2.4.

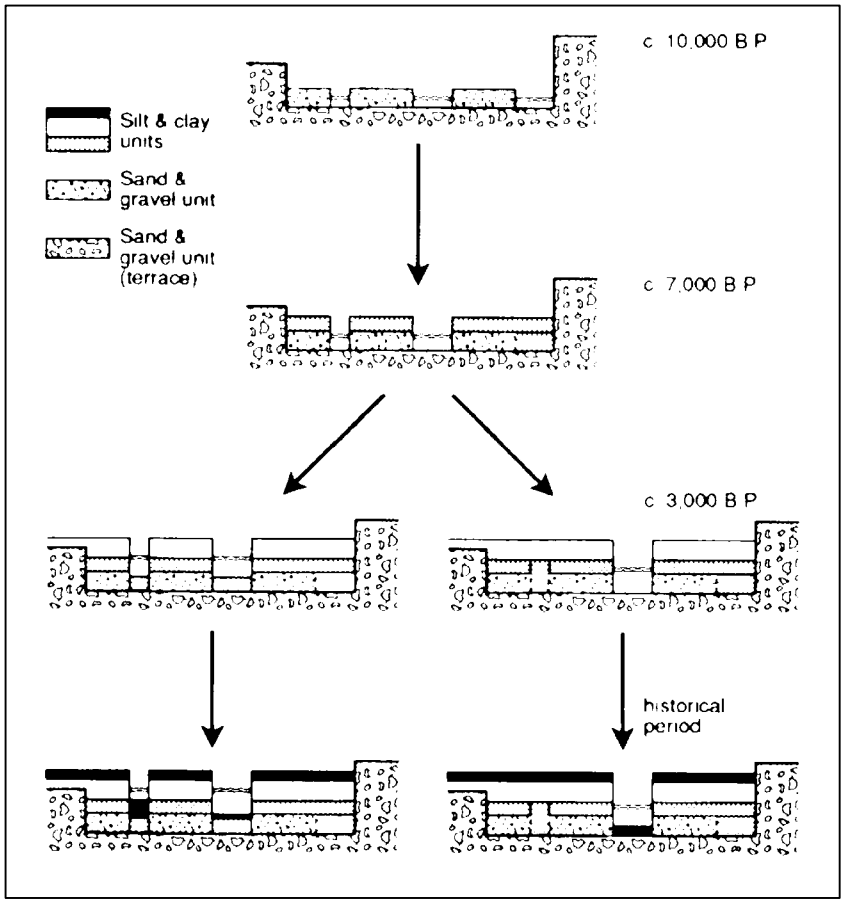


Figure 2.4 Floodplain evolution via the SBAB model
(from Brown *et al.*, 1994)

The SBAB model assumes that the river bed lies on Lateglacial gravel deposits, formed from the stabilized bars of a braided river system around 10 000 years before present (BP). Through the Holocene, the river channel became increasingly stable, enabling extensive floodplain aggradation to occur via overbank deposition (Brown *et al.*, 1994). The result is to produce cohesive river banks consisting of fine grained, low permeability Holocene material, resulting in river - aquifer interaction being focused primarily through the channel bed. The direct controls of bed sediment composition on exchange are considered below.

Comparing the floodplain cross-sections in Figure 2.3 with the conceptual scenarios of Figure 2.2 (representing a homogenous bedrock aquifer with no alluvial cover) shows that the heterogeneity of alluvial deposits necessitates a more detailed investigative approach. This is demonstrated by recent studies that investigated the sampling interval necessary to characterise alluvial sediments adequately. Bierkens (1993) studied the distribution of overbank sediments in the Rhine – Meuse delta using

geostatistical analysis and suggested that a sampling grid of 25m perpendicular to, and 100m parallel to, the main flow direction would be required to define the sedimentary architecture. The results of inadequate characterisation of complex alluvial sequences were assessed by Bierkens (1996) who modelled a complex confining layer in an alluvial sequence at four spatial scales, from sediment core (0.1 – 1m) to regional scale (1 – 100km). The modelling results showed that if the hydraulic conductivity values defined at the sediment core scale were not represented in larger scale models, then significant errors in predicted groundwater flow rates occurred.

Triska *et al*. (1993a,b) describe the influence of alluvial heterogeneity on interactions between floodplain sediments and the channel of the Little Lost Man Creek, (California, USA). Using groundwater tracers introduced into alluvial deposits, they found that groundwater discharges to the channel were focused at meander bends, but that subsurface flow could also pass beneath the channel, possibly utilising relic channel features. Similar behaviour was also recognised by Sophocleous (1991), who observed pressure pulses from flood waves passing preferentially through highly permeable palaeo-channels in the Great Bend alluvial aquifer in Kansas.

The hydrogeological significance of heterogeneous floodplain stratigraphies is dependent upon the permeability of their various constituent materials, which from Table 2.1 can be seen to extend over nine orders of magnitude.

Material	**Hydraulic Conductivity (m/d)**
Gravel	3×10^{1} to 3×10^{3}
Coarse sand	8×10^{-2} to 5×10^{2}
Medium sand	8×10^{-2} to 4×10^{1}
Fine sand	2×10^{-2} to 2×10^{1}
Silt	9×10^{-5} to 2×10^{0}
Clay	9×10^{-7} to 2×10^{-4}

Table 2.1 Hydraulic conductivity values for typical floodplain sediments
(after Domenico & Schwartz, 1990; Table 3.2, p. 65)

Given the absolute range of values in Table 2.1, the permeability of the channel bed and bank clearly represents an important control on the interaction between a river and an alluvial aquifer. However, the range within each lithology indicates the difficulty in accurately determining permeability, even when lithology is well defined.

Differences in the permeability of the channel bed and bank determine the area through which groundwater – river exchanges occur. For example, if the bank largely comprises silt / clay, then groundwater exchanges will be focused through the river bed, where drapes of fine sediment (of low hydraulic conductivity), may significantly reduce the connectivity between river and aquifer. In contrast, in situations of active river downcutting, continued mobilisation of the bed prevents the accumulation of fine sediments and enables river water and shallow groundwater to remain in close hydraulic contact. The influence of such channel modification on river –aquifer exchanges was incorporated in a mathematical model by Mwaka *et al*. (1995), who considered that the model would be able to predict the effects of changing land use or river engineering works.

The relative importance of seepage through the channel bed or bank is also a function of the relative surface area of contact between the channel component and the aquifer. In many cases, interaction through the river **bed** is promoted due to a proportionally larger area of contact (Calver, 1997), which remains true even if the bed material is of relatively low permeability. For example, Squillace (1996) estimated that contributions towards overall seepage losses from the bed and banks of the Cedar River in Iowa were 70% and 30% respectively. This was despite the fact that the average flux per unit area was four times larger through the banks than through the bed, which reflected the higher horizontal permeability of the bank sediments, compared to the vertical permeability of the channel bed material. However, the greater surface area of the bed (ten times larger than the banks) was the dominant control.

In a different and novel context, Younger *et al*. (1993) studied the permeability of bed sediments in the middle Thames, and assessed the degree to which they could protect riverside public water supply boreholes if river water was polluted. They found that due to the low permeability of the organic-rich silts (approximate hydraulic conductivity 2×10^{-8} m/s), water quality in the riverside wells would only exceed drinking water limits if the river were heavily polluted for at least a week. They concluded that stream bed permeability was more important than aquifer parameters in this context and that fieldwork would be best targeted at improving confidence in bed sediment permeability values, which are currently not well defined (Calver, 1997). In this respect, Calver's (1997) review of available bed sediment data was very valuable,

but the wide ranges in hydraulic parameters, for apparently similar lithologies, demonstrate the need to account for the geomorphological and hydrological contexts of individual sites.

When considering the influence of bed sediment permeability, it is essential to consider the dynamic nature of the stream bed environment and thus the changing nature of the bed sediments. The actual interchange between river and groundwater may influence sediment deposition and act to self-limit the exchange (Younger *et al.*, 1993), whilst the permeability of bed sediments can be reduced by the deposition of fine material through mechanical or biological processes (Huggenberger *et al.*, 1998). This clogging process (termed "colmation" by Brunke & Gonser, 1997) envisages the stream bed acting as a mechanical filter, leading to total sealing of the bed material, which can only be removed by bedload transport in spate conditions. In contrast, reaches dominated by upwelling groundwater suffer less from siltation and tend to maintain their vertical permeability intact (Schalchli, 1992).

The differing timescales of groundwater and river components

In order to apply a Darcian approach to quantify river – aquifer exchange, a value for hydraulic gradient between the river and adjacent aquifer is required. To be representative, the values for aquifer head and river stage should be recorded simultaneously and sufficiently frequently that short-term variations can be identified. This can be problematic, as groundwater levels are often recorded at daily or even monthly intervals (Younger, 1995), and is only overcome in specific studies where both river stage and groundwater levels are monitored at high temporal frequencies (e.g. Burt *et al.*, 2002). However, even in studies that record at high temporal resolutions, the problem of differing reaction times of river and aquifer systems can be exacerbated by the difficulty in obtaining high quality field data that can be used to isolate the component of water table variation due to river seepage (Bradley & Petts, 1995).

The best-recognised manifestation of differences in reaction times between groundwater levels and river stage is the **bank storage effect**, whereby rapid increases in river stage (due to heavy rainfall) lead to reversal of the 'normal' aquifer-to-river hydraulic gradient, allowing river water to infiltrate the alluvial material of the adjacent floodplain. Once river stage falls back below groundwater level, the aquifer-to-river

gradient is restored, and the bank storage water is then returned to the channel, sometimes forming an important component of baseflow (e.g. Squillace *et al.*, 1993).

The bank storage effect has been the subject of numerous studies over a long period (e.g. Rorabaugh, 1964; Pinder & Sauer, 1971; Gill, 1985; Hunt, 1990; Burt *et al.*, 2002), but a number of the underlying assumptions of these approaches (such as the homogeneity of alluvial aquifers, and the validity of Dupuit-Forchheimer conditions) may be inappropriate (Sharp, 1977). These studies have concentrated almost exclusively upon the interaction between rivers and alluvial aquifers / floodplain materials. A notable exception to this is work by Crandall *et al.*, (1999), which considered the bank storage effect in a bedrock aquifer.

Crandall *et al.* used the high concentrations of distinctive compounds (including dissolved organic carbon, tannic acid and chloride) in the water of the lower Suwannee River in Florida as natural tracers to identify seepage into the underlying Upper Floridian karstic limestone aquifer. At times when river discharge rose rapidly (due to a pulse of flow from a distant rainfall event), river stage exceeded the groundwater level, and river water was driven into the aquifer through spring 'vents' in the river bed. Despite the significant water resource management implications associated with these incursions (as the aquifer is the principal source for local public water supply), Crandall *et al.* did not assess river-water residence time, nor did they estimate what proportion of the incursive river water was subsequently returned to the river as the stage decreased. However, the study provides a bridge between the numerous examples of river – alluvial aquifer bank storage-type research, and the large karst limestone aquifer literature, where **all** river discharge is lost into the subsurface. However, karstic systems operate in a comparable manner to impermeable catchment systems in terms of their timescales, as the crucial storage parameter, which characterises permeable catchments, is very low in karstic aquifers.

Another manifestation of the differing reaction times between rivers and aquifers relates to the numerical modelling of such coupled systems, where traditionally one of the two components has been drastically simplified (Younger, 1995). This problem is particularly acute in regional aquifer flow models, in which groundwater – river exchange, occurring on a short time scale (e.g. hours) and small spatial scale (e.g. tens of square metres), needs to be simulated within a model using time steps of days

and grid elements of hundreds or thousands of square meters (Wilson & Akande, 1995). Given the rapid development of computing power over the last decade, the use of "internally coupled" river – aquifer models (*sensu* Dillon, 1983, quoted in Younger, 1995), which allow stable analysis of river flows by solving groundwater equations at very short time steps, has become more viable. Unfortunately, today (some eight years after the statement was originally made) they are still not "as widely used as might have been hoped" (Younger , 1995).

2.4 REPRESENTATION AND VERIFICATION OF CONCEPTUAL MODELS

The ability of a conceptual model to represent the function of a hydrological system can be directly evaluated using field data, combined with simple analytical techniques. However, most large-scale river –aquifer systems are too complex for this approach and require a numerical modelling approach to represent them adequately, with verification using suitable field data.

2.4.1 Numerical simulation of groundwater – river interaction

Background detail

Early numerical models of groundwater – river exchange were developed to simulate bank storage effects (e.g. Pinder & Sauer, 1971). These models were limited by the processing power available at the time, and the requirement to simultaneously solve two flow equations describing open channel and subsurface flow. Most models could not meet this requirement and could only represent one element (either groundwater or surface water) effectively, the other being limited to a crude approximation. As affordable processing power increased, more complex models were developed, albeit still focusing on either groundwater or surface water flow, but better able to represent the secondary component. Finally, whole catchment models, capable of integrated simulation of numerous surface and subsurface processes, were produced, for example MIKE SHE. This model and a selection of others used in simulation of groundwater – river interaction are described briefly in Table 2.2. [For more detailed information, an exhaustive recent review of integrated surface water / groundwater models has been undertaken by a major US environmental consultancy firm (Camp Dresser McKee, 2001)].

Model	Model characteristics		
	Source establishment	Functionality	References
Integrated Catchment Management Model (ICMM)	*Groundwater Development Consultants (Mott Macdonald)*	Integrated groundwater – surface water model using a modified version of the Stanford Watershed Model to calculate recharge	Rippon & Wyness (1994); Wyness *et al*. (1994); Pearce & Jones (1995)
Integrated Groundwater and Surface Water Model (IGSM)	*Montgomery Watson* (International water management consultants)	Basin planning model including groundwater, surface water, water quality and reservoir operation simulation routines.	Montgomery Watson (1995); Futter & Yoon (1995)
Lincolnshire Limestone Model	School of Civil Engineering, University of Birmingham, UK	Whole catchment model evolved from a groundwater flow model; includes representation of runoff recharge and river flow	Rushton & Tomlinson (1999)
MIKE-SHE	Danish Hydraulic Institute (DHI)	Based on the SHE system but including enhanced surface water flow representation	DHI (2003), Gray (1995)
MODBRANCH	United States Geological Survey (USGS)	Stream channel routing package integrated with MODFLOW groundwater model	Swain & Wexler (1992; 1996)
MODFLOW	United States Geological Survey (USGS)	Groundwater model with drain, river and stream modules for representation of surface water features	McDonald & Harbaugh (1988); Harbaugh & McDonald (1996)
SHE*	Danish Hydraulic Institute (DHI)	Purpose designed catchment modelling package able to simulate recharge, unsaturated flow, surface water flow and groundwater flow	Abbot *et al*. (1986); Bathhurst & Cooley (1995)
Single Layer Model (SLAY)	School of Civil Engineering, University of Birmingham, UK	Flexible groundwater flow model able to be adapted to simulate groundwater – river exchange	Wilson & Akande (1995)

Table 2.2 Details of selected numerical models used in simulation of groundwater – river interaction
*Système Hydrologique Européen

Limitations of current modelling practise

It is not possible to describe the exact method of simulating river – aquifer exchanges for many integrated models, as details are generally not given in journal articles, and reference manuals are unavailable. However, most models use the differential head between the river and the aquifer, which is then applied across an element of given hydraulic resistance that represents the bed sediment or aquifer hydraulic conductivity. This approach does not appear to address adequately the steep hydraulic gradients (with consequent significant vertical **and** horizontal components of flow) that are often encountered adjacent to river channels, and this shortcoming could lead to major errors in calculated flow exchanges. Whilst these approaches may be

acceptable at the catchment scale, where natural heterogeneity produces a degree of error correction, such errors are more problematic at smaller (e.g. subcatchment or reach) scales.

A general shortcoming of a number of modelling studies is the limited discussion on model calibration and / or verification. In many cases, due to the limited quantity of available field data, the same data are used for both calibration and verification. This is generally considered poor modelling practice (Anderson & Woessner, 1992) as it gives a false representation of the accuracy of the model simulation. This shortcoming can only be overcome by re-assessing the accuracy of the model some time after the original study when further data are available for verification (e.g. Rushton & Tomlinson, 1999). Some guidance on the quantity of calibration data required for regional groundwater models is provided by Christensen *et al*. (1998), who used a regional groundwater model to predict groundwater flow to streams in a poorly instrumented catchment. Christensen *et al*. found that using extensive river gauging data for model calibration did not markedly improve simulation accuracy, but noted that poor results were obtained if no gauging data were used in calibration. This appears to suggest that there is a critical threshold of gauging data, which could be considered as the minimum required for model calibration. Identification of this threshold, and its applicability in varying environments, would be a useful focus for future research. In addition, analytical methods, such as baseflow recession, can provide information to assist in the testing and verification of conceptual models (Talleksen, 1995).

2.4.2 Field-based and analytical verification techniques

The various diagnostic features indicative of groundwater river interaction, such as river flow gains/losses, local changes in river water/groundwater chemistry, and differential head levels between river stage and groundwater level, can be examined in the field using a number of investigative techniques. These techniques can be divided into two broad categories: hydraulic and hydrochemical methods. Hydraulic methods recognise the presence and magnitude of interaction by measuring hydraulic variables, such as discharge or water level. Hydrochemical methods rely upon identifying a change in natural water chemistry due to exchange, or detecting the presence of an artificially introduced compound (tracer), which has migrated from its injection point into the river or aquifer. Several studies have used a number of different methods,

allowing their results to be directly compared (e.g. Cey *et al.*, 1998; Kaleris, 1998; Robinson *et al.*, 1998).

A third category of techniques may be available in the future, based purely upon ecological methodology. For example, Valett *et al.* (1994) recognised that zones of upwelling groundwater in a desert stream promoted algal growth, and enabled its rapid recovery after disruption by flash floods. If the example of this study could be extended, there may be significant potential for using biological indicators to identify locations of groundwater – river exchange. However, the intrusive nature of sampling and monitoring is a problem common to both hydrological/hydrochemical and biological approaches, but one which is more acute in ecological studies due to the smaller size of the study sites (Palmer, 1993).

Hydraulic methods

Exchange of water between a river and an aquifer that occurs via seepage through the channel bed can be measured directly using a **seepage meter**. A seepage meter generally consist of a cylinder that is pushed sufficiently into the bed sediment to achieve a seal. It is then vented to a plastic bag containing a known volume of water, which is kept below the surface of the stream (Kaleris, 1998). If the stream is losing water, then the volume of water in the bag decreases, and *vice versa*. Evaluating the change in volume of the bag over the monitoring period allows the rate of seepage to be estimated.

Seepage meters may represent an under-utilised resource in studies of river – aquifer interaction, although they have been used extensively to measure groundwater flow to lakes (e.g. Taniguchi & Fukuo, 1993; Boyle, 1994; Shaw & Prepas, 1990). However, there are a number of limitations with seepage meters that may restrict their application and reliability.

Cey *et al.* (1998) compared a number of methods to measure groundwater inflow to a small stream in Ontario, and found that seepage meters were too insensitive to record groundwater discharges, which were estimated from other techniques at around 10 l/s/km. Kaleris (1998) also recognised problems with seepage meter measurements, especially their vulnerability to errors caused by poor installation, which was difficult to detect in the field. Blanchfield & Ridgeway (1996) demonstrated that where seepage meters used collection bags that were initially unfilled, flow rates could

be overestimated, perhaps by as much as an order of magnitude. Meanwhile, Belanger & Montgomery (1992) suggested that under controlled conditions, exfiltration measured by seepage meters was 77% of the actual seepage magnitude. Belanger & Montgomery also indicated that where seepage meters are properly installed, and their records adjusted correctly (using the 77% value above), then actual errors may be only 5%, which compare favourably to other sampling errors. Despite these mixed reviews, seepage meters may be useful in assessing groundwater – river interaction, providing that their limitations are explicitly understood prior to installation.

Changes in river discharge arising from groundwater – river interaction can be measured indirectly via **differential flow gauging**, provided the gauging points are a suitable distance apart (Rushton & Tomlinson, 1995; Kaleris, 1998) and the gauging technique is sufficiently sensitive relative to the magnitude of flow loss or gain. However, detecting seepage gains and losses becomes increasingly problematic downstream, as flows of a given magnitude represent an increasingly smaller fraction of the total river discharge, and can be undetected given the likely error in flow gauging, which is a fixed percentage of the discharge.

In a study that sought to quantify the exchange rate between groundwater and small streams using differential discharge measurements (and other techniques), Kaleris (1998) assessed the sensitivity of calculated exchange rates to various factors. He found that where a stream bed had low hydraulic resistance (high permeability), variations in aquifer hydraulic conductivity were highly significant. However, where the stream bed had high hydraulic resistance (low permeability), the rate of flow exchange was most sensitive to the value for the bed resistance, with the aquifer permeability being less significant.

Differential heads between a river and aquifer can indicate the potential magnitude of exchange flows. This piezometric-based approach has been used at two lateral scales to assess groundwater – river interaction. At the larger scale, river stage has been compared with floodplain water levels measured in boreholes/piezometers, which are generally installed to a depth of between 2m and 20m, to investigate exchanges between the channel and its associated alluvial deposits (often with regard to the bank storage effects discussed in the previous section, e.g. Bradley & Petts, 1995; Burt *et al.*, 2002). Meanwhile at smaller scales, water levels from mini-piezometers (i.e.

of small length and internal diameter, ID), installed to a depth of less than 0.5m in the stream bed, have been used to assess the interchange between the channel and the shallow hyporheic zone. For example, Valett *et al.* (1994) used mini piezometers (length <0.3m, ID 9mm) to map vertical hydraulic gradients in the bed of a desert stream in Arizona, finding that upwelling occurred at the base of riffles and the heads of runs, whilst downwelling occurred at the base of runs. Cey *et al.* (1998) used a network of 21 mini piezometers (length 0.6m, ID 9.5mm) along a 450m length of a small stream in Ontario to estimate exchange rates. To estimate the hydraulic conductivity of the underlying material, Cey *et al.* undertook a series of slug tests (Hvorslev, 1951) in the piezometers, but considering their small diameter (and the consequent difficulty in developing them after installation), the conductivity values are likely to have been subject to considerable error (Freeze & Cherry, 1979; p.342).

It is important to note that a differential head gradient between groundwater level and river stage is only an indicator of the **potential** for exchange, and where permeabilities are low no effective exchange will actually occur. Moreover, exchanges will not occur in the absence of a head gradient, although this situation suggests that the aquifer and the river may be in intimate hydraulic contact, such that if a gradient is applied than exchange flows may be significant.

Hydrochemical methods

Physico-chemical techniques for identifying groundwater – river interaction fall into two categories; firstly, those that use contrasts in the natural hydrochemical signature of groundwater and stream water to identify where exchange (mixing) is occurring; secondly, those using distinctive tracers, which are artificially introduced compounds whose movement through the river – aquifer system can be 'traced'.

For example, Redwine & Howell (2002) describe a **hydrochemical approach** using the contrast in major ions and stable isotopes (of hydrogen and oxygen) between groundwater and surface water to identify water leaking from a reservoir in Alabama, identifying a narrow zone of mixing controlled by geological structural features. A similar technique was used by Crandall *et al.* (1999), whilst Lawler (1987) used stable isotopes ($^{18}O/^{16}O$) to track rainfall events through dissimilar aquifer – stream systems. Lawler found that a distinctive event signature could be recognised in the discharge from a karstic limestone aquifer, but not in a chalk stream receiving baseflow from a

chalk aquifer. This illustrates the differing degree of mixing occurring within low storage and high storage systems, respectively.

In a novel application utilising contrasts in stream water and groundwater chemistry, Neal *et al.* (1997b) described changes in stream water quality arising from artificial enhancement of localised groundwater discharge, resulting from fracture development during drilling of a channel proximal borehole in an upland area (Plynlimon, Central Wales). The modification in stream water chemistry produced increases in pH, alkalinity and calcium concentrations, although the extent of the change varied with stream discharge. At high flows, there was little difference between points upstream and downstream of the borehole, but at intermediate flows pH increased from 5 to around 6.3. As a result, Neal *et al.* suggested that there was a significant potential for the remediation of acidic, upland water quality through utilising local groundwater.

Hydrochemistry can also facilitate hydrograph splitting, whereby distinctive hydrochemical signatures are used to differentiate recent runoff, soil water and groundwater components of stream flow (e.g. Sklash & Farvolden, 1979; DeWalle *et al.*, 1988; Cey *et al.*, 1998). One such hydrograph splitting technique is End-Member Mixing Analysis (EMMA), which uses chemical parameters such as base cations, electrical conductivity, acid neutralization capacity and alkalinity to differentiate hydrochemically distinct source zones for stream water (Neal *et al.*, 1997d). However, Hill & Neal (1997), working in the Plynlimon catchments, found that surface waters and groundwater displayed significant spatial and temporal variability. This limits the applicability of the EMMA method, which assumes spatially and temporally constant end member compositions.

Tracers provide a direct means of assessing paths of flow exchange between aquifers and rivers, but have been little used for this type of application, except in karst or karst-type aquifers (Ward *et al.*, 1998). The ideal tracer material should be non-toxic, easily measured at low concentrations, should move at the same velocity as the water carrying it, should not react chemically with groundwater or the aquifer material, and should be absent or present only at very low concentrations in the hydrological system being investigated (Atkinson & Smart, 1980). A number of different materials have

been used as tracers in groundwater studies, including suspended particles, solutes, dyes, gases, isotopes, and bacteria (Ward *et al.*, 1998).

Studies examining the application of tracers to groundwater – river interaction fall into two spatial categories. Firstly, regional scale tracing from focused inflow locations (e.g. swallow holes) to river headwater springs, and secondly, local scale tracing undertaken in close proximity to the river channel.

Regional scale tracing in non-karstic aquifers has not been widely used, although it has been undertaken in UK aquifers that exhibit some sub-karstic behaviour, such as chalk and Corallian Limestone, and where successful has illustrated behaviour that would be difficult to identify by other methods. For example, Atkinson & Smith (1974) used a fluorescent dye to trace water movement from a swallow hole to two springs in South Hampshire, and found that the modal (peak concentration) velocity was 2.21km/day, whilst Banks *et al.* (1995) used a similar approach at a site in Berkshire, producing a peak concentration velocity of 5.78km/day. In both cases, far higher velocities were detected than would be expected from analytical calculations, which has significant implications for groundwater source protection.

Harvey *et al.* (1996) describe a **local scale** study, using a solute tracer (lithium chloride) to characterise hyporheic exchange along a 36m length of a Rocky Mountain stream in Colorado. Harvey *et al.* found that the tracer approach was reliable at low flows but was inconsistent at higher flows, when compared to rates of exchange determined from measurements of hydraulic head and hydraulic conductivity. Other studies using similar methods include Triska *et al.* (1993a,b) and Harvey & Bencala (1993), while Valett *et al.* (1994) used subsurface injections of fluorescent dye and releases of visible dye at the stream bed surface to verify the occurrence of advective exchanges inferred from vertical hydraulic gradients measured in mini piezometers.

Smith (1971) describes the use of tritium (^{3}H) to examine interaction between the lower reaches of the River Lambourn, a chalk stream, and the underlying gravels and chalk aquifer. Tritiated water was injected into the river at a near-constant rate for 25 days and samples were then taken from pumped chalk boreholes and channel-proximal, shallow wells in alluvial gravels located downstream. No tritium was detected in any of the pumped boreholes, but it was detected in 19 out of the 30 wells. This indicates a good connection between the river and the underlying gravels, but a

generally poor connection between the channel / gravels and the underlying chalk aquifer.

Analytical characterisation of permeable catchment systems

Winter (1995) reviews analytical methods of determining groundwater - river interaction but suggests that techniques such as hydrograph separation (baseflow recession analysis) have been superseded in recent years by other analytical techniques and by numerical modelling. However, Talleksen (1995) reviewed methods of baseflow recession analysis and suggested that output from recession analysis can help determine parameters in numerical models (e.g. Harlin, 1991 cited in Talleksen, 1995). Examples of analytical or lumped parameter approaches to river aquifer exchange include Headworth (1972), Foster (1974) and Keating (1982), but the physical representation of the stream - aquifer system resulting from these techniques may be over-simplistic.

Numerous methods have been developed to distinguish the base flow component of a flow hydrograph (reviewed by Tallaksen, 1995). However, some of the classic assumptions underlying conventional baseflow recession analysis techniques are questionable for long recession periods. This partly reflects the high variability in gradients of individual segments (thought to represent different stages of the outflow process), and also how these different segments relate to physical factors controlling the flow regime. The conventional baseflow recession function implies that an aquifer acts as a single linear reservoir but an unconfined aquifer consists of a system of hydraulically interconnected pore and/or fissure systems and hence a *non-linear* response function would be more realistic (Wittenberg, 1999), which is contrary to the traditional conceptualisation of storage in permeable catchment systems.

2.5 GROUNDWATER–RIVER INTERACTION IN CHALK CATCHMENTS

2.5.1 A historical perspective

Research on chalk stream – aquifer interaction has a long history. For example, an early study by Macdonald & Kenyon (1961) described the monitoring of river discharge and groundwater levels in the chalk catchments of Hampshire. However, human interest in the behaviour of chalk streams, and particularly their headwater springs, probably extends back nearly 2000 years, as indicated by the location of Roman villas adjacent to such springs (*ibid*). From the early 1960's onwards, the pattern of

research on river – aquifer interaction in chalk catchments mirrored the development of scientific and regulatory practises within a framework of developing legislation (reviewed by Smith, 1997).

The first decade following the Water Resources Act of 1963 was dominated by major water resource development schemes, which included flow augmentation projects using pumped groundwater in chalk catchments (reviewed by Owen *et al.*, 1991). Examples of this included the Thames (West Berkshire), Great Ouse (East Anglia) and Candover (Hampshire) Groundwater Schemes. During this period, investigations focused on maximising yields for supply and augmentation, and there was little environmental assessment of the consequences of such activities. This was partly because no recognised methodologies for environmental assessment then existed (Smith, 1997). Almost the sole evaluation of the influence on discharge in chalk streams during flow augmentation schemes was through calculation of *net gain*, this being the amount by which the natural flow was increased by the pumped discharge, expressed as a percentage of the pumped volume: (Owen *et al.*, 1991)

$$\text{Net gain} = \frac{G - (I + R)}{G} \times 100 \qquad \text{Equation 2.2}$$

Where:

G = Pumped groundwater discharge to the river

I = Natural river baseflow intercepted by pumping

R = Recirculation of water back into the aquifer from river bed leakage

Following the rapid recovery of groundwater levels and stream flows after the severe drought of 1975/76, there was more than a decade of relative quiescence in hydrological research on chalk groundwater – river interaction. During this period, environmental assessments became a standard element of water resource development schemes, and numerous ecological studies of chalk streams were also undertaken (e.g. Ladle & Bass, 1981; Pearson & Jones, 1984; Pinder & Farr, 1987; Wright & Berrie, 1987). This period effectively ended with the 1989-92 drought, which clearly showed the parlous state of groundwater resources in a number of chalk catchments, where stream flows were heavily impacted by groundwater abstractions, principally for public water supply. These impacts were recognised by the disproportionate occurrence of fifteen chalk streams in a list of the top forty low flow rivers in England and Wales

(NRA, 1993). This encouraged further research directed towards chalk aquifer – river interaction, and resulted in a number of studies that used numerical groundwater models to simulate the behaviour of highly impacted chalk catchments, with the aim of devising and testing resource management strategies in order to alleviate low flows (e.g. Rippon & Wyness, 1994; Wyness *et al.*, 1994; Pearce & Jones, 1995; Cross *et al.*, 1995; Wilson & Akande, 1995).

Since this time, the need for better-coordinated research of groundwater – river interaction in the UK has been consistently recognised in the scientific community (e.g. Acreman & Adams, 1998; Sear *et al.*, 1999). Furthermore, the move towards integrated management of surface water and groundwater resources, through the Environment Agency's CAMS process (Catchment Abstraction Management Plans) and the European Union's Water Framework Directive, have provided the legislative drivers to promote river – aquifer research. One recent product of this has been the Natural Environment Research Council's LOCAR (Lowland Catchment Research) project, a thematic programme to investigate the integrated hydrological systems of lowland permeable catchments, with two of the three research catchments being located on chalk.

2.5.2 The character of the chalk aquifer and its control on groundwater – river interaction

The properties of the chalk aquifer in the UK have been described in a number of key studies (e.g. Price, 1987; Downing *et al.*, 1993; Price *et al.*, 1993; Lewis *et al.*, 1993; Allen *et al.*, 1997; MacDonald & Allen, 2001), which have shown that the chalk is a complex aquifer, exhibiting heterogeneity at scales ranging from the microscopic to the regional.

The Chalk Formation, as a lithostratigraphic unit, is a soft, white limestone of very pure calcium carbonate, formed from the remains of marine micro-organisms (dominantly planktonic algae), laid down over extensive areas of north-west Europe mainly in the Upper Cretaceous period 100 to 65 million years ago (Downing *et al.*, 1993). The Chalk outcrops widely across southern and eastern England (shown in Figure 2.5) and is also present beneath younger strata of the London Basin. The Chalk Formation is divided into three divisions: the Upper, Middle and Lower Chalk, with recognised hardgrounds (indurated horizons) separating the Middle Chalk from the

divisions above and below. The proportion of argillaceous (clay grade) material increases down through the sequence, with the lower part of the Lower Chalk being known as the Chalk Marl, because of its high (~30%) clay content (Allen *et al.*, 1997).

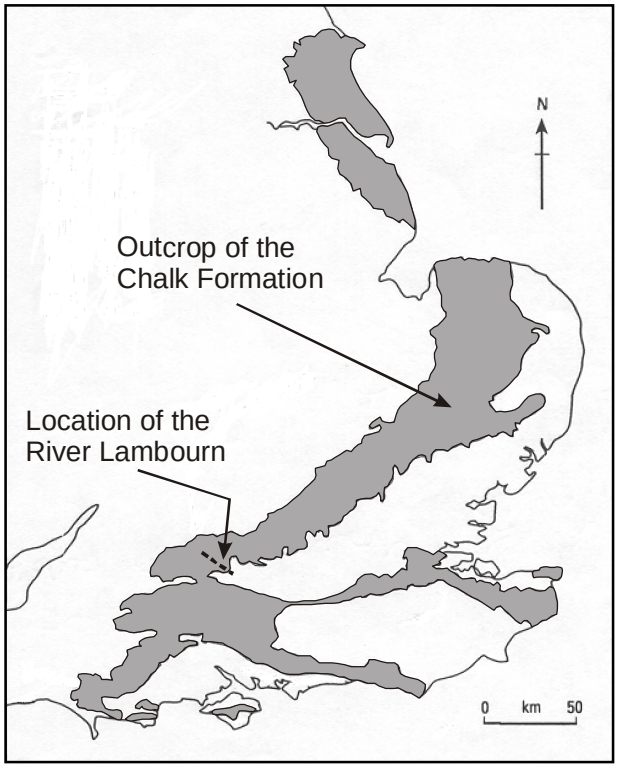


Figure 2.5 Generalised outcrop of the Chalk Formation in the UK
(after Edmonds, 1983)

The soluble nature of chalk allowed the development of a major aquifer, which possesses a dual porosity nature. The chalk aquifer is dependent upon solution-enlarged fissures for its permeability, whilst the micro-fractures and larger pores of the matrix provide storage. The chalk aquifer has a high bulk porosity of 20 – 45%, but as matrix pore throat diameters are very small (owing to the small size of the matrix particles), the effective porosity is low, producing low matrix permeability, and a bulk storage value (unconfined specific yield) of 1 to 3% (Price *et al.*, 1993).

Aquifer properties and flow processes

The principal properties of the chalk aquifer (permeability and storage) are not constant, but vary both areally (on various scales) and vertically, being influenced by numerous factors including stratigraphic location, regional location, topographic context and degree of confinement (Allen *et al.*, 1997).

Most information on chalk aquifer properties is derived from investigations in abstraction boreholes, which are recognised as being non-randomly distributed across the outcrop, with the majority being located in valleys, where permeability is highest (so as to maximise yields), and very few located in interfluve areas. The non-random distribution of the sampling points inevitably introduces bias into the database of chalk aquifer property values, leading to poor (overestimated) characterisation of the bulk properties of aquifer as a whole (Allen *et al.*, 1997).

On a national scale, values from ***measured*** sites indicate that transmissivity approximates a log – normal distribution, with a median value of 540m^2/day, and 25th and 75th percentiles of 190m^2/day and 1500m^2/day respectively (MacDonald & Allen, 2001). Using 50m as an estimate for the effective aquifer thickness, the transmissivity values above give hydraulic conductivities of 10.8m/day, 3.8m/day and 30m/day respectively. Median values for storage coefficient are 0.008 for unconfined sites and 0.0006 for confined sites (*ibid*). Regionally, transmissivity is highest in the indurated chalks of Yorkshire and Lincolnshire (to the north of the Wash: see Figure 2.5), which possess a median value of 1800m^2/day, whereas in East Anglia the value is 410m^2/day, in the Thames Valley it is 580m^2/day and in the southern chalk provinces of Hampshire and Dorset it is 1000m^2/day (*ibid*).

Meanwhile at a local scale there is a well-recognised control exerted by topography upon aquifer properties, with both permeability and storage being highest in river valleys and lowest beneath interfluve areas (Price *et al.*, 1993), although this pattern should be considered in the context of the valley-biased dataset mentioned above. The exact nature of the reduction in permeability away from valley areas is unclear, but could result from a general reduction in the permeability of the full thickness of the effective aquifer or from a reduction in the effective aquifer thickness itself. Both potential patterns are illustrated schematically in Figure 2.6.

In a stratigraphic context, permeability generally decreases down through the Chalk sequence, with a pronounced reduction in the Lower Chalk division due to a significant increase in the content of argillaceous material. At a locally scale, most groundwater circulation occurs in the uppermost 50m of the aquifer, with the highest permeability being developed within the zone of water table fluctuation. The presence of hardgrounds, displaying enhanced fracturing, can locally increase the permeability of

the sequence, up to a depth of around 100 metres below ground, and this is shown schematically in Figure 2.7.

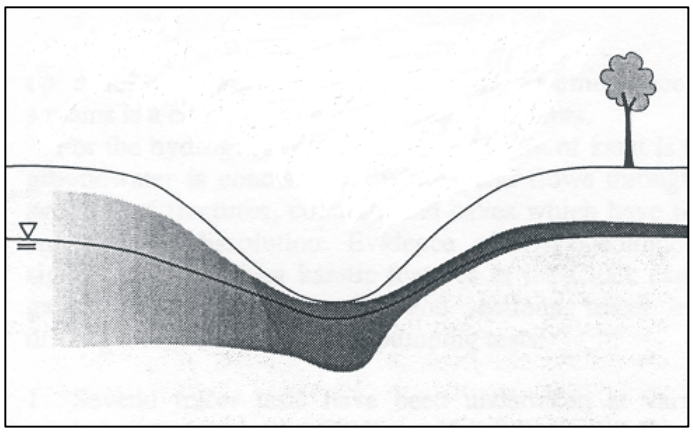


Figure 2.6 Schematic representation of chalk permeability showing potential patterns of lateral reduction (from Allen *et al.*, 1997)

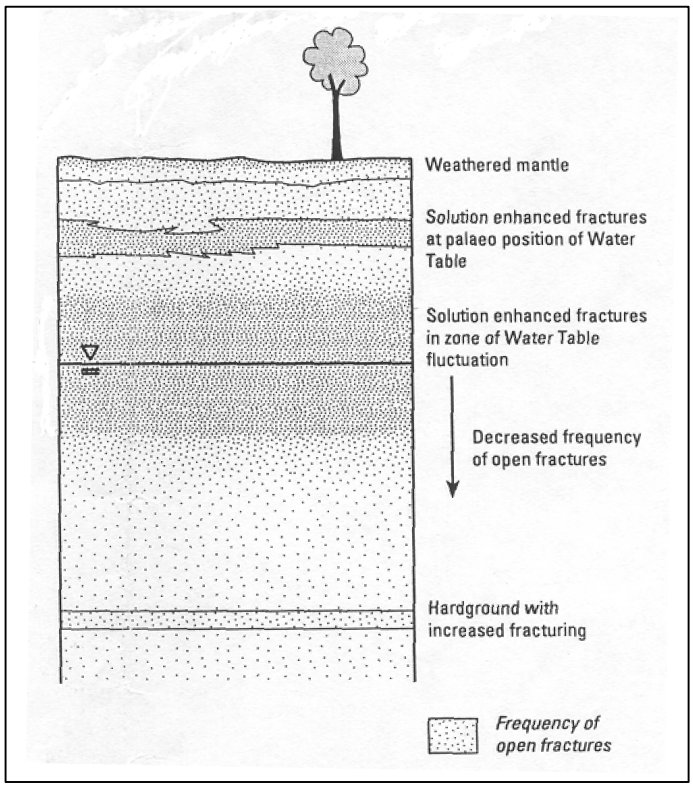


Figure 2.7 Schematic representation of the variability of fracturing with depth for the Chalk (from Allen *et al.*, 1997)

Whereas the heterogeneity of the chalk aquifer is well recognised (e.g. Price, 1987), the influence of this heterogeneous nature upon both the spatial and temporal

aspects of river – aquifer interaction in chalk catchments is less well understood, and these aspect are explored in the following sections.

Spatial controls on river – aquifer interaction in chalk catchments

Flow accretion profiles are a basic hydrological tool for investigating spatial patterns of flow accretion, in both impermeable and permeable catchments. They have been produced for a number of chalk streams in order to present results from groundwater modelling studies (for example: Oakes and Pontin, 1976; Connorton & Hanson, 1978; Wyness *et al.*, 1994; Wilson & Akande, 1995). Often these profiles have displayed asymmetric patterns, but no attempts have been made to explain possible controls. Indeed, specifically seeking to recreate chalk stream flow accretion profiles, and test their sensitivity to various parameters, has not been a specified objective of any known groundwater modelling project. Similarly, the influence of valley floor controls on chalk stream – aquifer exchange (such as alluvial deposits and channel-related parameters) does not appear to have been the subject of any investigation described in the literature.

In a paper partly based upon analytical work described in this thesis, Bradford (2002) suggested a topographic-related control on the spatial pattern of aquifer discharges, advocating a sub-scarp theory related to the presence of chalk dry valleys and resistant layers in the Chalk. There are several types of such layer present in the Chalk, including marl bands, flint horizons and hardgrounds. It is the latter category, which are indurated horizons representing a period of quiescent sedimentation (Hancock, 1993) that appear to exert the most significant control on groundwater flow in the chalk aquifer. It is unclear whether cleaner fracturing in hardgrounds promotes flow within them (Price, 1987), or whether their lithified texture restricts cross-formational flow, forcing water to move parallel to their bedding orientation. However, whatever their function, they are recognised as important controls on the locations of springs at the base of the Chalk escarpment (Allen *et al.*, 1997).

In addition to these recognised lithological discontinuities within the Chalk sequence, there are also hydraulic discontinuities. These are formed by enlarged fissures within the normal structure of the chalk aquifer, which render it locally karstic in nature. Where such features have been identified they are usually connected to points of focused surface drainage such as swallow holes (e.g. Atkinson & Smith, 1974;

Banks *et al.*, 1995). These sites are often located on the current or former margins of low permeability Tertiary strata, whose minimal carbonate content produced aggressive acidic run-off that promoted localised dissolution of the Chalk. In addition, the development of shallow, high permeability fissure systems in valley floor areas is likely to be at least partly due to groundwater – river interaction, as illustrated in Figure 2.8.

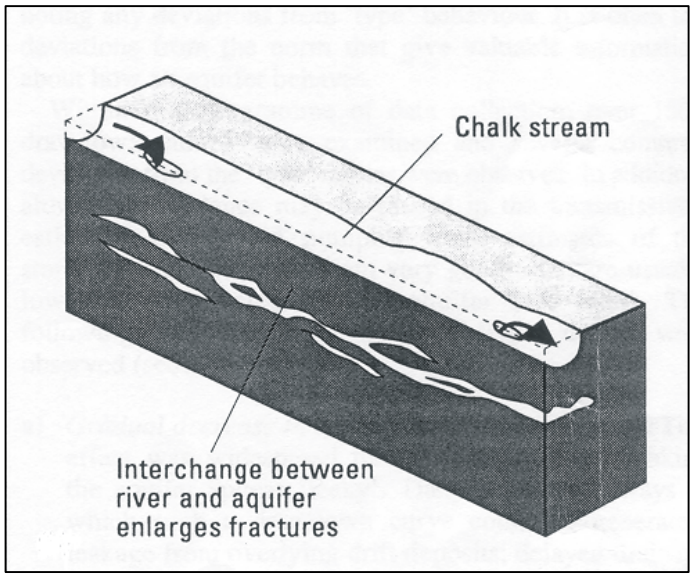


Figure 2.8 Schematic representation of water exchange in a chalk system (from Allen *et al.*, 1997)

Intricately associated with the spatial pattern of chalk stream – aquifer interaction is the occurrence of bourne (seasonal/ephemeral) sections of chalk streams, and the controls on their form and function. Whilst drainage network expansion and contraction is a phenomenon observed in many types of catchment (Gregory & Walling, 1971), chalk streams are unusual in that the network variability is a seasonal event, rather than a response to a specific rainfall event. Headworth *et al.* (1982) considered that the presence of a thin zone of high permeability and storativity in the Candover Valley (Hampshire) controlled the flow pattern in the bourne section of the river. However, their evidence is inconsistent with earlier work (Headworth, 1972), and whilst the presence of the zone is plausible, its role as the dominant control on bourne flows appears less certain.

Unpublished work on the bourne sections of chalk streams in south-west England indicates a large variety of spatial discharge regimes, suggesting a complex series of controls (W. Stanton, pers. comm.). [An illustration of one such discharge

regime is presented by Allen *et al*., 1997; Figure 4.1.12, p.30]. There has been no published assessment of potential controls on the nature and occurrence of bourne stream flow regimes, which evidently presents an opportunity for future research, particularly in the light of groundwater flooding problems in chalk 'dry' valleys following the extreme rainfall in autumn 2000. In addition, there is also a need to understand controls on the location of chalk headwater springs, both perennial and ephemeral, as these can form important wetlands (Petts *et al*., 1999).

Temporal controls on groundwater –river interaction in chalk catchments

Chalk streams exhibit flow regimes, which are stable, in terms of both discharge and physico-chemical parameters (Berrie, 1992). This reflects the buffering effect of the storage within the chalk aquifer, which smoothes short-term variations in recharge to produce a consistent, seasonal response. The buffering effect is not restricted solely to controls in the saturated zone, as unsaturated zone processes can also exert a considerable influence.

There have been numerous studies of shallow unsaturated zone processes in chalk catchments for the purpose of point recharge estimation (e.g. Wellings & Bell, 1980; Wellings & Cooper, 1983; Gardner *et al*., 1990; Jones & Cooper, 1998, Mahmood-ul-Hassan & Gregory, 2002). However, these studies have been generally limited to a small area and a shallow depth (<5m), which makes them less useful for extrapolating to the catchment scale for water resource applications, since over the bulk of the chalk outcrop the water table is generally more than 10m below ground level. However, Zaidman *et al*. (1999) describe processes in the deeper sections of the unsaturated zone of the Yorkshire Chalk, and found that water movement in steeply inclined fractures could be restricted by the presence of sub-horizontal marl bands. Recognition of the processes operating in the deep unsaturated zone, including the occurrence and significance of lateral migration, is an important element of chalk hydrogeology that remains largely unresearched.

Where the chalk matrix has relatively high permeability, most drainage occurs through the matrix, and fissure flow is rarely, if ever, initiated (Wellings, 1984). However, where the matrix has lower permeability, then a greater fraction of drainage occurs via fissures (Cooper *et al*., 1990). The presence of soil and a chalk weathered

zone, which can both function as a temporary store for rainfall that buffers inputs to the unsaturated zone, may significantly influence the initiation of fissure flow (Cooper *et al.*, 1990). Piston flow may cause the rapid displacement of water from the base of the unsaturated zone (Price *et al.*, 1993), as the matrix remains saturated at high negative pressures, but there is no doubt that some rapid recharge does occur via fissure flows, hence the appearance of bacteria and suspended sediment in some boreholes following heavy rain. This phenomenon was recognised during hydrochemical sampling of a number of wells in the South Downs by Downing *et al.* (1978), who concluded that fissure flow was likely to occur if average infiltration exceeded 4mm/d for a number of successive days.

The only reliable, long term basis for estimating recharge to a catchment uses the discharge from the catchment, providing unrecorded losses from the catchment, such as groundwater discharges across boundaries or beneath river gauging stations, are small. However, few studies have attempted catchment-scale calibration of point-based estimates of recharge rates in the Chalk. A rare exception to this is Limbrick (2002), who used the discharge of the River Wey (Dorset) to calibrate a simple recharge estimation model. Using six different root constants to produce six estimates for HER (hydrologically effective rainfall), Limbrick then used three different hydrological models (CAPTAIN, IHACRES and INCA) to calculate mean daily flows, and identified a root constant of 200mm as being optimal for the Chalk outcrop in southern England.

The shortfall in calibrated estimates of recharge clearly needs to be addressed, since correlating the pattern of recharge with catchment discharge would provide a means of quantifying the timing of catchment scale flow processes. However, this approach needs to be undertaken in a catchment where groundwater abstraction is insignificant, so that any anthropogenic influence on the discharge regime can be discounted. This work would also allow the magnitude of errors in recharge estimations to be assessed, which can only be achieved (on a catchment scale) through comparison with long-term patterns of discharge.

Another significant element of the time lag between rainfall and the discharge of water from the aquifer is the residence time in the saturated zone, which is controlled by hydraulic gradient and permeability. Most rainfall in chalk catchments falls on interfluvial areas, but definition of permeability in these areas is poor, as pumping tests

are heavily biased towards high permeability valleys (MacDonald & Allen, 2001). Temporal correlation of recharge and discharge would also enable residence times in the interfluvial saturated zone to be assessed, allowing independent bulk values for interfluve permeability to be estimated.

2.5.3 The resource management context for chalk streams

The chalk aquifer is the most important in the UK, in terms of both total volume of groundwater abstractions, and volume of abstractions for public water supply (Downing, 1998). As a consequence of this intense abstractive regime, chalk streams have been subjected to a number of impacts, including reductions in discharge (Strevens, 1999), decline in the frequency and duration of periods of flow in their seasonal, upper (winterbourne) reaches, and in severe cases, the permanent downstream migration of their perennial sources (Owen *et al.*, 1991). Low flows resulting from groundwater abstraction may also promote indirect impacts such as increased silt retention (Walling & Amos, 1999), which is detrimental to the survival of incubating brown trout embryos (Acornley & Sear, 1999).

Chalk streams are greatly valued as ecological resources (Petts *et al.*, 1999), with the UK steering group on biodiversity recognising chalk streams as one of the most species-rich of lowland river types (Anon., 1995), and the European Commission defining them as Special Areas of Conservation (reported by Sear & Armitage, 1999). Chalk streams are also highly prized for their amenity value, and as high quality salmonid fisheries (Johnson *et al.*, 1995; Acornley & Sear, 1999; Strevens, 1999; Walling & Amos, 1999). The importance of groundwater – river interaction in the function of chalk streams has been clearly recognised, especially with regard to the deleterious effects of groundwater abstraction on habitats (e.g. Armitage & Petts, 1992; Bickerton *et al.*, 1993; Wood & Petts, 1994; Wilby *et al.*, 1998).

Management of water resources in chalk catchments has become increasingly reliant upon groundwater models as predictive tools to assess the effects of different strategies, especially the reduction in abstraction to alleviate low flows (e.g. Rippon & Wyness, 1994; Cross *et al.*, 1995, Pearce & Jones, 1995). Additionally, management tools such as the IGARF II (Impact of Groundwater Abstractions on River Flows II) methodology (Parkin *et al.*, 2002) have been developed to assist in generic assessments of abstraction-related effects. The impacts associated with channel proximal

abstractions are relatively simple to define, especially where the river channel is recognised as being in close hydraulic contact with the underlying aquifer. However, impacts related to more remote abstractions, especially ones of a seasonal nature (e.g. for irrigation) are far more difficult to quantify, due to the poor understanding of catchment scale flow durations. Enhanced knowledge of the duration of bulk flow processes will assist in determining the impacts of remote abstractions. This could improve the overall management of permeable catchment systems by allowing the balancing of proximal and distal abstractions so as to minimise their impact on the river flow regime.

There is general perception that reductions in groundwater abstractions will help to alleviate low flows, but Rushton (2002) questions the efficacy of this approach. There is also some debate as to whether low (late summer) flows are the most important limiter on ecological productivity. Rushton suggests that reduction in groundwater abstraction would not necessarily produce ecological benefits in terms of significant increases in late-summer flows, with the presumption that this would be the most ecologically sensitive time of the year. However, this is contrary to the results described by Wood *et. al* (2000), concerning the timing of peak ecological sensitivity, from work on a chalk stream in Kent. In sampling of macro-invertebrate communities over a 6-year period, Wood *et al.* found that indices of high discharge in the late recharge season, four to seven months prior to sampling, were the most important variables for describing the macro-invertebrate communities in each September, with late summer discharge having relatively little significance. Thus, a reduction in groundwater abstraction, whilst not increasing late-summer flows, may have an ecological benefit by optimising discharge at the end of the recharge season, especially in years with below average winter rainfall.

Target flows to protect in-channel needs have become a more common element in chalk catchment water resource management, and the ecological methodology to justify such targets has been the focus of many studies. One methodology for setting target flows on ecological grounds is PHABSIM (Physical Habitat Simulation Model), whose application to a chalk stream in Dorset is described by Johnson *et al.* (1995). Outputs from PHABSIM were combined with habitat suitability data for life stages of trout and salmon to develop habitat (expressed as weighted usable area) versus discharge relationships. These relationships were used in conjunction with 20 years of historical and

naturalised flow data to assess the impact of groundwater abstractions on habitat availability, and thence to set target minimum summer discharges.

Strevens (1999) describes a similar study on the River Piddle in Dorset, where PHABSIM was used in conjunction with output from a groundwater model to assess the impact of groundwater abstraction on habitat availability for brown trout. It was found that there had been large habitat losses for juvenile trout, but using the relationship between discharge and habitat allowed an enhanced flow regime to be defined, which met both ecological and recreational needs.

Another technique that can be used to link riverine ecology with hydrological parameters is the LIFE (Lotic-invertebrate Index for Flow Evaluation) method, developed by Extence *et al.* (1999), which uses data available from established ecological and hydrological databases. The method is based upon allocating common British macroinvertebrate species into six groups, five of which represent a specified river flow velocity (ranging from 0 to >1m/s) while the sixth is associated with drying or drought-impacted sites. Abundances of the various sampled taxa are weighted using a pre-determined flow score matrix and based upon this the LIFE index for the site is calculated. This value, representing the ecological 'health' of the site, can then be statistically correlated with various river flow parameters (e.g. mean, minimum or maximum flow over a specified period) to identify which are the most significant in controlling ecology quality. These parameters can then be used to define a baseline flow regime to maintain or improve the ecological quality of the watercourse.

Rippon & Wyness (1994) used an integrated catchment model to represent the catchment of the River Darent in Kent, which had been severely affected by groundwater abstraction. The model was used to test a number of water resource management strategies and the RIVPACS (River InVertebrate Prediction And Classification System) aquatic database was used to help define an environmentally acceptable flow regime. This example of an integrated hydrological / ecological approach should provide a basis for similar studies in the future. Armitage & Petts (1992) also used the RIVPACS database to assess sites on UK rivers. They found that using RIVPACS by itself was unsuitable for setting 'minimum ecological flows' but it could identify areas of concern or determine the potential conservation value of sites. The conservation value of the River Darent as a public resource was assessed by Willis

& Garrod (1995), who undertook cost benefit analysis of plans for the alleviation of low flows, and found that preventing further deterioration in flows produced a net benefit, but improving the flow regime produced a marginal result, with no clear net cost or benefit identified.

As water resources become scarcer and public demand for reduction or reversal of perceived environmental degradation increase, water resource managers are faced with a difficult task: the need to plan effectively for the future in order to safeguard public water supplies, whilst maintaining or even increasing the resource component which is left 'untouched' to provide river baseflows (Erskine & Papaioannou, 1997). The target level for such baseflows may be in the form of an Ecologically Acceptable Flow Regime, *sensu* Petts (1996), but this must be defined in the context of a changing climate, characterised by increased seasonality (Wilkinson & Cooper, 1993; Marsh & Sanderson, 1997), where statistical analysis of rainfall and temperature trends from the past may not represent realistic analogues for the future.

2.5.4 Research gaps in the field of chalk stream – aquifer interaction

On the basis of the preceding sections, which have reviewed research in chalk catchments, the following important research gaps that require further investigation were identified:

A) Assessment of time lags between recharge and discharge in chalk systems to allow timescales of catchment scale flow to be quantified to assist in determining the impacts of groundwater abstractions located remotely from the river channel;

B) Recognition of the control exerted by groundwater levels (catchment storage) upon river discharge in order to define baseline flow regimes for impacted catchments;

C) Identification of spatial variability in chalk stream - aquifer interaction, as an indicator of channel proximal chalk aquifer flow processes;

D) Assessment of the applicability of Darcy’s Law in quantifying river – aquifer fluxes, especially in relation to the poor definition of multi-lithology valley floor hydraulic conductivity values;

E) Identification of controls on the location of chalk stream headwater springs, as these can support ecologically valuable wetlands that are vulnerable to effects of groundwater abstraction.

In addition, our understanding of the following research elements has been recognised as currently incomplete, although these are less directly related to the specific area of groundwater – river interaction:

F) Definition of bulk (interfluve) chalk aquifer properties (especially hydraulic conductivity)

G) Verification of recharge estimates at the catchment scale via comparison with long term records of stream discharge

H) Investigation of deep (>10m below ground) unsaturated zone processes, especially in terms of potential occurrence of lateral flow migration

The research elements outlined above formed the framework for defining the aims and objectives of the study, detailed in Chapter 1. This thesis seeks to specifically address elements A, B and C but also investigates elements D, F, G and H to a lesser degree. Data was collected to support investigation of element E, but the results are not reported in this thesis due to space constraints.

Chapter 3 Site description and research methodology

3.1 INTRODUCTION

The literature on river-aquifer interaction described in the previous chapter shows that considerable research effort has been directed towards chalk streams impacted by groundwater abstraction. In so doing, however, it could be argued that the mechanism of groundwater - surface water exchange within 'un-impacted' (natural) chalk catchments has been neglected, which represents a significant research gap that this study seeks, in part, to address.

This chapter describes how the data collection aspects of the research project were conceived and implemented, with details of the physical characteristics of the catchment described first in Section 3.2. This is followed by a summary of past research and investigation in the catchment, which was an important factor in determining its selection, because of the existing infrastructure and historic data that could be utilised for this study. The determination of research methods is then described in Section 3.3, whilst Section 3.4 describes how the field data was collected.

The selection of a suitable catchment for the study was evidently of considerable importance, and was based upon the following five criteria:

1. The catchment should be located principally on outcropping chalk;
2. The catchment should have low contemporary rates of groundwater abstraction;
3. An existing groundwater monitoring network should be present, with a record of historic data available;
4. The catchment should contain a stream with a length of perennial channel exceeding any seasonal length (i.e. be dominantly perennial in nature);
5. The catchment should be located within a reasonable distance of Birmingham.

The second criteria was the most difficult to fulfil, as almost all chalk catchments in the UK are subject to at least some modification in their flow regime, as a result of groundwater abstraction. However, the River Lambourn, a chalk stream in southern central England, appeared to satisfy all the criteria.

3.2 OUTLINE CATCHMENT DESCRIPTION

The River Lambourn is located in the chalk hills of the West Berkshire (North Wessex) Downs in central, southern England (Figure 3.1).

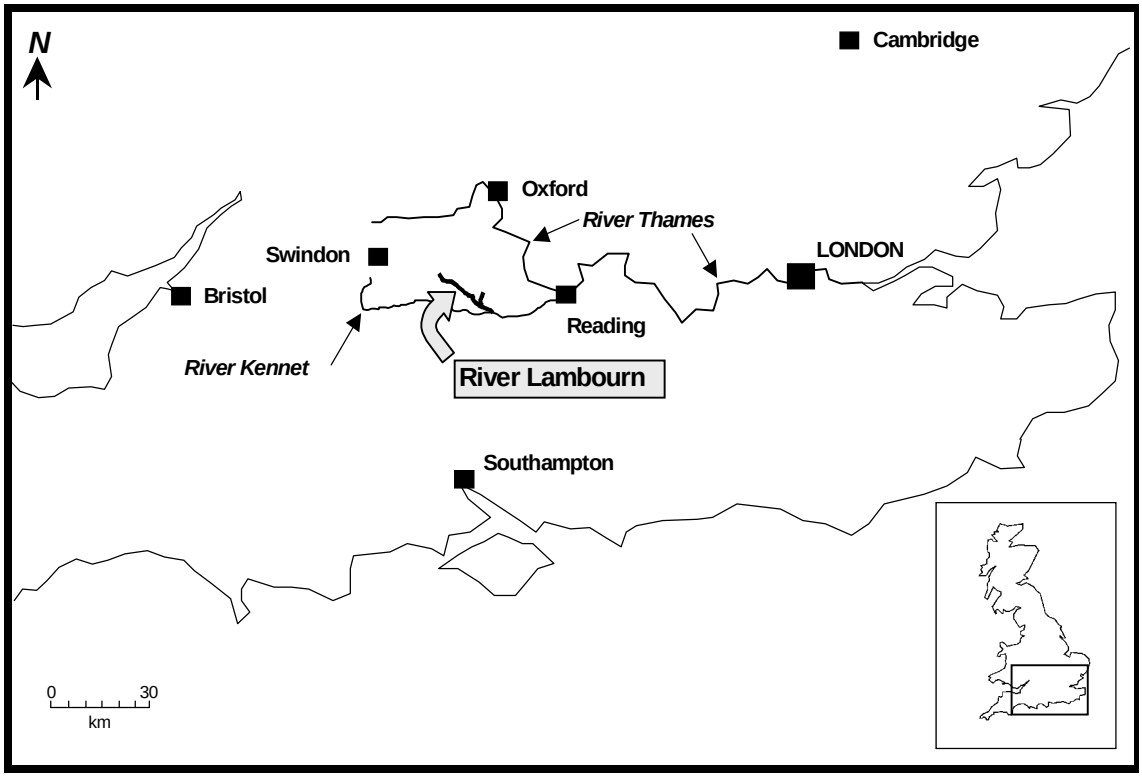


Figure 3.1 The regional location of the River Lambourn

Topographically, the catchment is 234km^2 in area and comprises rolling hills that are dissected by a dense, dendritic network of dry valleys. Elevations in the catchment range from over 250mOD in the north and north-west to around 70mOD in the south-east (Figure 3.2).

The River Lambourn is characterised by an apparently near-natural flow regime, and 71% of its channel is classified as "retaining geomorphological diversity, and a gravel bed" (NERC, 1998). The River Lambourn was notified as a Site of Special Scientific Interest (SSSI) in 1995, and is considered a classic example of a lowland chalk river. The upper 8 to 10km of the river are seasonal, forming a characteristic winterbourne that normally experiences an absence of flow for three months of the year, in late summer. The flora is naturally poor in these upper reaches and includes pond water crowfoot (*Ranunculus peltatus*) and fool's watercress (*Apium nodiflorum*). In the middle and lower perennial reaches of the river (extending for some 15km) the aquatic flora are

typical of shallow, gravel bed channels; and include river water crowfoot (*Ranunculus penicillatus*), and lesser water parsnip (*Berula erecta*). The invertebrate fauna are typical of a calcareous watercourse, and have been studied extensively by Wright (e.g. Wright & Symes, 1999).

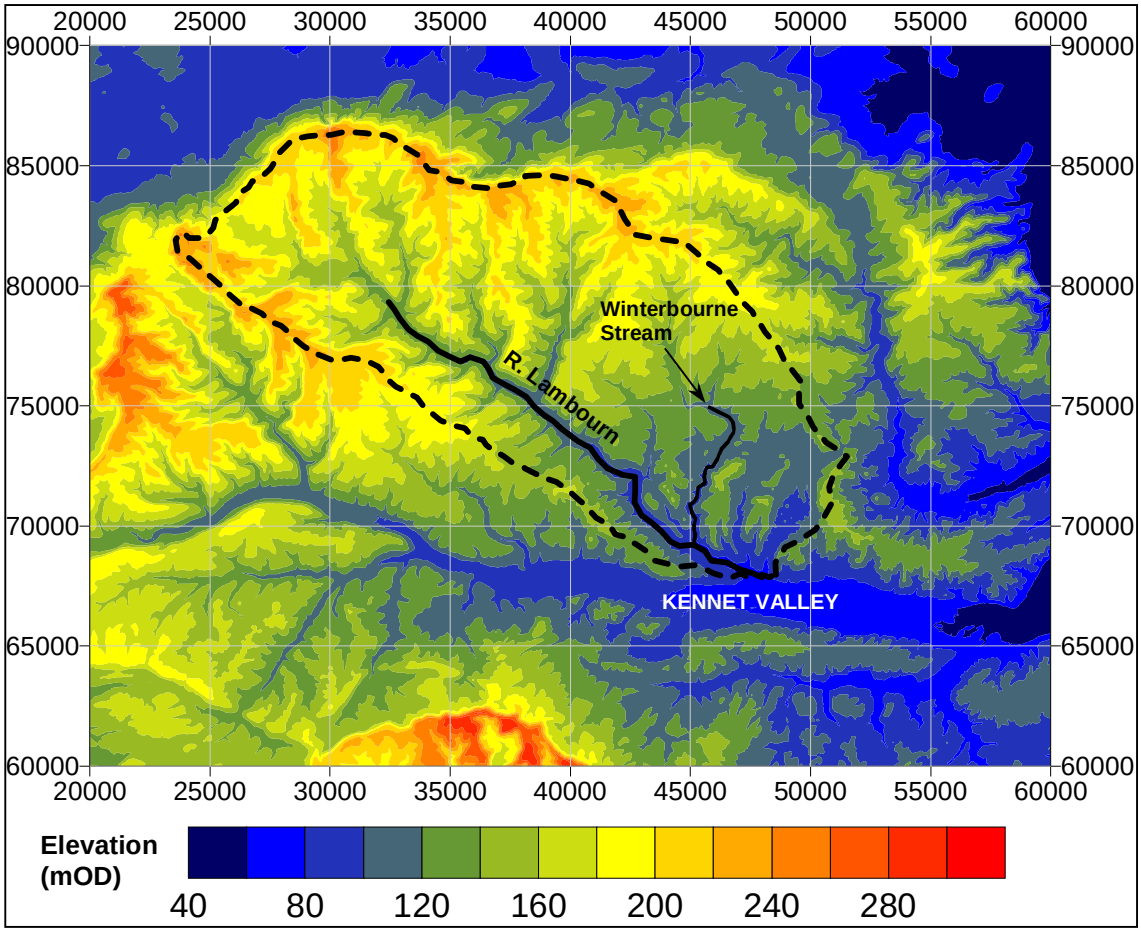


Figure 3.2 Topography of the West Berkshire Downs and the surface water catchment of the River Lambourn

Based on digital spatial data licensed from the Institute of Hydrology, © IH; includes material based on Ordnance Survey 1:50,000 maps, © Crown Copyright (0186A)

[The grid is based upon Ordnance Survey *Landranger* co-ordinates for square SU, with a major interval of 5km]

The floodplain of the Lambourn is separately notified as a SSSI, together with the Kennet floodplain, principally given its significance as habitat for the Desmoulin whorl snail (*Vertico moulinsinia*).

The landuse in the catchment is a mixture of fine pasture, employed for livestock grazing, and arable cultivation, mainly comprising cereal crops. There are also a number of gallops consisting of improved pastureland, used for exercising racehorses,

particularly on the downland around Lambourn village and East Garston. Plates I and II, showing examples of landuse in the catchment, are presented below.

Plate I A view to the west from SU 338 837 across the upper part of the Lambourn catchment in January 2000 showing the rolling nature of the landscape, dominated by grassland and arable cultivation, with very limited tree cover

Plate II A view to the north east from SU 378 754 across the Lambourn Valley upstream of Great Shefford in January 2000 showing rough pasture on the valley floor, improved pasture on the lower valley slope in the foreground and fields prepared for arable cultivation on the far valley slope

Localised areas of woodland occur in the lower part of the catchment, especially on the ridge crest to the south of the river and in the catchment of the Winterbourne

Stream. The increase in tree cover reflects the presence of low permeability, Tertiary deposits that overly the chalk in these areas, rendering them less suitable for agriculture.

The only significant urban area in the catchment is the town of Newbury, which is located on the south-eastern margin of the catchment at the confluence of the River Lambourn with the River Kennet (Figure 3.6). The largest villages in the catchment are Lambourn and Great Shefford, both located on the river, with populations in 2001 of 4265 and 970 respectively (WBDC, 2001). There are a number of more minor settlements, both along the river and up on the downs, but their combined population does not exceed 5000.

3.2.1 Geology

Lithology

The Chalk Formation, whose general properties were described Section 2.4.2, is present beneath the whole of the Lambourn catchment, although its visible presence at the ground surface is rare, being restricted to occasional small areas in the bed and banks of the river. A simplified geological map of the catchment is shown in Figure 3.3 and a longitudinal section down the Lambourn valley is given in Figure 3.4. The majority of the Lambourn catchment is directly underlain by the Upper Chalk, whilst the Middle Chalk outcrops only in the north-east of the catchment, although both divisions are extensively intersected in boreholes. The Lower Chalk has a very small area of outcrop, and is intersected in only a small number of deep boreholes.

A stratigraphic column for the Berkshire Downs area, using the traditional Chalk nomenclature, is presented in Figure 3.5. A new stratigraphy of the Chalk has been defined by Bristow *et al*. (1997), and is slowly gaining in popularity, including its use in the recent remapping of the Pang / Lambourn catchments by the British Geological Survey, described by Aldiss and Royse (2002). However, the traditional nomenclature is more relevant in the hydrogeological context in which the Chalk is being described here, for example with reference to the hardgrounds of the Chalk Rock and Melbourn Rock, which are not specifically recognised in the new stratigraphic system.

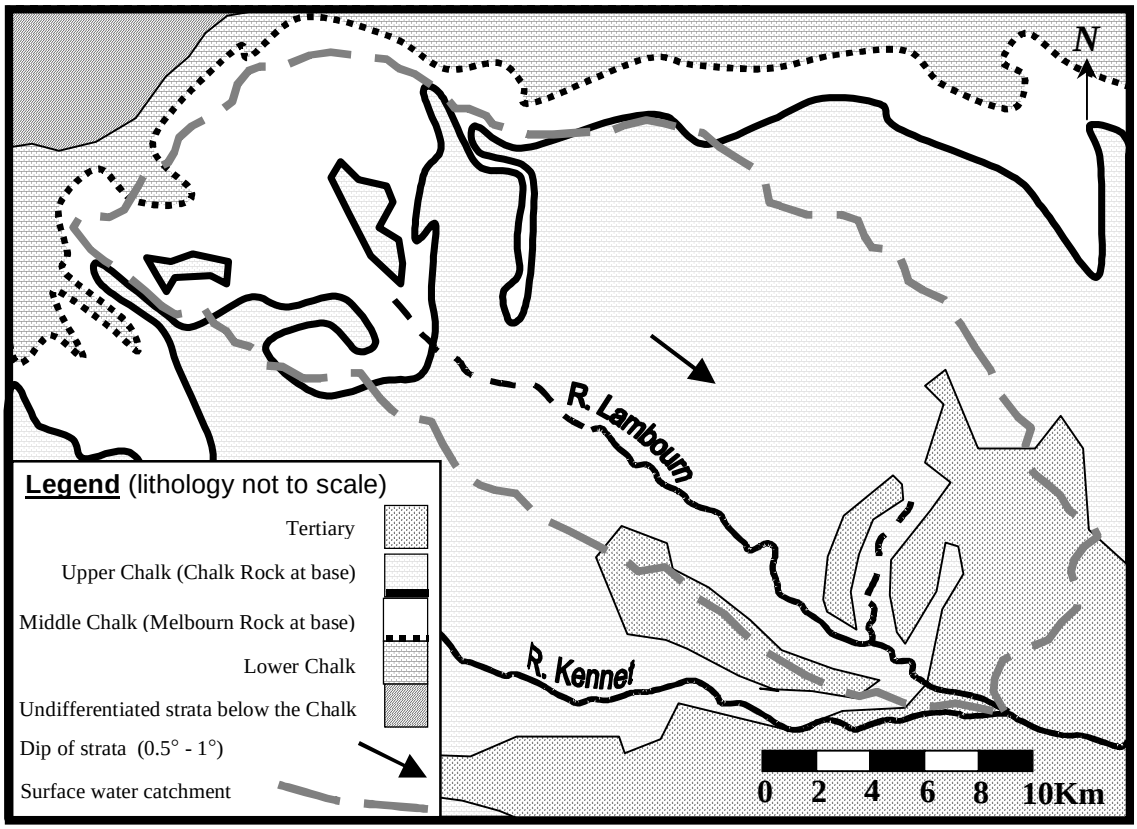


Figure 3.3 Simplified geological map of the Lambourn catchment
(based upon British Geological Survey 1:50 000 scale sheets 253: Abingdon and 267: Hungerford)

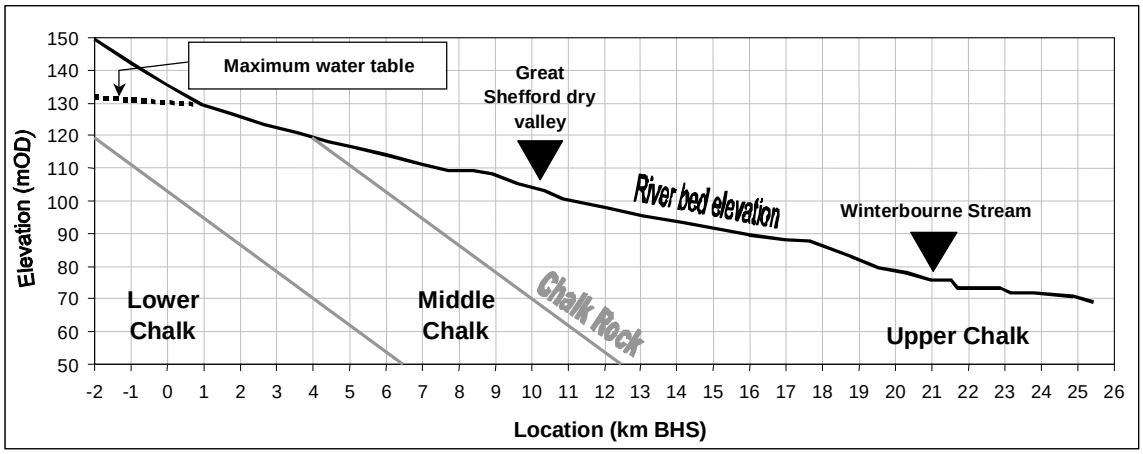


Figure 3.4 Schematic longitudinal section along the Lambourn valley from north west to south east
(BHS relates to the distance Below Highest Source of the River Lambourn)

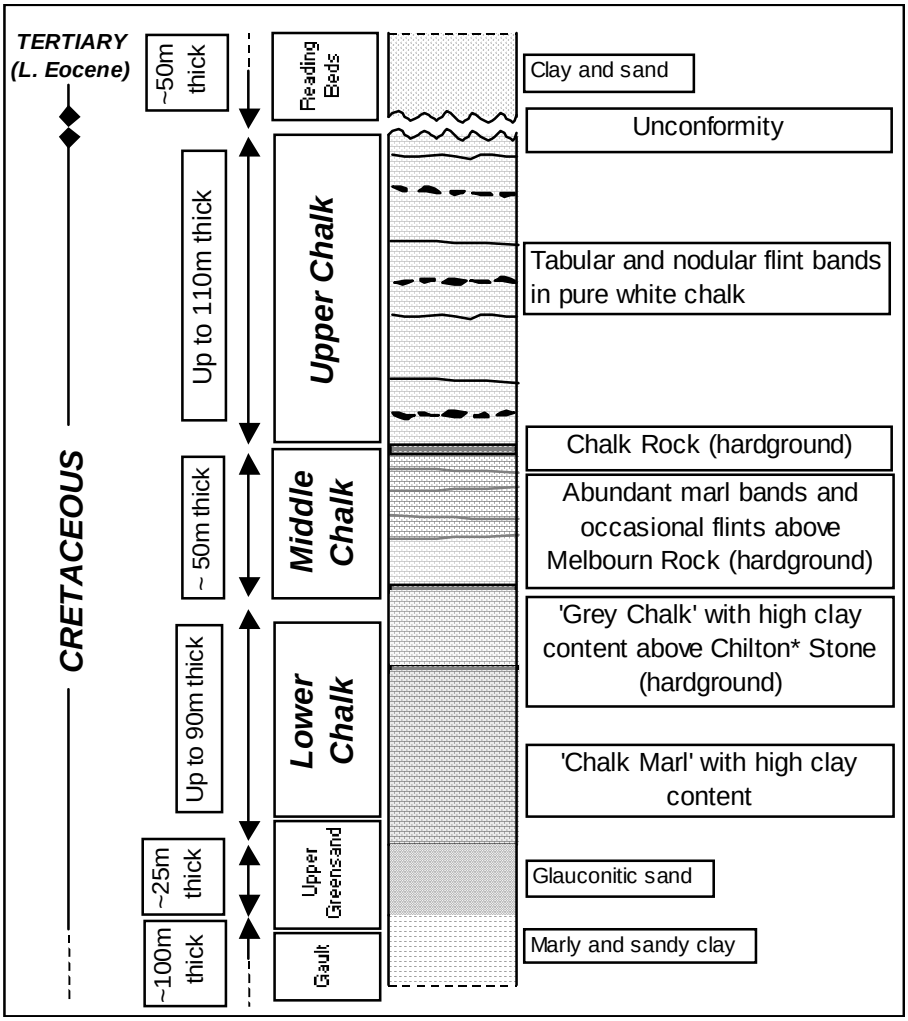


Figure 3.5 Generalised stratigraphic column for the West Berkshire Downs
(*Local designation for the Totternhoe Stone)

The Upper Chalk is the thickest of the three divisions beneath the Lambourn Catchment, and also has the lowest content of argillaceous material. However, it contains the largest number flints (chert) of the three divisions, and these can occur either as discrete nodules or as tabular bands. At the base of the Upper Chalk is the Chalk Rock, a limestone band or hardground comprising indurated chalk up to 3m thick. The Middle Chalk is less than half the thickness of the overlying division and is characterised by numerous thin bands of marl (calcareous mudstone) and by the presence of a much reduced number of flints. At its base is the Melbourn Rock, a hard, white, porcellaneous limestone up to 2.5m thick. The Lower Chalk contains a far higher propertion of argillaceous material than the upper two divisions and consequently is of much lower permeability. Due to its depth of burial (>50m) under most of the catchment

area it has little significance for this study (Brettell, 1971). Beneath the Chalk Formation is the Upper Greensand, a thin glauconitic sand unit that outcrops at the base of the chalk escarpment. Underlying this is the Gault, a thick clay formation, which together with the underlying Jurassic clays, forms the low lying ground of the Vale of the White Horse and the Oxfordshire Plain to the north of the chalk escarpment.

In the Lambourn catchment, a number of younger deposits overlie the chalk bedrock, and these include:

- Muds and sands comprising the Reading Beds of Eocene age (laid down 53 to 38 million years ago) that unconformably overlie the Upper Chalk in the lower part of the catchment;
- Periglacially-derived head deposits (coombe rock) comprising structureless chalk (transported locally by solifluction), which coat the floors of some dry valleys;
- Clay with flints (a product of in-situ chalk dissolution) that mantle the Upper Chalk on higher ground throughout the catchment;
- River gravels and fine alluvial material, which occur discontinuously on the floor of the Lambourn valley and in some of the principal dry valleys in the catchment.

Soils within the Lambourn catchment are generally less than 0.5m thick, and consist of two main soil types: Hornbeam 2 and Andover 1. The Hornbeam 2 unit includes clay soils (clay with flints comprising 23.5%), which occur on the ridge of the southern catchment divide and on the higher ground of the Winterbourne catchment. The Andover 1 type includes the chalk soils that occur in the upper part of the catchment and on the downs surrounding Lambourn village (Soil Survey of England and Wales, 1983).

Structure

The Lambourn catchment lies on the northern flank of the London Basin syncline, close to its western extremity. The large-scale geological structure of the area is straightforward, with the Chalk dipping at a shallow angle (0.5 - 1°) to the south-east or

SSE. At depth, the whole of the Middle and Lower Thames Valley rests upon the London Platform, part of an upstanding regional massif, which is supported by either low-density strata at depth, or by an upstanding block of Carboniferous age. The presence of this underlying feature produced draping-related structures in the overlying strata on its flanks (Anderton *et al.*, 1979; p. 243). Reactivation of such structures, in addition to inherited Carboniferous structures, is likely to exert a significant control on the major discontinuities in the Chalk. Certainly Tertiary deformation has been recognised as reactivation of earlier structures throughout southern England, including in close proximity to West Berkshire (e.g. the Pewsey anticline) (*ibid*; p. 255, 256).

The near perfect straight line of the Lambourn valley strongly suggests an underlying structural control, and its orientation closely parallels the strike of Carboniferous (Westphalian) strata, which underlie the area at depth. These strata were intersected in the lower half of a 1300m deep borehole drilled at the (former) Welford Park Station, close to the centre of the Lambourn catchment (Foster *et al.*, 1989). At this location, the base of the Westphalian strata is dipping steeply to the south-west at the edge of the Berkshire Syncline (*ibid*; Figure 2), which makes it a potential location for the occurrence of a drape structure at the margin of the Carboniferous basement block. It seems likely that the upward migration of such a structure into the overlying Mesozoic strata, and the enhanced fracturing that would be expected to result, are the underlying controls on the formation of the Lambourn Valley. The lack of recognised displacement in the Cainozoic strata of the Lambourn Valley is consistent with the low displacement characteristic of a drape structure.

3.2.2 Hydrology

The River Lambourn is a major tributary of the River Kennet, which is itself a tributary of the River Thames. The Lambourn displays characteristics typical of chalk streams, which are dominated by interaction with the underlying regional chalk aquifer. Aquifer storage exerts a strong temporal control on chalk stream flow regimes by buffering variability in recharge timing and intensity (Sear *et al.*, 1999). As a result, the River Lambourn has a stable flow regime with a Mean Annual Flood to Mean Flow Ratio of 2.1, whilst its value of Q_{95} represents 46% of its mean flow.

Spatial characteristics

Figure 3.6 shows the surface water catchment of the River Lambourn, which is 234.1 km^2 to its lowest gauging station at Shaw (**A**). The National River Flow Archive (NRFA) station summary sheets for Shaw and the other gauging stations in the Lambourn catchment (Bagnor [**B**], Welford [**C**] and East Shefford [**D**]) are presented in Appendix 2, with summary details given in Table 3.1 below.

Gauging station	Grid reference†	Location (km BHS*)	Catchment area (km^2)
East Shefford	SU 390 475	10.90	154.0
Welford	SU 411 731	13.85	176.0
Shaw	SU 470 682	23.35	234.1
Bagnor	SU 453 694	N/a (on Winterbourne Stream)	49.2

Table 3.1 Summary details of gauging stations within the Lambourn catchment
(†from NRFA summary sheets; *BHS is distance Below Highest Source)

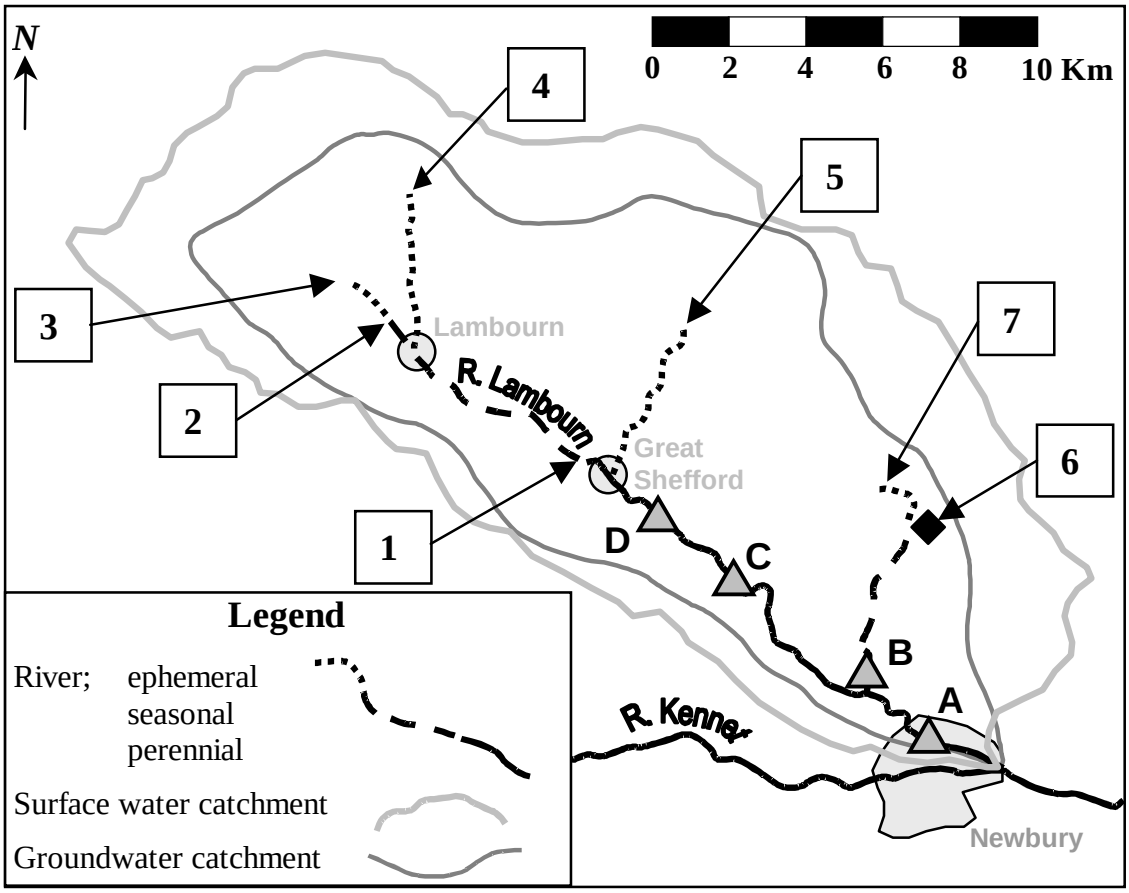


Figure 3.6 Hydrological characteristics of the Lambourn catchment
(see text for key to numbering)

The normal perennial source of the River Lambourn (**1** in Figure 3.6) is situated in the reach upstream of Great Shefford, although in August 1976, owing to the exceptionally low groundwater levels, the source temporarily migrated some 2km downstream below East Shefford gauging weir. The seasonal source of the river lies immediately upstream of Lambourn village at a series of springs in Lynch Wood (**2**). This location normally represents the source of the river between December and September in each hydrological year. In October and November, the source normally migrates towards the perennial location above Great Shefford. In years preceded by winters with above average recharge, the springs maintain their flow through to the onset of the next recharge period. This occurred in 1985, 1993 and 2000, so that there was continuous discharge from the seasonal source for a period of about 18 months. However, in years with low winter recharge, the springs cease to flow for periods of over 12 months, which occurred in 1991/1992 and between 1996 and 1998.

In exceptionally wet years, the source of the river migrates 1.9km upstream from Lynch Wood to the highest head location in the hamlet of Upper Lambourn (**3**). At these times of high groundwater levels, surface water flow can also occur in some of the principal dry valleys of the catchment, particularly in the Seven Barrows valley north of Lambourn and in the Great Shefford valley to the north north-east of Great Shefford. In the early months of 2001, groundwater levels were at their highest for at least 30 years and ephemeral streams extended up the Seven Barrows valley as far as Westcot Down (**4**) and up the Great Shefford valley to Woolley Down (**5**), details of which are given in Table 3.2.

The single permanent tributary of the Lambourn, the Winterbourne Stream, has a short perennial section of around 1km. The upstream, seasonal section of the Winterbourne receives a significant portion of its discharge as effluent from Chieveley sewage treatment works (**6**). Occasionally an ephemeral section of channel upstream of this point is active and at its maximum extent, the Winterbourne rises at Chapel Wood (**7**).

Water course	Location name	Significance	Elevation (mOD)	Distance from Upper Lambourn (km BHS+)	Average gradient to the Kennet (m/km)
River Lambourn	Upper Lambourn	Highest source location of River Lambourn	133	0	2.4
	Lynch Wood springs	Seasonal source location of River Lambourn	124	1.9	2.3
	West Shefford	Perennial source of River Lambourn	107	9.4	2.5
	Bagnor	Confluence of Winterbourne Stream and River Lambourn	80	21.1	2.1
	Newbury	Confluence of River Lambourn with River Kennet	70	25.8	N/a
Winterbourne Stream and ephemeral dry valleys	Westcot Down	Highest flow location in Seven Barrows valley	158	*4.5	*7.3
	Woolley Down	Highest flow location in the Great Shefford valley	144	*6.3	*6.2
	Chapel Wood	Highest source of Winterbourne Stream	109	*7.5	*3.9
	Chieveley STW	Seasonal source of Winterbourne Stream	104	*5.6	*4.3
	Bagnor Marsh	Perennial source of Winterbourne Stream	84	*1.0	*4.0

Table 3.2 Characteristics of key hydrological locations in the Lambourn catchment
+BHS = **B**elow **H**ighest **S**ource location
*from designated location to the channel of the River Lambourn

Due to the permeable nature of the underlying chalk aquifer, the Lambourn catchment has a low, but variable drainage density (Table 3.3). For comparison, the total drainage length of a typical impermeable catchment of equivalent size would exceed 250km (Gregory & Walling, 1973; Figure 5.12, p. 273), which is five times higher than the maximum drainage length of the Lambourn catchment and more than twelve times its perennial channel length.

Source Location	Length of River Lambourn (km)	Length of Winterbourne Stream (km)	Length of ephemeral streams (km)	Total length of drainage network (km)	Drainage density (km/km^2)*
Perennial	17.1	1.0	0	18.1	0.08
Seasonal	23.9	5.6	0	29.5	0.13
Maximum ephemeral	25.8	7.5	10.8	44.1	0.19

Table 3.3 Variation in the drainage network properties
*based upon the surface water catchment of $234km^2$

Temporal characteristics

Owing to the buffering effects of the underlying chalk aquifer, the River Lambourn has a stable flow regime, with a well defined seasonal discharge pattern, which is illustrated in Figure 3.7.

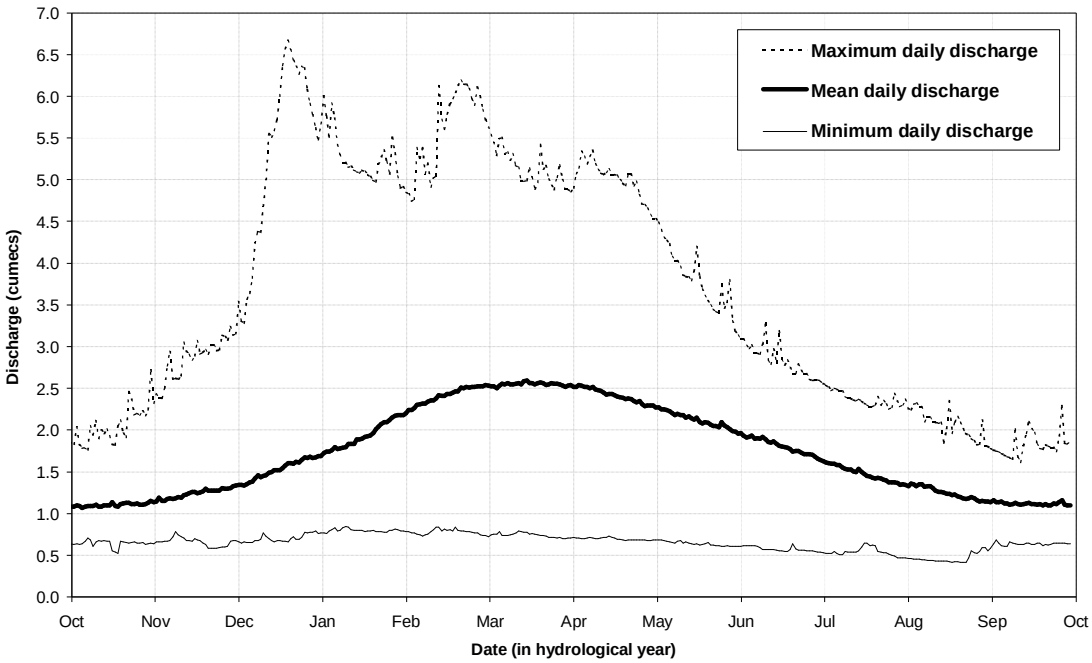


Figure 3.7 Maximum, mean and minimum daily discharges at Shaw gauging station for the period 01/10/62 to 30/09/01

The plot of mean daily discharge shows the normal seasonal pattern, with peak flows of around 2.5 cumecs in February, March and April, and low flows of around 1.1 cumecs in September and October. The maximum plot shows that significant increases in discharge, after the onset of autumn recharge, do not occur before the beginning of December, but peak flows can occur at any time between mid-December and mid-April. In periods experiencing above average recharge, discharge may remain above 1.5 cumecs for most of the year. The minimum plot shows very little variability, indicating that there is a consistent baseflow component of around 0.5 to 0.8 cumecs at all times of year, regardless of climatic extremes.

Rainfall and recharge

The average annual rainfall (1961-1990) for the Lambourn at Shaw is 736mm, whilst the long-term mean flow (1962-2003), which equates to long-term recharge, is 1.76 cumecs (NRFA, 2003). Using the surface water catchment area of 234.1km^2, this

flow equates to a mean annual recharge of 228mm, giving a recharge rate of 31%, if the differing periods of record are ignored. If the groundwater catchment area of 168km^2 is used, the mean annual recharge increases to 314mm and the recharge rate rises to 43%.

3.2.3 Hydrogeology

The chalk beneath the Lambourn catchment forms part of a regional aquifer, which is the most important in the UK in terms of water supply (Downing, 1998), and whose general properties have been described in Section 2.4.2. Most groundwater flow in the Lambourn catchment occurs in the Upper and Middle Chalk, whilst the Lower Chalk, because of its lithology and burial depth, effectively functions as an aquitard, except in the uppermost portions of the catchment. Transmissivity and storage in the catchment follow the recognised pattern, being elevated beneath valleys and reduced beneath interfluve locations.

Hardgrounds are generally recognised to exert a strong influence over flow in the chalk, and Price (1987) ascribes to them enhanced permeability, relative to the surrounding strata, due to their higher degree of cementation producing cleaner fractures. This hypothesis appears to contradict data from extensive geophysical logging of boreholes in the Lambourn catchment (e.g. Tate *et al.*, 1971), which indicates that there is high sub-horizontal permeability **adjacent to**, but not within, hardgrounds. This geophysical-based evidence also suggests that the vertical permeability of hardgrounds is very limited, because they normally form the base of the effective aquifer, which is clearly demonstrated by flow, temperature and EC logs. Thus hardgrounds in the Lambourn catchment, particularly the Chalk Rock, act to divide the chalk aquifer into layers with differing properties. The fact that horizontal permeability is enhanced where vertical permeability is restricted suggests that vertical gradients are present within the aquifer, but that water is being forced to move laterally above or below hardgrounds (leading to preferential parallel development) depending upon whether the location is in a recharge or discharge area.

The Chalk Rock is locally the most important hardground and based upon flow logging in a number of boreholes, it appears to control the base of the active aquifer in the middle and lower reaches of the catchment (Tate *et al.*, 1971). Its influence can be observed from two boreholes: SU37/1 at Great Shefford in the middle of the catchment

and SU46/4G near Newbury, just beyond the southern margin of the Lambourn catchment. The Chalk Rock marks the base of the active flow system in both boreholes, being at 30m below ground in SU37/1 (*ibid*) but at over 100m below ground in SU46/4G (Tate *et al.*, 1970). Thus, the recognised thickness of 50 - 60m for the active flow zone can be locally modified by the presence of a dominant hardground.

The prevailing groundwater flow direction beneath the Lambourn catchment is to the south-east. This is parallel to the orientation of the river valley and to the shallow regional dip of the chalk. At the lower end of the catchment, the Chalk is overlain by Tertiary deposits and the aquifer becomes confined to the south of Newbury.

In order to define the boundaries of the hydrogeological system of the River Lambourn, work was undertaken to delineate the local groundwater catchment, a procedure analogous to the definition of a surface water catchment, but using groundwater levels in place of topographic elevations. The groundwater catchment outline shown in Figure 3.6 was defined from average groundwater levels in 111 boreholes. Elevations of twelve scarp slope springs, in addition to river bed elevations from the River Lambourn, the Winterbourne Stream and the River Kennet were also used to define the water table surface, the latter being derived from a hydrologically-focused digital elevation model (Morris & Flavin, 1990; 1994) [supplied under license by CEH – Wallingford]. The data points used are shown in Figure 3.8. The data were interpolated on a 500-metre grid using the *Surfer* software package to produce a contour map of average groundwater levels across the catchment. The boundaries of the groundwater catchment were then drawn 'by-eye', based on the premise of constructing conceptual groundwater flowlines (to the catchment outlet) that intersect groundwater contours at right angles. The catchment area defined was then measured (by counting squares) as 168km^2, representing 72% of the surface water catchment. The same procedure was also undertaken for maximum and minimum water levels, and whilst the shape of the groundwater catchment was found to vary, the actual area of the catchment remained constant to within a few square kilometres. Consequently, the average area has been used for calculations throughout this study.

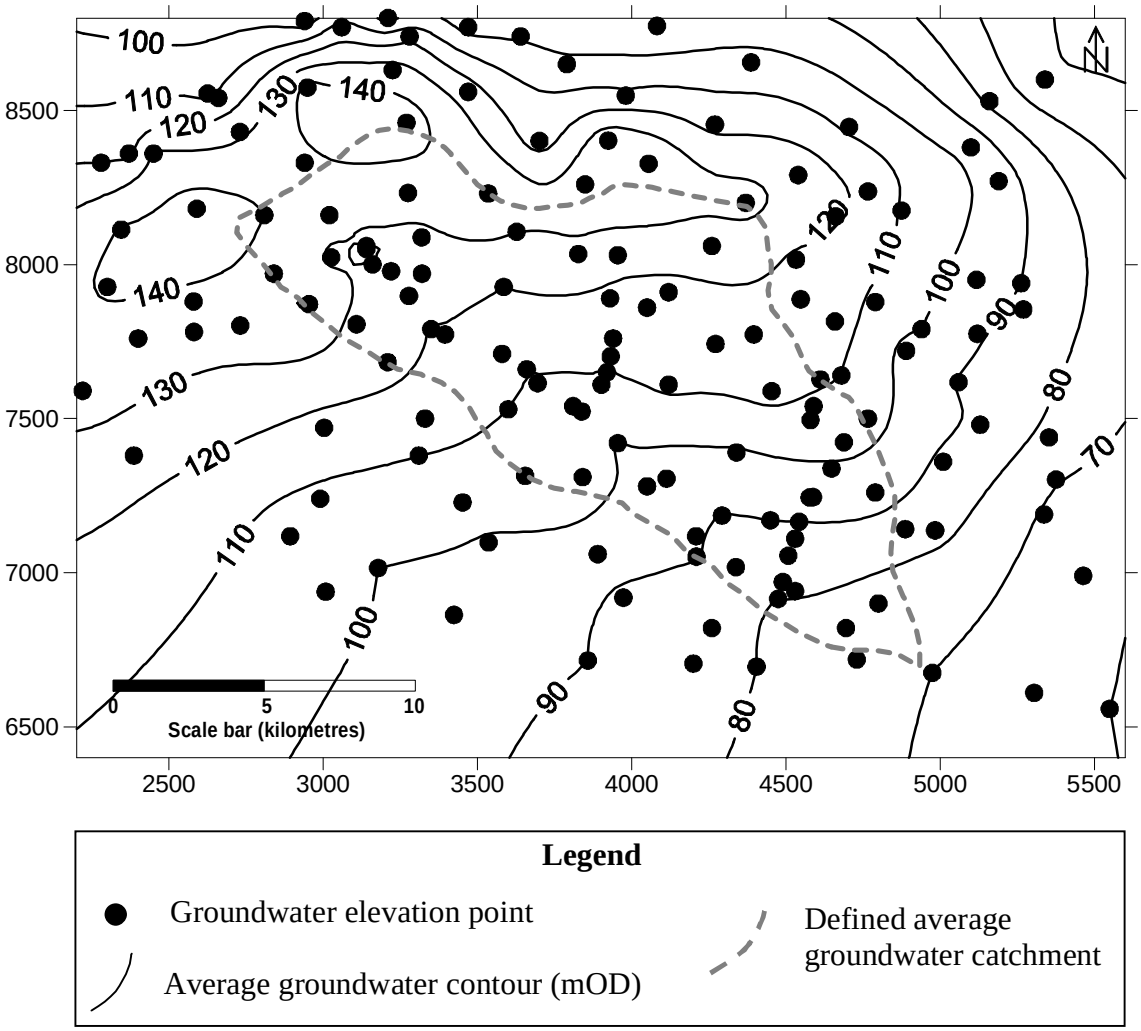


Figure 3.8 Groundwater elevation points used in plotting of average groundwater contours and the average groundwater catchment
(The axis labels are Ordnance Survey *Landranger* co-ordinates for square SU, with units of 10's of metres, giving major axis intervals of 5km)

Whilst groundwater catchments can never be as well defined as surface water catchments, given the difficulties in defining the elevation of the water table to the same degree of accuracy as a topographic surface, the number of data points used in this study are considerably higher than the number normally available for such procedures. In this context, the definition of the groundwater catchment in this study is a justifiable and necessary element to characterising the local groundwater system.

Taking a more general perspective, there is the question of how representative the Lambourn catchment might be of chalk catchments in general. This is particularly important if results and interpretations from this study are to be extended to other catchments. Importantly, Owen (1981) considered the chalk aquifer in the lower

Lambourn catchment to be unrepresentative of the chalk in the western London basin. Geophysical logging of boreholes drilled in the lower Lambourn catchment showed that the effective aquifer was anomalously thick (up to 100m), and that transmissivity and storativity were atypically high compared with results from the wider area (given in Table 3.4). This may influence patterns of interaction between the aquifer and the river in the lower part of the catchment, but its significance to this study is thought to be limited as most of the work was undertaken in the upper and middle reaches of the river.

Parameter / **Location**	**Median transmissivity (m^2/d)**	**Median Storage Coefficient (%)**
Lambourn catchment*	1490	1.50[+]
Kennet Valley[†]	830	0.75
Thames Valley[†]	650	0.58
All Chalk provinces[†]	650	0.40

Table 3.4 Comparison of chalk aquifer properties from the Lambourn catchment, Kennet Valley, Thames Valley and all Chalk provinces
*Mean values from Brettell, 1971 [+]Specific Yield
[†]From MacDonald & Allen, 2001

3.2.4 Historic groundwater resource evaluation in the Lambourn catchment

Several stages of hydrogeological investigation for a flow augmentation scheme took place in the West Berkshire Downs between 1967 and 1976. The plans for the scheme anticipated the use of groundwater pumped from under-exploited aquifers in the Kennet basin to supply London during drought, using the Thames and its tributaries as natural 'pipelines' to convey the water to the city. Given the magnitude and experimental character of the proposed scheme, it was decided to first undertake a pilot study (subsequently known as the Lambourn Valley Pilot Scheme; LVPS) to assess its feasibility. The results of the LVPS, whilst not as favourable as initially predicted, indicated that between 11 and 15 x 10^6 m^3 of water would be available under drought conditions for flow augmentation (Brettell, 1971).

On conclusion of the pilot scheme, work then began to implement the full Thames Groundwater Scheme (TGS), with the Lambourn catchment representing a major component. The TGS was authorised in March 1973, with drilling and test pumping being undertaken between 1973 and 1976 (Hardcastle, 1978). In total, 43

abstraction boreholes and 67 observation boreholes were drilled for the LVPS and TGS. In addition, four permanent gauging structures were installed in the Lambourn catchment; at East Shefford, Welford and Shaw on the River Lambourn, and at Bagnor on the Winterbourne Stream.

In August 1976, the TGS was brought into emergency operation to provide river augmentation due to the exceptionally low recharge of the preceding winter. It was pumped for three months and provided nearly 7 x 10^6 m^3 of water for flow augmentation (Hardcastle, 1978), at an average rate of 0.85 cumecs, representing around 50% of the average discharge in the River Lambourn. Various aspects of the TGS have been described in the literature, for example; infrastructure development (*ibid*), characterisation of the Chalk aquifer (Owen & Robinson, 1978), hydrograph analysis (Mander & Greenfield, 1978), groundwater modelling (Oakes & Pontin, 1976), groundwater resource evaluation (Owen, 1981).

The scheme (now designated the West Berkshire Groundwater Scheme) was last operated for a period of 24 days in September 1989 (when it yielded a total of 1.5 x 10^6 m^3 of water; Owen, 1990) but the infrastructure is still maintained on an on-going basis. A more detailed history of the groundwater resource investigations is given in Appendix 3.

3.2.5 The current hydrological condition of the catchment

There has been little further development of groundwater resources within the Lambourn catchment following installation of the infrastructure associated with the TGS. Thames Water abstracts limited quantities for public water supply (PWS) from two sources in the extreme north west of the catchment, (Fognam Down, SU 296 802; Ashdown Park, SU 288 811), both having annual licensed abstractions of just below 100,000m^3. In recent years, actual abstraction from both sources has been below the licensed quantities, which together represent less than 4% of annual average catchment discharge.

In addition to the PWS sources, there is only one other licensed abstraction in the catchment, for either groundwater or surface water, which exceeds 100,000m^3 per annum. This is a surface water abstraction for Lambourn Valley Trout Farm (SU 455 690) of 2.745 x 10^6 m^3. As this is non-consumptive, it has little impact

volumetrically upon the flow regime, although it may influence water quality in the lowest few kilometres of the river.

Other anthropogenic influences, that could potentially impact the flow regime of the River Lambourn (particularly water quality), include effluent discharge from sewage treatment works, and runoff from roads and agricultural land. There are four sewage treatment works (STWs) in the catchment (detailed in Appendix 4) and their mean combined discharge represents around 2% of the mean flow of the River Lambourn.

Although much of the Lambourn catchment remains as grazing land or open grassy downland, there is some arable cultivation on or adjacent to the floodplain, especially along the ephemeral section of the river between Lambourn village and Great Shefford. During fieldwork for this study, it was observed that in the upper part of the ephemeral channel the bed was extensively coated with fine sediment and even in the lower, perennial section of the river, silt mantled the banks in all but the fastest flowing sections, indicating a significant store of fine material. However, data from the Environment Agency (plotted in Appendix 5) shows that suspended sediment concentrations are generally less than 10mg/l, suggesting that there are few effects from fine sediment relative to impacted rivers such as the Test and upper Piddle (Acornley & Sear, 1999; Walling & Amos, 1999, respectively).

Throughout the catchment, drainage from minor roads is directed into the river, but this appears to have little impact. Road drainage does present a potential problem for water quality in the lower reaches of the river (below Bagnor), as here it receives run-off from the A34 Newbury Bypass, but balancing ponds are used to filter the run-off prior to discharge. Overall, considering the various stresses to which the River Lambourn is exposed, it appears from the measures of river 'health' detailed above that the river retains a high degree of naturalness, at least in its upper and middle reaches.

3.3 SELECTION OF RESEARCH METHODS

3.3.1 Objectives and practical implementation

The overarching aim of this study is to improve understanding of the processes controlling groundwater – river interaction in the Lambourn catchment. To fulfil this aim requires implementation of the objectives outlined in Chapter 1, which are summarised below:

1. To investigate the bulk flow dynamics of the Lambourn catchment by elucidating temporal characteristics of the recharge – storage – discharge sequence;
2. To use spatially averaged groundwater level data to estimate catchment discharge, as a means of providing a baseline flow regime for an impacted catchment;
3. To investigate spatial influences on river - aquifer interaction through correlating the longitudinal pattern of groundwater – river exchange with topographic, geological and hydrological variables;
4. To assess the application of Darcy's Law, in the context of river – aquifer exchange, by calculating bulk hydraulic conductivity values for valley floor deposits;
5. To use a numerical groundwater model of the Lambourn catchment to investigate the influence of aquifer properties on flow exchange, and the sensitivity of the flow accretion pattern to valley floor controls;
6. To broaden the knowledge of chalk flow dynamics by proposing an expanded conceptual model of flow paths from recharge to discharge.

The practical implementation of these objectives falls into three broad areas of field investigation:

a) Identifying the location and direction of flow exchanges;

b) Identifying the magnitude and temporal variability of water fluxes;

c) Identifying the potential pathways for flow exchange.

The potential methodologies available in each area of field investigation, and those utilised in this study, are described below, some extending upon their generic descriptions presented in Chapter 2. The methodologies generally fall into two categories; direct or indirect. Direct methods measure the relevant parameter itself, whilst indirect techniques measure one or more alternative parameters from which the desired variable can then be calculated.

3.3.2 Methodology: selection and justification

Identifying the location and direction of flow exchanges: <u>direct methods</u>

Three direct methods would be appropriate for this objective: upwelling groundwater could be monitored directly via **seepage meters**; in-channel vertical flow components could be detected via **multi-axis flow metering**; and water exchange could be identified using appropriate **tracers**.

The first method, although possibly useful, was not attempted as it was considered that there are serious questions concerning the representativeness of results from seepage meters, which are explored in Section 2.3.2.

Multi-axis flow metering, to identify vertical flows, was attempted at several locations, but was found to be impractical. The equipment was too unwieldy to be used for reconnaissance work, which required surveying the variability in vertical flows over a 100m length of channel. The instrument was also very sensitive, with minor discontinuities in the bed surface (e.g. pebbles) causing significant vertical flow components. The instrument was tested at several locations in a reach with known inflows and also in several locations in a reach with low inflows. The results were compared but no systematic differences between the two reaches could be detected.

A qualitative groundwater tracer test was undertaken to provide an independent means of assessing the location of groundwater discharges, to help fulfil objectives 3 and 4. An optical brightener tracer was injected into an observation borehole located 1.5km north east of the River Lambourn at Great Shefford. Monitoring took place for a period of 2 months after injection, using passive cotton detectors, but no tracer was detected. Tracer was still present in the injection borehole at the cessation of the monitoring period. The null result provided little insight into the local chalk aquifer flow system, but did demonstrate the difficulty of undertaking natural gradient tracer tests over significant distances. Full details of the tracer test are given in Appendix 6.

Identifying the location and direction of flow exchanges: <u>indirect methods</u>

Two indirect methods are appropriate to this objective: **non-continuous flow accretion profiling** and determination of **valley-floor hydraulic gradients**. The former was one of the most important methods used in the research as it provided a means of spatially identifying exchange locations. Over 2200 current meter gaugings had been

undertaken at fixed locations along the Lambourn during previous, flow augmentation-related investigations in the catchment, and these were the key resource to allow detailed flow accretion profiles to be plotted. Considering the number of historic gaugings that had been undertaken, it was considered an inappropriate use of field time to simply replicate the existing dataset. Instead, additional flow gauging was undertaken mainly to define rating relationships at locations where stage was continuously measured, but a larger number of gaugings were recorded at the headwater springs of the river, as this location had been historically under-represented in the current meter database.

Valley floor hydraulic gradients were also calculated, as they provided important information about a primary control on river - aquifer exchanges. Limited records of groundwater levels in close proximity to the River Lambourn were available from boreholes and piezometers installed during previous investigations, and these were supplemented by additional field data from this study. By measuring river stage elevations at these locations, aquifer – river hydraulic gradients could be defined and thus the potential direction and magnitude of exchanges could be estimated.

Identifying the magnitude and temporal variability of water fluxes

No reliable method is available to directly measure the magnitude of flow exchanges and thus the magnitude and variability of water fluxes were studied indirectly by **temporally continuous flow accretion profiling**, which was essential to assess the temporal variation in fluxes down the long profile of the river. Although the current meter database mentioned above provided a degree of temporal control, it was necessary to complement this with continuous flow records to improve temporal precision. Both historic and contemporary records of continuous discharge have been used in this study, including data from the three continuous monitoring sites set up specifically for this investigation. The establishment, calibration and maintenance of these three sites were the dominant focus of the field work element of the study and due to logistical and budgetary constraints other potential field elements were consequently restricted in scope.

Identifying the potential pathways for flow exchange: direct methods

This objective could be studied by two direct techniques: **geophysical surveying** and **quantitative tracer testing**.

Geophysical surveying could have provided valuable information for subsurface characterisation, but unfortunately, it was not possible to utilise it in this study due to time constraints. Resistivity profiling could have been used in valley floor locations to ascertain the depth to bedrock and provide detail on the morphology and lithology of alluvial deposits. Ground penetrating radar (GPR) could also have been used to provide information on the depth to the water table, and a detailed stratigraphy of the shallow alluvial material, but may have suffered from limited penetration where fine grained material (clays and silts) were present.

The second method could provide additional information on flow path geometries beyond that achievable by the non-quantitative (presence/absence) tracer testing mentioned above. However, it would require a large amount of tracer to be used, and continuous sampling to be carried out, in order to identify breakthrough curves. Given the status of the River Lambourn as a SSSI, it proved to be unfeasible to use a sufficiently large volume of tracer to permit a quantitative test, but a qualitative test, as previously described, was undertaken (with details given in Appendix 6).

Identifying the potential pathways for flow exchange: indirect methods

Two indirect techniques could be used to elucidate the pathways of water movement: they could be inferred from **sub-surface lithological data** or from **hydrochemical data**.

As it was not possible to undertake an extensive subsurface investigation during this study, characterisation of the subsurface was dependent upon historic data. These were derived from boreholes drilled during previous investigations and comprised lithological logs, geophysical logs and infrequent data from cored boreholes. Lithological data on the chalk bedrock was generally of reasonable quality, being sufficiently detailed to allow the major divisions of the Chalk to be recognised, but was much poorer for the alluvial deposits. Downhole geophysical data was particularly valuable in defining the levels of the principal inflow horizons, and identifying the effective base of the local aquifer system. However, the presence of solid casing, installed in most boreholes to a

depth of around 10m, prevented detailed characterisation of the shallow chalk and alluvial aquifer systems, where the interaction with the channel water actually occurs.

Water quality indicators offered the only practical means to identify the pathways and sources of exchanges on a catchment-wide basis. This was potentially critical in identifying whether discharges to the river consisted of recycled river water or chalk groundwater. The method assumed that water quality parameters could be used as natural tracers to identify the source of discharges. A limited number of hydrochemical samples were taken and analysed to provide values for alkalinity (essentially the concentration of bicarbonate: HCO_3^-) and pCO_2 (the partial pressure of CO_2 present, relative to atmospheric conditions). The results of this hydrochemical investigation represented a minor aspect of the overall research effort and have not been reported in this thesis due to space constraints.

3.3.3 Data requirements and availability

The data required for the selected investigative methods are described below in Table 3.5 and any shortfalls in data availability identified during the data review (i.e. prior to the field-work phase of this research) are indicated.

Selected method	Data requirement	Data availability	Data shortfall
Valley floor hydraulic gradients	Valley floor groundwater level data and proximal river stage elevation data	No suitable data	Need for measurement of combined groundwater levels and river stage from at least 1 site
Non-continuous flow accretion profiling.	Good spatial coverage of synchronous flow gaugings	Extensive historic database	Recent data
Qualitative tracer testing.	Records of successful tracer test in the catchment	None	Need for a test to be undertaken
Continuous flow accretion profiling.	Spatial coverage of continuous flow records	Good historic record for lower part of catchment, limited in upper part	Need for continuous flow records in the upper part of the catchment
Infer from subsurface data.	Borehole records	Numerous lithological logs and geophysical logs	None
Infer from water quality indicators.	Spatially distributed water quality data	Long record but at low frequency and spatially limited	Need for improved spatial and temporal measurement frequency

Table 3.5 Data requirements, availability and shortfalls

The shortfalls in data identified in the table above provide the focus for the fieldwork campaign, which is described below in Section 3.4. Given the history of research in the Lambourn Catchment a significant number of external datasets were available (summarised in Appendix 7).

3.4 METHODOLOGY FOR FIELD DATA COLLECTION

The objectives for the fieldwork were to satisfy the shortfalls in data outlined above (Table 3.5), which identified the need for:

- The combined measurement of groundwater levels and river stage at a number of locations;
- Continuous flow accretion data to complement the available current meter database;
- Monitoring of baseline water quality parameters;
- A qualitative groundwater tracer test.

3.4.1 Monitoring network description

Three continuous monitoring sites were instrumented specifically for this study. Their details are given in Table 3.6 and their locations are shown in Figure 3.9.

Site name	**Grid reference**	**Location** (km BHS*)	**Monitored parameters**	**Start date**	**End date**
West Shefford	SU 3812 7547	9.4	• River stage (discharge) • River temperature / electrical conductivity (EC) • Deep (chalk) groundwater level • Shallow (alluvial) groundwater level • Spring discharge, temperature / EC (*n/c*)	08/06/99	30/10/01
East Shefford	SU 3895 7457	10.9	• River stage (discharge) • River temperature / EC • Shallow (chalk) groundwater level (*n/c*) • Shallow groundwater temperature / EC (*n/c*)	27/05/99	30/10/01
Westbrook	SU 4268 7225	16.0	• River stage (discharge) • River temperature / EC	13/08/99	30/10/01

Table 3.6 Details of continuous monitoring sites
(*BHS = Below Highest Source of River Lambourn; *n/c* = non-continuous)

The sites to be continuously monitored were selected principally to provide data to meet the fieldwork objectives outlined above, but logistical considerations regarding access and existing infrastructure were also taken into account. The rationale for selection of each of the three sites is described below.

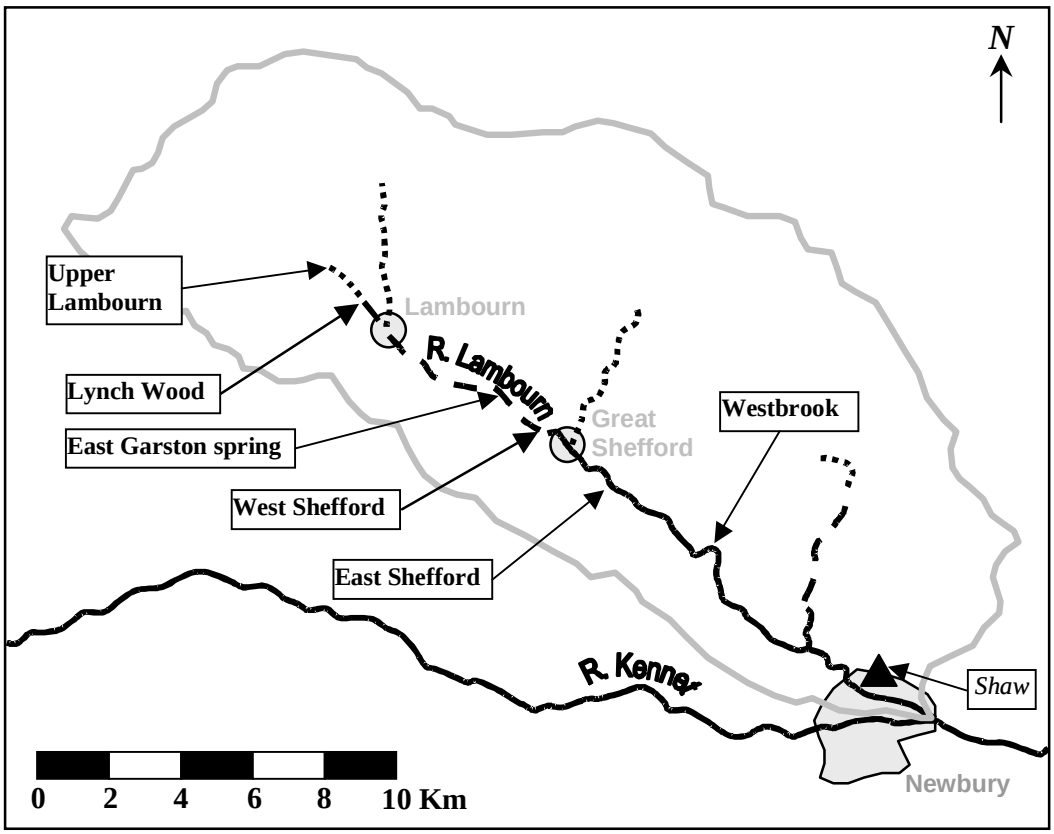


Figure 3.9 Locations of sites monitored for this study
(*Shaw* is the lowest gauging weir on the river, maintained by the EA)

West Shefford (Shefford Church) site

This site was chosen as it lay close to the perennial source of the river, described from previous investigative work (e.g. Brettell, 1971), and this was considered a significant hydrological location. The site had been used as a current meter gauging location during the LVPS and TGS investigations and there was thus an existing record of data, albeit discontinuous. The presence of an observation borehole within 20m of the river offered the potential for comparison of chalk groundwater levels and river stage. The site presented the only control structure (bridge) that was readily accessible over a considerable length of the river, which was important as the channel locally was generally broad and shallow making it insensitive for a stage – discharge approach.

East Shefford site

The East Shefford site was selected due to the presence of an existing gauging structure, a compound crump weir (NRFA, 1999) installed during the LVPS, which could be used to accurately measure discharge, and hence produce a continuous record of flow accretion in the reach downstream from the West Shefford site. This reach included the village of Great Shefford where a major dry valley intersected the Lambourn Valley. The weir had been used to continuously monitor discharge from 1966 to 1983 but had remained uninstrumented until its use in this study.

Westbrook site

The Westbrook site was selected to provide a continuous discharge record at a location roughly halfway between East Shefford and the lowest gauging station on the Lambourn at Shaw (near Newbury), which is maintained by the Environment Agency (EA). Westbrook was chosen as it provided an accessible control structure (road bridge) in a section of channel that was generally broad and shallow, making it insensitive for a stage – discharge monitoring approach.

Non-continuously monitored sites

In addition to the continuous sites, a number of other locations were monitored on a non-continuous basis (with readings taken at roughly monthly intervals) and their details are given below. These sites were recognised as being of hydrological significance, representing key outflow points from the chalk aquifer under differing groundwater level conditions, but their ephemeral nature rendered them less suitable for a continuous monitoring approach. The locations of these sites are shown in Figure 3.9.

Monitoring site name	**Grid reference**	**Location** (km BHS)	**Monitored parameters**	**Start date**	**End date**
Upper Lambourn	SU 3142 8053	0	Flow presence/absence (river stage)	26/02/99	30/10/01
Lynch Wood	SU 3276 7922	1.90	Stage (discharge), temperature, EC	21/04/99	30/10/01
East Garston spring	SU 3647 7687	7.05	Water level, temperature, EC	14/10/99	30/10/01

Table 3.7 Details of non-continuous monitoring sites

3.4.2 Methodology at continuously monitored sites

Equipment and installation details

Each of the three sites was equipped with a Campbell Scientific Ltd. (CSL) 21X datalogger powered by a 12V deep-cycle leisure battery, with a second battery powering the sensors. At West Shefford, the datalogger and batteries were located in a concrete kiosk, built to house the top of EA observation borehole SU37/1. At East Shefford the equipment was placed in the existing stilling well shed at the gauging weir, whilst at Westbrook the equipment was positioned in a weatherproof environmental housing on the riverbank adjacent to the stilling well. The layouts of the three sites are shown in Plates III to VI.

At each site, river stage was measured using a pressure transducer installed in a stilling well. At West Shefford and Westbrook, the stilling wells were constructed specifically for this study, using 100mm diameter plastic piping, with holes drilled in their submerged sections. At East Shefford, an existing stilling well connected to the gauging weir was utilised. Two types of pressure transducer were installed: Druck Ltd. PTX 630 and Dynamic Logic Ltd. “Shape” SH3500. The “Shape” sensors produced a millivolt output that could be directly measured by the datalogger, but the Druck sensors required use of a CSL *CURS100* 100 Ohm current shunt terminal input module to convert the 4 – 20mA DC (direct current) output from the sensor to a suitable voltage that could be measured by the datalogger (Campbell Scientific, 1996).

At West Shefford, two pressure transducers were also used to measure groundwater levels, one located at a depth of 2.45m in a deep EA observation borehole, the other in a shallow piezometer installed to a depth of 1m for this study. The water level in the observation borehole (SU37/1) reflected a vertically averaged groundwater level in the local chalk aquifer over a depth from 12.5 to 100.6m below ground level. The piezometer measured the piezometric surface in shallow alluvial gravels, which were locally confined by 1.0m of organic sediment.

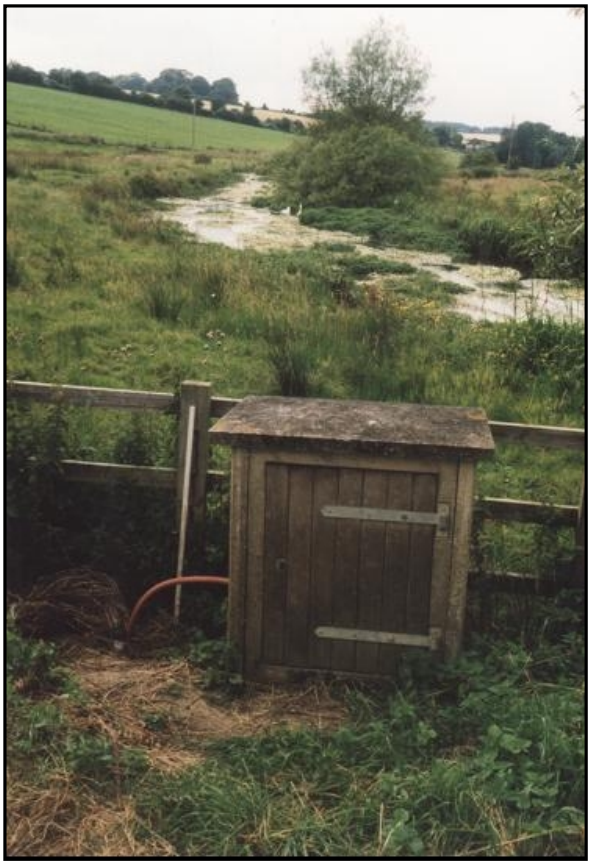


Plate III The monitoring site at West Shefford looking upstream, showing the borehole kiosk (in which the datalogger and batteries were located), with the top of the shallow piezometer visible to the left of the kiosk

Plate IV The River Lambourn at West Shefford looking downstream, showing the stilling well, with white plastic pipe (protecting the sensor cabling), extending to the borehole kiosk located 12m to the right of the picture

Plate V The monitoring site at East Shefford weir, looking upstream under high discharge conditions, with the central and side channels all carrying flow

Plate VI A view upstream at the Westbrook site, showing the stilling well containing the pressure transducer, with the temperature / EC probe (the white object) affixed to the bracing strut in the foreground. The datalogger is located in a weatherproof housing, 3m to the left of the picture.

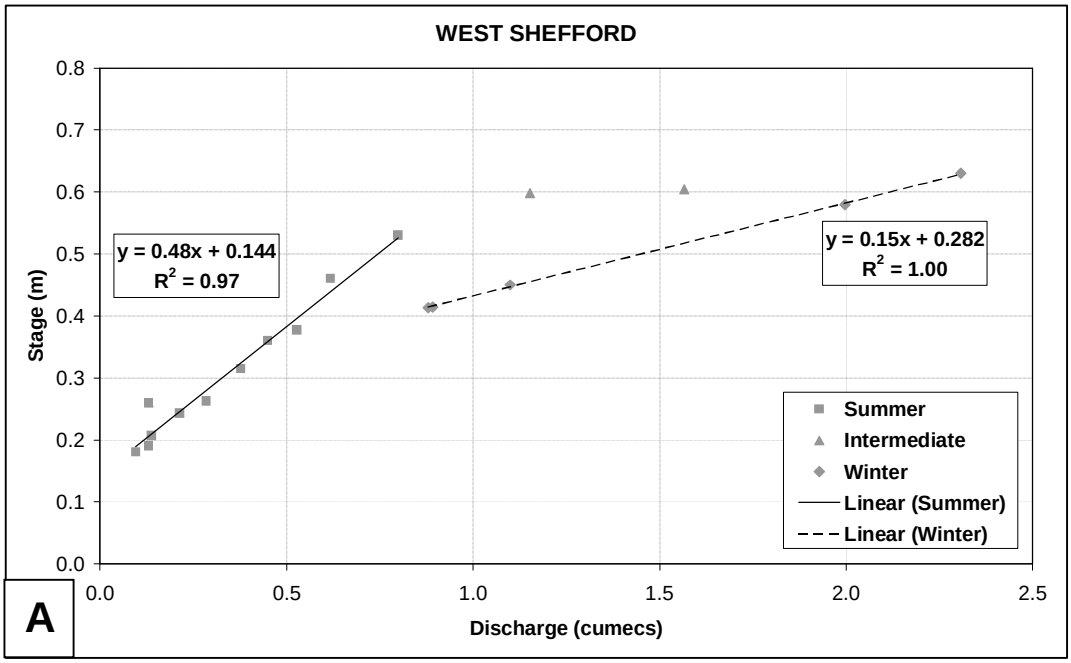
Prior to installation, all pressure transducers were tested in the laboratory over the anticipated measurement range, and calibrated accordingly. The data logger programs used the calibration data to produce a true output of water depth in metres, and the logged output was verified by manual readings. Temperature and EC were measured at each site using a CSL 247 joint EC and temperature sensor, installed adjacent to the pressure transducer recording river stage, except at East Shefford where the sensor was mounted in the river adjacent to the gauging weir, not in the weir stilling well. The CSL 247 produced a millivolt output that was measured directly by the datalogger. The raw EC data were automatically calibrated to a reference temperature of 25°C by the datalogger programme. At all sites readings of both water levels and physico-chemical parameters were measured every 15 seconds, with mean values being calculated and output to final storage at 30-minute intervals.

Discharge measurements

Stage-discharge rating curves were derived principally using an ADS Sensa-RC2 electromagnetic flow meter. Measurements of flow velocity were undertaken consistently at depths of 0.6 times the water depth at a minimum of ten locations per section (Shaw, 1994; p.107). Mean velocity over a 50 second interval was recorded for each location and discharge was calculated using a velocity-area technique (the mid-section method, Shaw, 1994; p.112).

The relationship between stage and discharge at monitoring sites was established by gauging under various flow conditions, and rating equations were derived which allowed river flows to be determined from records of river stage. Most sites required more than one rating equation (shown in Figure 3.10), as the stage-discharge relationship was significantly influenced by seasonal weed growth (Plate VII).

The discharge at East Shefford gauging weir was calculated from the rating formula used formerly by the EA, validated against a generic Crump weir formula (Ackers *et al.*, 1978; Equation 4.1, p.91), and additionally verified in the field by current meter gauging. There were no equipment malfunctions at this site, resulting in a continuous, reliable record of discharge for the period 27/05/99 to 30/10/01.



Summer rating equation: Discharge = (0.22 x Stage) – 0.28 $R^2 = 0.97$
Winter rating equation: Discharge = (6.64 x Stage) – 1.87 $R^2 = 1.00$

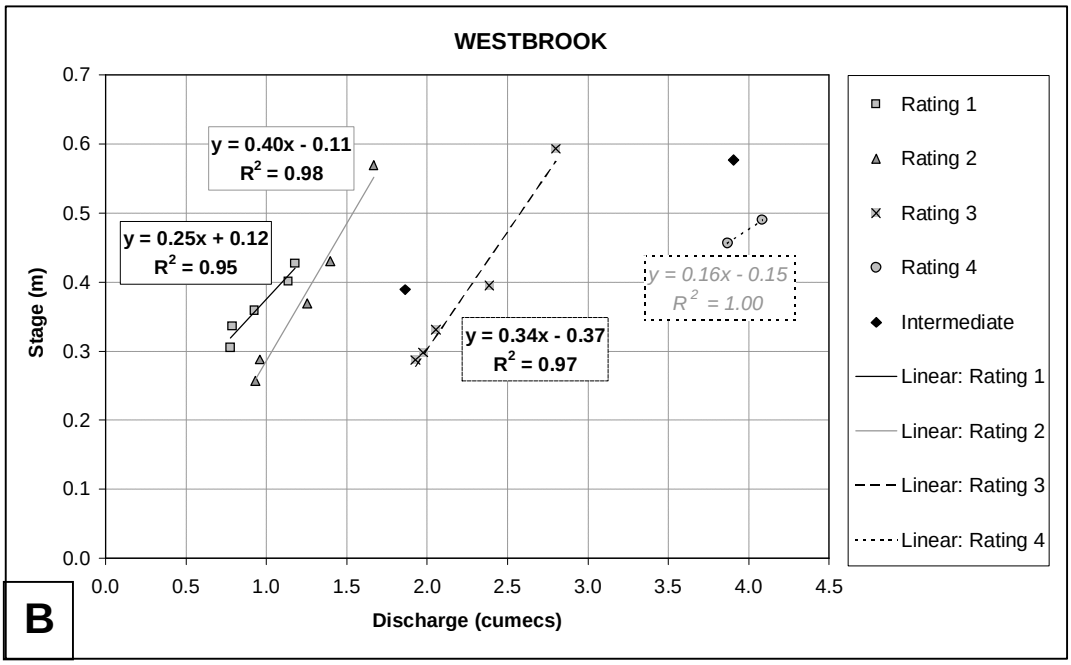


Figure 3.10 Seasonally variable stage – discharge relationships for (A) West Shefford and (B) Westbrook monitoring sites

Westbrook rating details:

Rating 1	Summer / Autumn 1999	Discharge = (3.76 x Stage) -0.41	$R^2 = 0.95$
Rating2	Multiple occurrences	Discharge = (2.46 x Stage) -0.30	$R^2 = 0.98$
Rating 3	Late Winter / Spring 2000 (rising limb)	Discharge = (2.87 x Stage) -1.14	$R^2 = 0.97$
Rating 4	Late Winter / Spring 2001 (receding limb)	*Trendline equation for comparison only*	

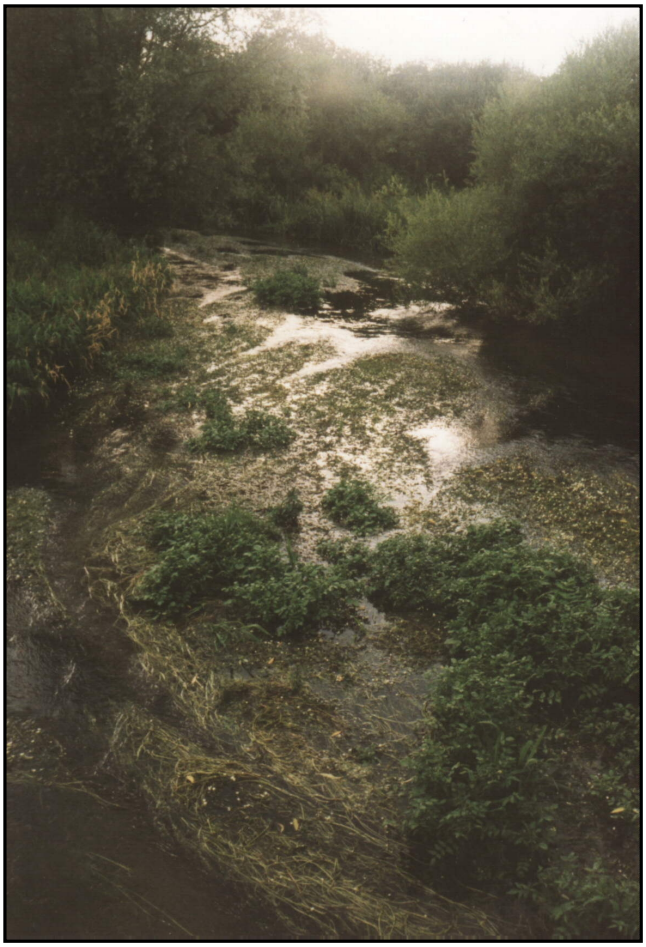


Plate VII The channel immediately upstream of the Westbrook site, showing extensive seasonal weed growth restricting flow in July 2000

Surveying of datum points at monitoring sites

Information on Ordnance Survey benchmark locations and elevations was supplied by West Berkshire District Council. Traverses were then taken from these benchmarks (using a Leica electronic distance-measuring instrument), to local elevation datum points at each monitoring site, which were then used as reference points for all water level elevation data.

3.5 DATA PROCESSING

3.5.1 Field data from this study

The principal manipulation required for field data collected during this study was the calculation of discharge records based upon continuous measurements of river stage at West Shefford and Westbrook. Unfortunately, the seasonal and inter-annual variability of the rating relationships reduced the confidence in some of the discharge data, which

together with equipment malfunction restricted their continuity (Figure 3.11), and thus their usefulness in the final analyses.

The EC data from all sites required additional temperature-related correction, as the sensor internal temperature compensation was insufficient. Calibration equations for each site were developed, based upon temperature and EC data from a Jenway R4150 hand held conductivity meter, and were found to be consistent and reliable.

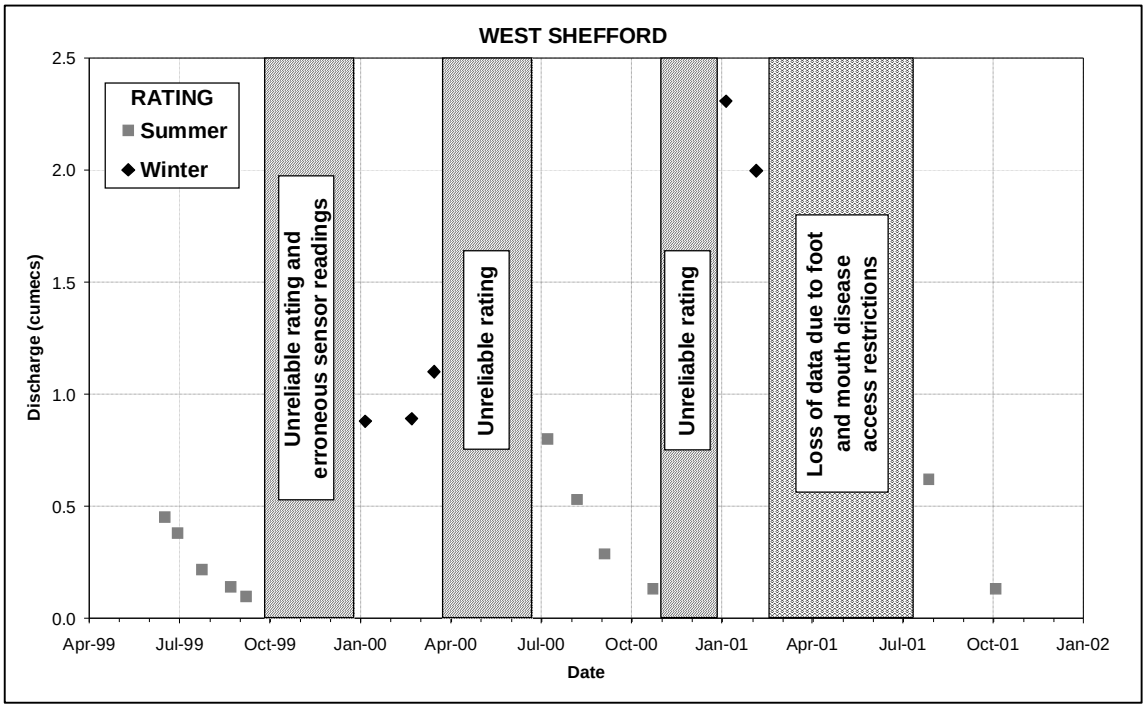
All remaining temperature data and water level data were found to be consistent with manual readings and were used unmodified, with the exception of periods when sensor malfunction occurred.

3.5.2 Measurement errors

The data were inevitably subject to both systematic and random error, which are assessed in Table 3.8, together with estimates of data accuracy.

Equipment and usage	**Error type**	**Error / accuracy**
Metre rule or gauging staff for measuring stage whilst flow gauging	Manual reading	2% (e.g. to nearest 1.0cm for depths up to 50cm)
Sensa RC2 electromagnetic flow meter for flow velocity measurement	Instrument precision	+/- 0.5% (manufacturers specification)
Ott C 2 propeller flow meter for flow velocity measurement	Instrument precision	Estimated as 2% (Shaw, 1994; p.108)
Combined error for velocity-area method	Calculation	For ratings using between 10 and 20 verticals, the error in a single discharge determination should be in the range 6 to 12% (Herschy, 1978)
Jenway R4150 conductivity meter	Instrument precision	EC: +/- 0.5% Temperature: +/- 0.5°C
CSL 247 temperature/conductivity sensor	Instrument precision	+/- 10% (conductivity range 5 to 440µS/cm) +/- 5% (conductivity range 440 to 7000 µS/cm) +/- 0.4°C (temperature range –35 to +48°C)
Druck PTX630 pressure transducer	Temperature -related	< 2% over temperature range –10 to +50°C
“Shape” SH3500 pressure transducer	Instrument precision	+/- 0.25% full range output

Table 3.8 Quantifiable errors in measurements and methods



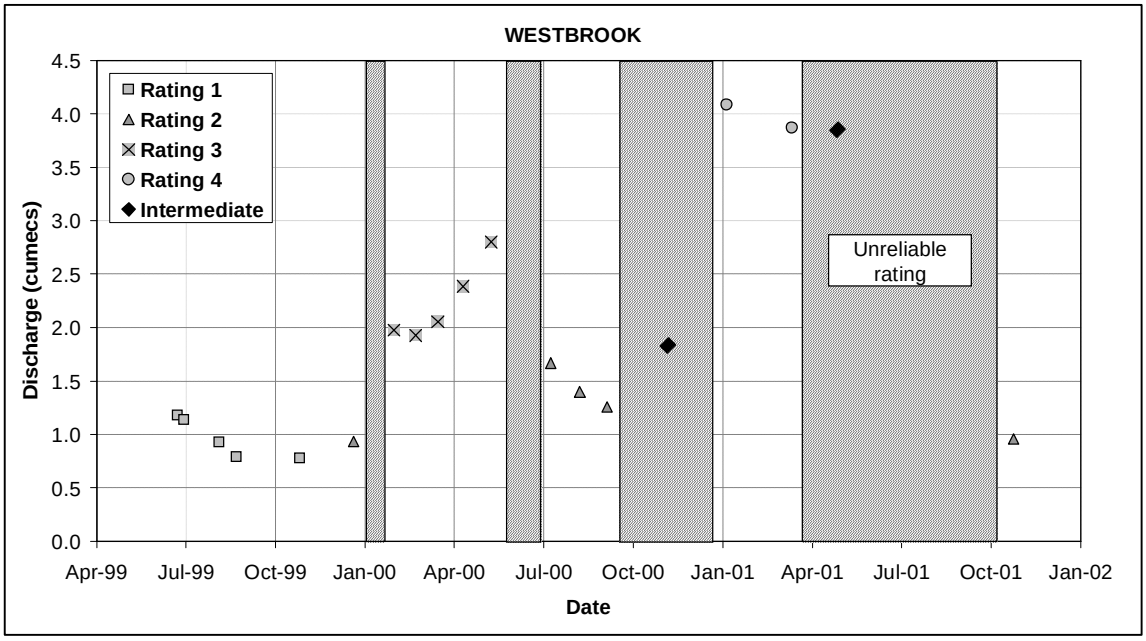


Figure 3.11 Timing and duration for periods of reliable, continuous discharge measurement at West Shefford and Westbrook monitoring sites

Rating designations relate to the linear regression equations shown in Figure 3.10

3.5.3 Calculation of the Mean Groundwater Stage

In order to provide a representative measure of catchment-wide groundwater levels it was necessary to produce a time series representing an average groundwater level for the catchment. Such a procedure was undertaken for the Lambourn Valley Pilot Scheme, using monthly records from 22 observation boreholes, and weighting their influence with Thiessen polygons (Brettell, 1971). The resulting value was defined as the Mean Groundwater Stage (MGS).

A similar process was undertaken in this study, using records from 21 boreholes, selected on the basis of their monitoring frequency (at least monthly), length of record (at least 15 years) and reliability of record (minimal absences of data). (The borehole locations and the Thiessen polygons are given in Appendix 8). The water level records from the boreholes were first reduced to a single, representative value for each month, and then a weighted average value was calculated, using Thiessen polygons, to produce a monthly record of MGS for the period from September 1973 to December 1993. This period was chosen because of the need for a sufficient number of boreholes that were monitored at a suitable frequency. From 1994 onwards, the monitoring of a number of boreholes ceased, rendering the calculation of the MGS less reliable.

In order to provide a representative value for catchment average groundwater levels for the period before and after the 1973 – 1993 period, a proxy measure of MGS was required. Using the same approach as Brettell (1971), a borehole with a long, high frequency, continuous record was selected which could be closely correlated with the MGS record. This was then used, via a linear regression equation, to calculate a synthetic value of the MGS. The linear regression correlation is shown in Figure 3.12, and a comparison between the true MGS and the synthetic (proxy) MGS is presented in Figure 3.13.

It is apparent that the synthetic MGS record shown in Figure 3.13 provides a good representation of the MGS for all except low recharge years, when it tends to underestimate the peak level (e.g. 1988/89, 1990/91, 1991/92).

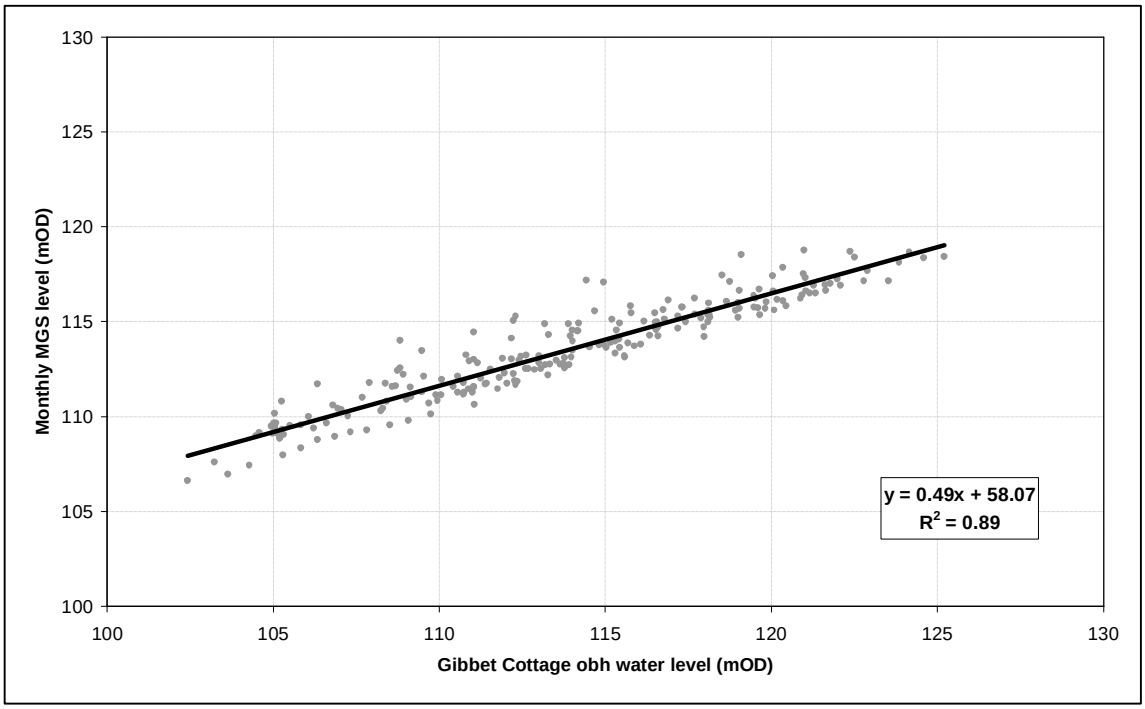


Figure 3.12 Linear regression correlation between groundwater levels in Gibbet Cottage observation borehole (obh) and the MGS for the period September 1973 to December 1993

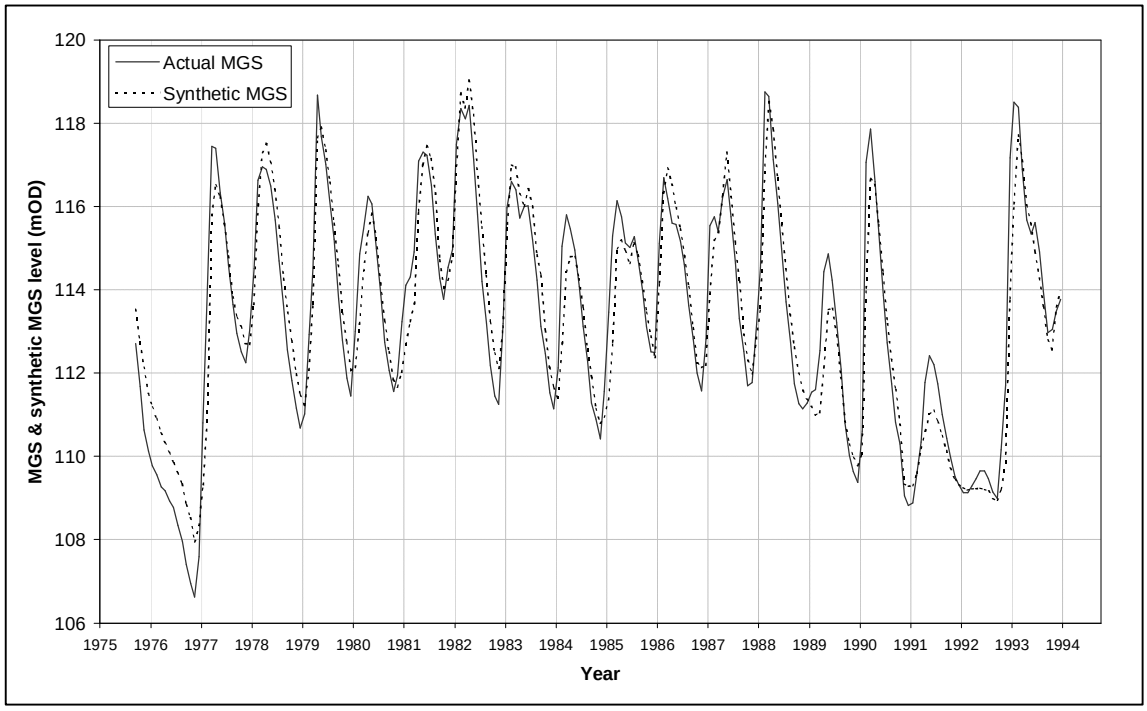


Figure 3.13 Comparison of synthetic MGS (derived from Gibbet Cottage obh) and actual MGS

3.5.4 Verification procedure for the current meter dataset

During the LVPS and TGS investigations carried out between 1967 and 1976, a large number of current meter surveys were undertaken. These produced a database comprising around 2500 individual spot discharges. Prior to its use in this study, the current meter database underwent a process of verification to produce an accurate, representative picture of natural flow exchanges, and for this reason it was important to remove as many anthropogenic influences as possible. Some anthropogenic factors, such as the PWS abstractions, have a negligible influence and can be ignored, as in the relevant years the annual PWS abstraction represented less than 4% of annual flow. In the same manner, private abstractions generally have an insignificant effect on flow exchanges. However, anthropogenic influences arising through infrastructure such as weirs, channel diversions and millstreams may be more significant. These features are essentially fixed and were assumed to act in a quasi-natural manner. During the verification procedure, a conservative approach to data quality was undertaken, so that if data were at all suspect it was rejected. Thus the final verified dataset may be smaller than the number of actual reliable data points, but it can be considered as reliable in itself. However, this clearly does not preclude errors in the original gauging dataset, both in terms of field measurements and during subsequent data processing. The following stages were used to produce a representative dataset of current meter (CM) gaugings:

1. Removal of dates/sites that could have been influenced by pumping tests or pumped discharges;
2. Removal of sites where there were too few paired data (upstream and downstream) to provide a realistic representation (an arbitrary minimum of 10 paired readings was used as a cut off);
3. Removal of sites that were too close together to allow flow gains/losses to be assessed, as the change in flow was within the gauging margin of error (10%);
4. Removal of more than one data point occurring at a site in any month, to prevent temporal bias;
5. Weighting of mean flow exchange for each reach, based upon monthly mean exchanges;

6. Finally, the reduced dataset was assessed in terms of its reliability in representing long term mean conditions.

All the points above relate principally to the calculation of representative records of natural flow exchange. However, some of the data excluded from this approach, for example from sites adjacent to a borehole being test pumped, are important in their own right and could be used to assess local conditions.

Accounting for pumping tests and site rationalisation

Pumping tests of individual boreholes were undertaken after their construction. This occurred in two main phases, relating to the period of the Lambourn Valley Pilot Scheme (LVPS) and the later Thames Groundwater Scheme (TGS) (briefly described in Appendix 3).

Pumping tests on individual boreholes were generally of short duration (20 days) and would have had no perceptible impact on flow exchanges, unless located immediately proximal to the river, or the water from the test was discharged into the river. Both these elements were taken into consideration and any data considered potentially suspect was rejected.

The original dataset of CM readings was derived from a large number of different sites throughout the length of the river. These were rationalised such that sites with less than ten readings were rejected. Similarly, sites that produced less than ten paired readings (requiring measurement at two adjacent sites on the same day) were also rejected.

Removal of temporal bias

To remove the potential for temporal bias, months where multiple gaugings had been undertaken at a site were reduced to a single, representative value, which allowed calculation of summary statistics without bias towards a period of time when high frequency readings were undertaken. The calendar month was arbitrarily chosen as the distinct time unit on the basis that flows varied little within a month, and so one value would be representative. Where several values were present within a single month, the one recorded closest to the 15th of the month was retained, thus maintaining optimum temporal spacing between values from the preceding and following months.

Weighting for mean flow exchange

In order to minimise bias between months, the frequency of readings for each month was found, and from this a mean frequency of occurrences per month was calculated. This was necessary as the number of readings in certain months (e.g. June) were far higher than other months (e.g. December), which could skew the mean exchange flow towards the more frequently occurring month. To counteract this, a weighting was used, which increased representation for months with fewer readings;

$$\text{Weighting parameter} = \frac{\text{average number of occurrences in all months}}{\text{number of occurrences in any month}}$$

This created a weighted average exchange flow that was representative for all months of the year. The results of this weighting should have ensured that the mean exchange flow values are fully representative of the years from which the data are derived.

Long term representativeness

Clearly, if data extrapolated from a limited number of years is to be representative of long-term mean conditions, the approach needs to be verified. Most of the 431 verified CM gaugings used in this work were derived from relatively few years. In fact, data from the most intensely monitored years from 1965 to 1970 (inclusive), plus 1975 (i.e. 7 years in all), account for 86% of the verified dataset, which is drawn from the period 1964 to 1979. To demonstrate that this dataset, which is of restricted temporal distribution, is representative of long-term average conditions, the data were verified against a long-term representative parameter, the discharge at Shaw gauging station. Summary statistics from the principal period of CM gaugings (1965-1970, 1975), and the full record of discharge available (1962-2001), are compared in Table 3.9, and flow duration curves are presented in Figure 3.14.

It is apparent from both Table 3.9 and Figure 3.14 that the CM dataset period was one of slightly elevated flows relative to long-term mean conditions. The Q_{10} to Q_{90} values for the CM dataset all exceed long-term values, with the error ranging from 9% to 28%. Overall, it appears that the CM dataset adequately represents the pattern of flow occurrence, but that the actual magnitude of flows is estimated as being 15% to 20% higher than long-term average conditions.

	Discharge at Shaw (cumecs)		
Parameter	**CM data period**	**Complete record**	**CM data error**
Mean	1.98	1.75	+13%
Minimum	0.78	0.41	+89%
Maximum	4.01	6.67	-40%
Q_{10}	1.09	0.85	+28%
Q_{25}	1.30	1.08	+20%
Median (Q_{50})	1.87	1.51	+24%
Q_{75}	2.51	2.26	+11%
Q_{90}	3.16	2.91	+9%
Inter-quartile range	1.21	1.18	+3%
Standard deviation (SD)	0.77	0.88	-13%
SD/Mean	39%	51%	

Table 3.9 Comparison of discharge statistics from the principal current meter dataset period with statistics from the complete discharge record

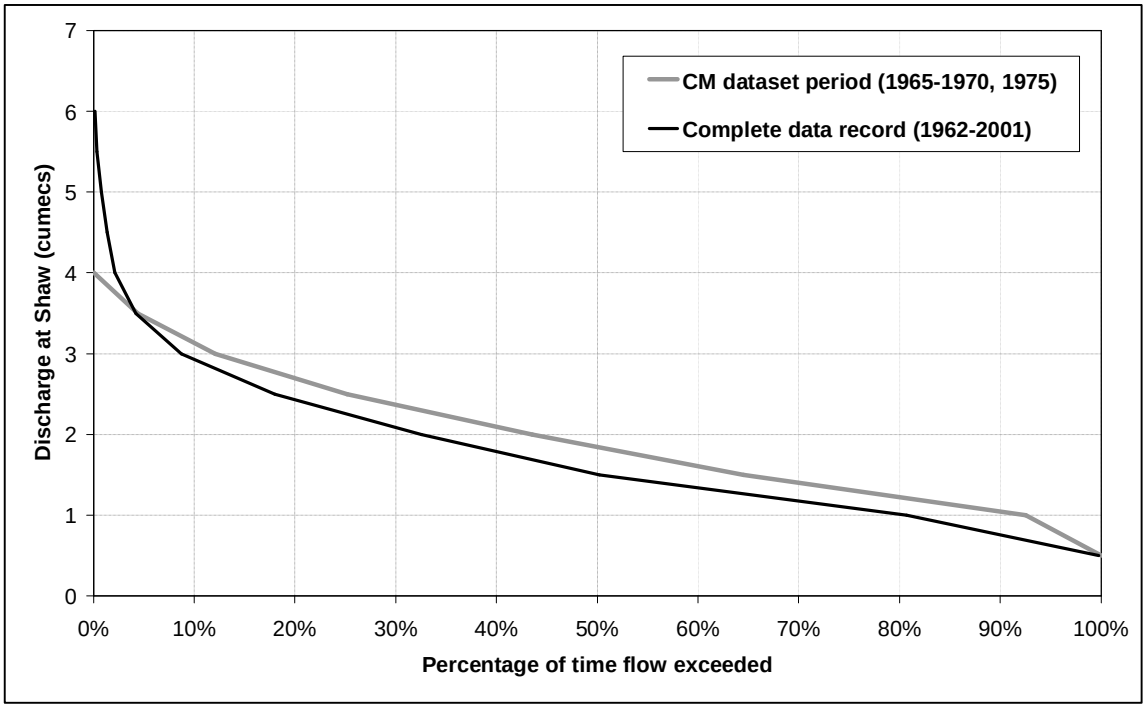


Figure 3.14 Flow duration curve for Shaw gauging station to compare the principal current meter dataset period with the complete discharge record

3.6 OVERVIEW

This chapter has sought to provide the context within which the research has been undertaken, and the sources of data upon which it is been based. The Lambourn catchment has been subjected to intensive investigation in the past, which has left a legacy of extensive monitoring infrastructure and low rates of groundwater abstraction, which are critical factors in its selection for this study. The data used here are derived from both external sources and field monitoring specific to this study. The collation of external, historic data and contemporary data is a common theme throughout this study, and is initially demonstrated in Chapter 4, which assesses the temporal aspects of the recharge – storage – discharge sequence in the Lambourn catchment.

Chapter 4 Catchment flow path characterisation through time series analysis

4.1 INTRODUCTION

A key requirement in understanding interlinked river – aquifer systems is to identify and quantify controls on the differing response times of the system components in the recharge – storage – discharge sequence. This could relate to the lag time between recharge at the ground surface, and the subsequent water table response (e.g. Calver, 1997b), or equally the delayed impacts of groundwater abstraction on river flows (e.g. Bullock *et al.*, 1995), although in catchments affected by abstraction, the anthropogenic impacts often obscure responses associated with natural climatic variability. In this chapter, an attempt is made to identify the lag times between system components as a means of characterising the flow processes operating in the catchment. A method for providing bulk estimates of aquifer parameters and unsaturated zone properties is proposed, based upon quantifying components of the lag time between recharge and discharge. This method offers a means of verifying estimates of bulk properties derived from baseflow recession analysis and, combined with pumping test data from valley locations, could be used to estimate the properties of interfluve areas, which constitute the majority of most catchments.

Patterns of rainfall and recharge are explored first in Section 4.2, at both the monthly and annual (water year) timescale. Recharge is correlated with catchment discharge, and estimates are made for the average and maximum lag times between these components. The rapid response of the catchment to intense rainfall is investigated in Section 4.3 by examining a particular event that occurred in August 2000. Based upon results from the two preceding sections, a simple conceptualisation of the recharge – storage – discharge sequence operating in the Lambourn catchment is presented in Section 4.4, with preliminary quantification of some system components. Section 4.5 examines patterns of groundwater level and discharge variation, using linear regression analysis to define values for the remaining components of the conceptual system. Multiple linear regression is used in Section 4.6 to optimise a relationship between recharge, storage and discharge, culminating in the production of a synthetic time series,

which accurately represents catchment discharge. Section 4.8 gives an overview of the chapter and briefly discusses the implications.

4.2 PATTERNS OF RAINFALL AND RECHARGE

The pattern of groundwater level change, and hence catchment discharge, is ultimately controlled by precipitation, or more precisely excess precipitation (EP). EP (also known as Hydrologically Effective Rainfall; HER) is calculated from rainfall minus evaporation, when the soil moisture deficit (SMD) is zero (Hough & Jones, 1997). On a practical level EP relates to the fraction of gross rainfall that is able to pass through the soil zone, without being lost via evapotranspiration, and is thus available to recharge the aquifer. The spatial and temporal patterns of recharge tend to have relatively little influence on the spatial patterns of river - aquifer interaction, except in some localised storm events, but recharge dynamics provide the dominant control on the timing and magnitude of catchment discharges. The relationship between recorded recharge and resultant discharge is not straightforward, as it reflects firstly the influence of aquifer storage (which buffers the variability in recharge input), and secondly, the limitations of recharge estimation, especially at the catchment scale. The first of these factors forms the basis of this chapter, whilst the second factor is specifically examined in Section 4.2.3.

The recharge dataset used in this study is derived from The Meteorological Office Rainfall and Evaporation Calculation System (MORECS), the enhanced version of which is described by Hough & Jones (1997). MORECS-based estimates of EP are available on a site-specific basis (for a fee), but are routinely calculated on a weekly basis for 40 x 40km squares, which form a grid covering England, Scotland and Wales, and such data have formed the basis of a number of hydrological investigations (e.g. Jolley & Wheater, 1996; Calver, 1997b; Erskine & Papaioannou, 1997; Soley & Heathcote, 1998).

The MORECS dataset comprises all the base meteorological variables used in the calculation (total rainfall, hours of sunshine, temperature, vapour pressure and wind speed), and the derived parameters of Potential Evapotranspiration (PE), Actual Evapotranspiration (AE), EP, SMD and crop stress (AE/PE) (Hough & Jones, 1997). The MORECS outputs are calculated for a number of different crop and soil scenarios. For the purposes of this research, the recharge data used were based upon real land use

(RLU) data and a medium soil type. The data for the Lambourn catchment, which lies entirely within MORECS Grid Square 159, are available from April 1978 onwards. Calculated totals, to the nearest month, for RLU-based EP and gross rainfall in square 159 are given in Figure 4.1, which shows that the highest individual recharge month for the period of MORECS record to February 2001 was 133mm in November 2000 (1), closely followed by January 1995 with 132mm (2). The most significant cumulative recharge event occurred in the 2000/2001 water year, when the cumulative four-monthly sum of EP to February 2001 totalled 387mm (3), 38% higher than the next highest event on record, 281mm in the four months to February 1995 (4). At the opposite end of the scale one year stood out for its particularly low winter recharge, with the six months to March 1992 producing only 58mm of EP (5).

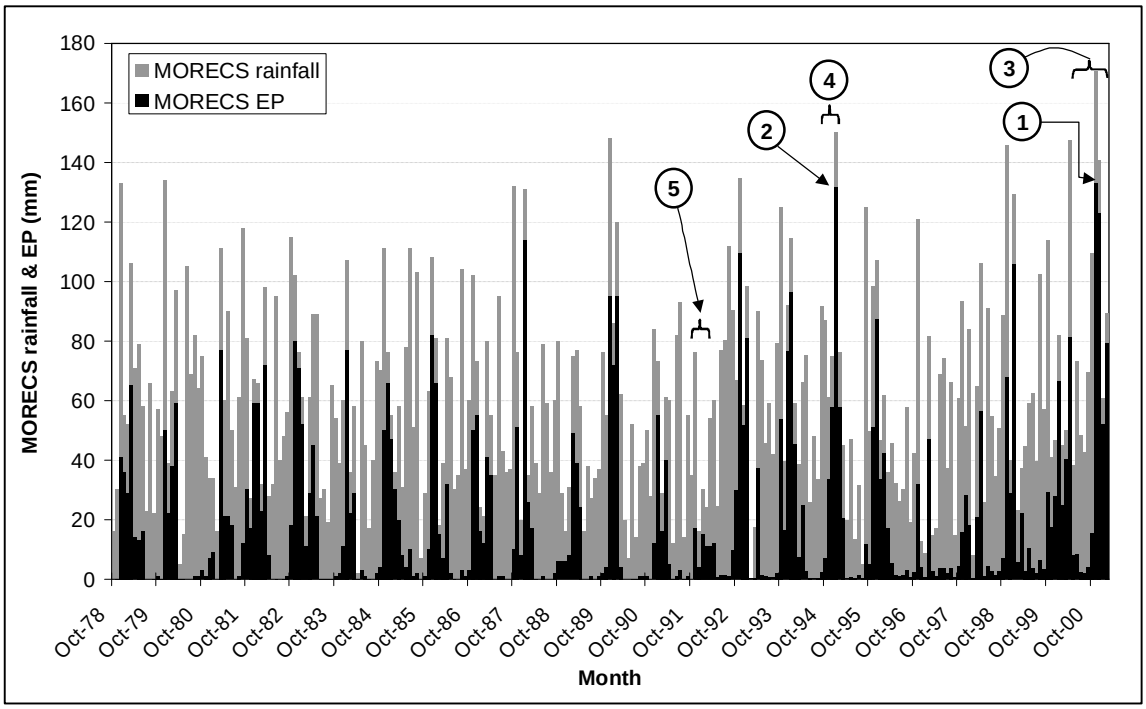


Figure 4.1 Comparison of monthly total MORECS RLU EP and MORECS rainfall for square 159 for the period October 1978 to February 2001
(see text for explanation of annotation)

The period from October 1989 to October 2000 has been characterised by a preponderance of extreme seasonal recharge events, relative to the preceding period from October 1978 to September 1989. The four highest winter recharge seasons all occurred during the former period (1994/95, 1993/94, 1992/93, 1989/90), as did the three lowest winter recharge totals (1991/92, 1997/98, 1996/97). This pattern is also

apparent from Figure 4.2, which illustrates annual (hydrological year) totals of EP and rainfall, even without the inclusion of the extreme events of the water year 2000/2001. There is greater variability in both annual rainfall and recharge from 1989 to date and this factor should be considered when contextualising field measurements undertaken during the period of the current study (April 1999 to October 2001).

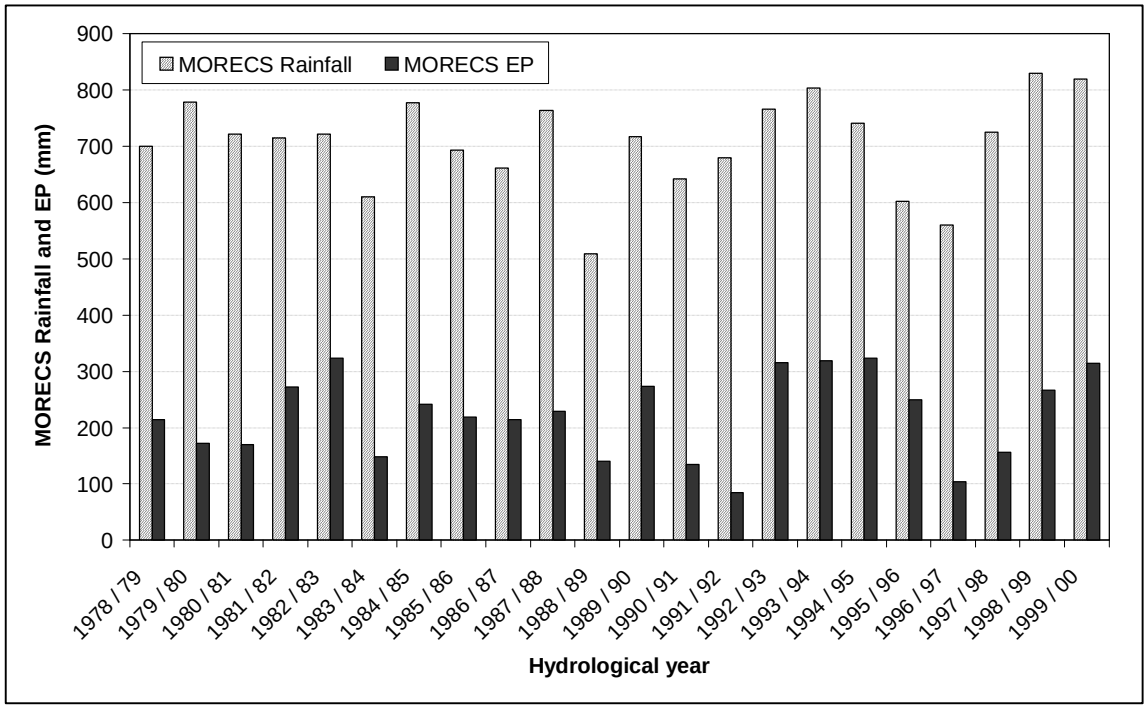


Figure 4.2 Water year totals of MORECS EP and rainfall from 1978/79 to 1999/00

4.2.1 The water-year pattern of rainfall and recharge

From Figure 4.1 it is apparent that monthly EP is significantly lower than total rainfall, and that there is a seasonal pattern, with the bulk of the annual total EP occurring in the first six months of each hydrological year (commencing in October), with little EP being recorded over the summer months. This pattern is illustrated in more detail in Figure 4.3, which shows monthly average values for MORECS EP and rainfall.

Figure 4.3 shows that the monthly peak rainfall tends to occur between October and January, with the peak recharge months being December and January. Whilst rainfall in October is comparable to other winter months, EP is low, reflecting the residual soil moisture deficit that needs to be overcome before recharge can occur. Meanwhile recharge in February is limited due to the low average rainfall of only 44mm, compared to 72mm in January and 60mm in March. January has the maximum EP with an average

value of 54mm from the average rainfall of 72mm, which represents an average EP / rainfall value of 68% for the period of record.

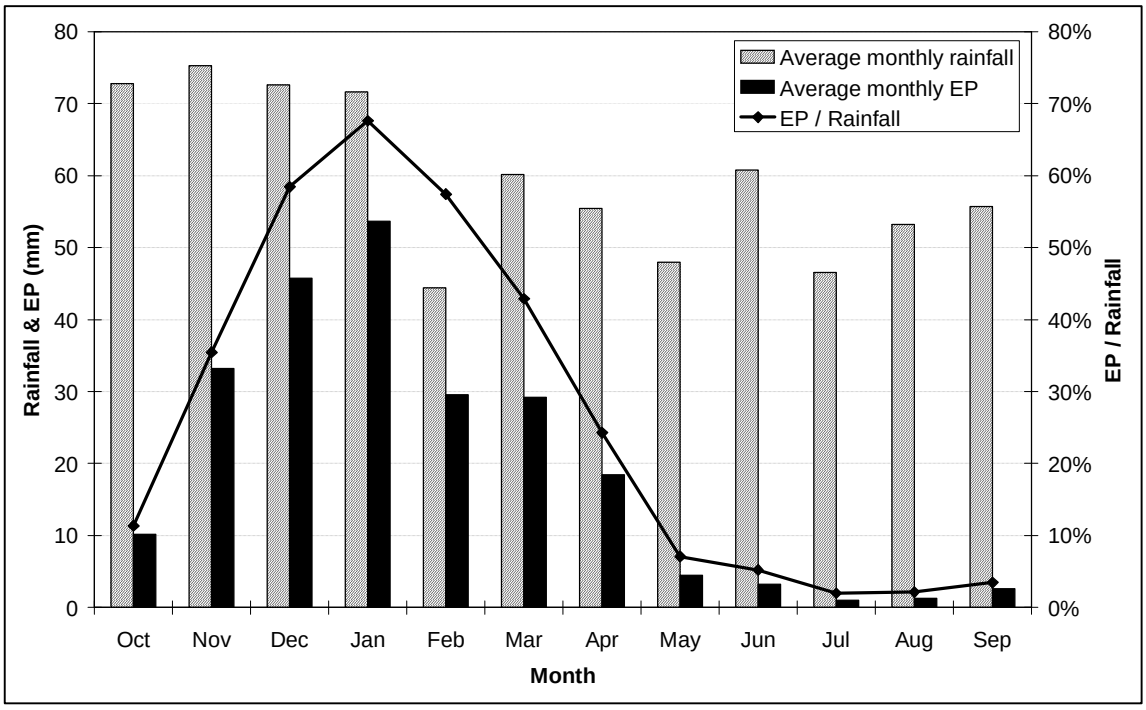


Figure 4.3 Monthly average MORECS EP and rainfall for square 159, with EP as percentage of rainfall, for the period April 1978 to February 2001 inclusive

Figure 4.3 shows the strong seasonal pattern of recharge inputs to the Lambourn catchment, and it is this pattern, modified by the storage capability of the aquifer, which determines the seasonal discharge pattern of the River Lambourn. Correlating these temporal patterns is the focus of the following sections.

4.2.2 Correlating water-year recharge and catchment discharge

MORECS data may be used in water resource management, but they can be inaccurate, especially at the cessation and onset of the soil moisture deficit in autumn and spring, which are the most problematic periods for recharge calculation (Hough & Jones, 1997). In addition to this, the necessary homogenisation that takes place when a single value represents an area of 1600km^2 is an additional source of error. The manifestation of this error is shown in Figure 4.4, which illustrates the calculated annual MORECS input to the Lambourn catchment, compared with the recorded catchment discharge. The total catchment outflow is assumed to be represented by the surface water discharge

recorded at the lowest gauging weir. This approach neglects groundwater discharge from the catchment as well as any underflow at the gauging station, and thus the catchment outflow represents a minimum value. The groundwater catchment area of 168km^2 (derived from average groundwater levels) is used to calculate the catchment discharge in millimetres using:

$$Q = (Q_t / A) \times 1000 \qquad \text{Equation 4.1}$$

Where:

Q = Annual catchment discharge (mm)

Q_t = Annual total discharge (m^3) [sum of daily discharges]

A = Groundwater catchment area (m^2)

The variation in groundwater catchment area with time is insignificant and thus no temporal correction need be applied.

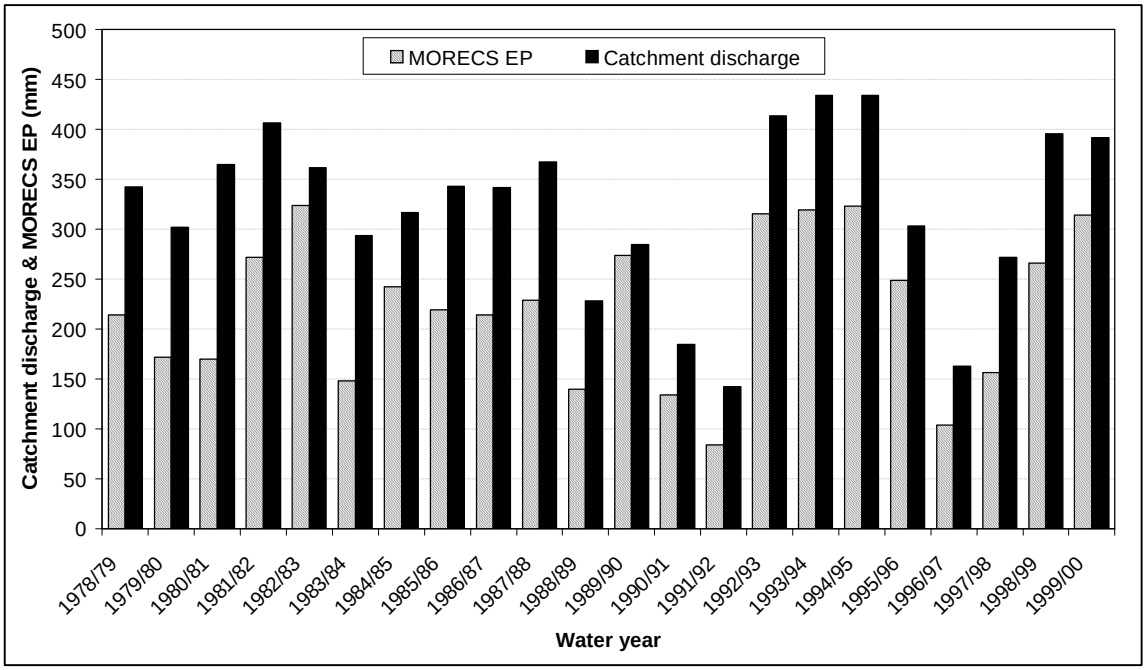


Figure 4.4 Comparison of water year MORECS EP with discharge from the Lambourn catchment for the period 1979 to 2000

Figure 4.4 shows that values of EP are lower than the catchment discharge values on all occasions, indicating that MORECS consistently underestimates the annual recharge to the Lambourn catchment. In fact, over this period (1979-2000) total EP is 69% of total catchment discharge. However, this value displays significant inter-annual

variability, with the maximum value of 96% occurring in the hydrological year 1989/90 and a minimum value of 47% being recorded in 1980/81.

An independent verification of MORECS EP in a chalk catchment was reported by Jones & Cooper (1998), using two years of data from a large lysimeter on the Middle Chalk at Fleam Dyke near Cambridge. When compared with data from the lysimeter, they found that MORECS EP accounted for 87% of recharge in 1982 and only 73% in 1983, which suggests that the long-term value of 69% derived here is not unrealistic. To assess the relationship between water year total EP and discharge, the parameters are plotted in Figure 4.5.

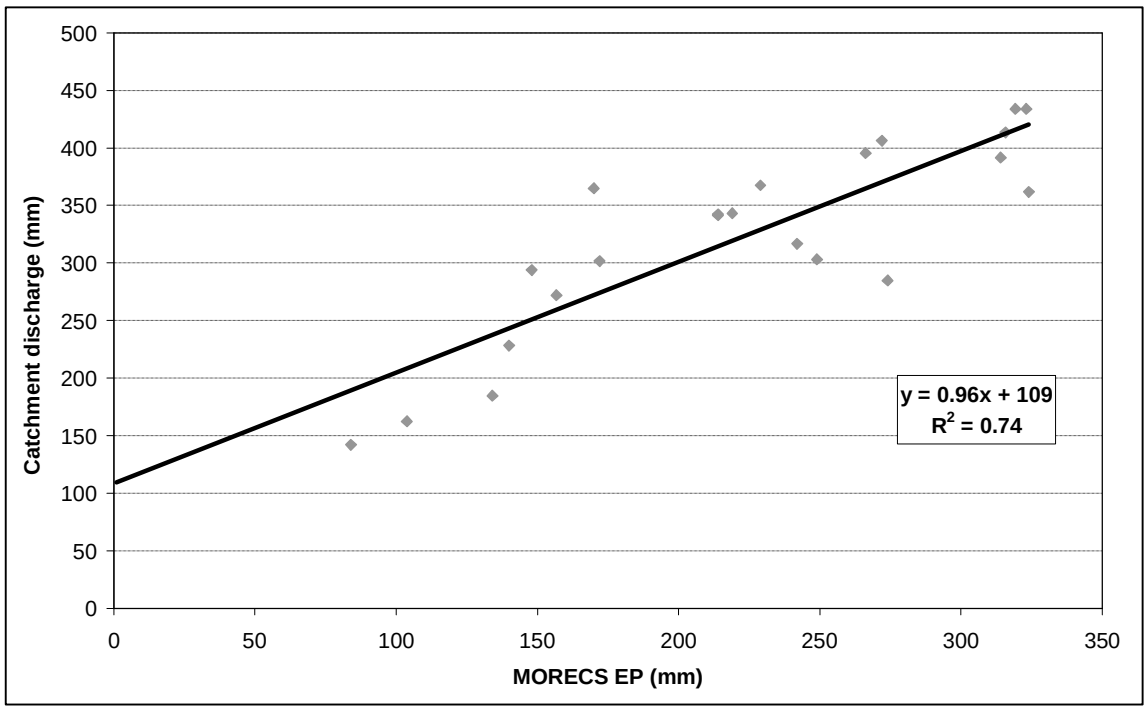


Figure 4.5 Water year total MORECS EP versus catchment discharge for the period October 1979 to September 2000

It is clear from Figure 4.5 that there is a strong correlation between water year total EP and discharge, but that EP is consistently in excess of 100mm less than the catchment discharge, with the assumption that there is no change in storage from year to year. The fact that the best fit line does not pass through the origin is initially counter-intuitive, but indicates correctly that there would still be discharge (derived solely from storage), even during a year with zero recharge. Whilst this relationship is helpful in establishing possible margins of error for MORECS EP data, it does not contribute

significantly to elucidating catchment processes, as the annual time steps are too coarse. In Section 4.2.4, EP and discharge data are considered at the monthly timescale, which allows the recharge – discharge time lag to be quantified. However, before undertaking this more detailed temporal analysis, the potential sources of error in the water-year based comparison of EP and catchment discharge are assessed.

4.2.3 Potential errors in the MORECS EP – catchment discharge relationship

Calculation of catchment discharge based upon catchment area

Curiously, the MORECS EP underestimate of about 30% of catchment discharge is almost identical to the relative size of the groundwater catchment compared with the surface water catchment. Thus, if the surface water catchment of 234km^2 were used to calculate the catchment discharge in millimetres, then on average, the MORECS EP would be of a similar magnitude. However, groundwater level data consistently demonstrate that the groundwater catchment is significantly smaller than the surface water catchment. Moreover, the absence of surface runoff in the marginal areas of the catchment suggests that the groundwater catchment provides a more accurate representation of the stream – aquifer unit than the surface water catchment. However, using the groundwater catchment takes no account of either shallow interflow in marginal areas (where topographic gradients are high), or of lateral flows in the unsaturated zone, both of which may contribute to an enlargement of the effective groundwater catchment.

If there was significant lateral migration of recharge (for example on a scale of hundreds of metres) whilst passing through the unsaturated zone, this would lead to errors in the definition of the groundwater catchment area and subsequent errors in recharge calculations. Whilst this scale of lateral migration appears unfeasible, we must consider that the unsaturated zone can be over 60m thick in areas close to the catchment divides, and the influence of minor, sub-horizontal, lithological features (such as flint horizons and marl bands) could exert a lateral control on the direction of descending recharge. There has been little research on the deep unsaturated zone of the chalk aquifer (at greater than 5m below ground surface), although research at a site on the Chalk in Yorkshire by Zaidman *et al*. (1999) showed that the occurrence of a numerous marl bands could interrupt the downward migration of recharge in sub-vertical fissures.

However, a proportion of any potential lateral migration is likely to occur as shallow interflow in the soil, particularly where a weathered zone is developed in the chalk bedrock, producing a permeability contrast at the base of the soil profile. The key controls on interflow occurrence and magnitude are soil structure and topographic gradient (Leaney *et al.*, 1993). Given that even low angle slopes (~1°) can permit the incidence of interflow (Walton *et al.*, 2000), then there would be no topographic constraint on the occurrence of interflow on the flanks and upper portions of the dry valley network in the Lambourn catchment, where slope angles are often in the order of 5 to 10° (derived from Ordnance Survey contour information). However, the soil structure will also exert a considerable control on the type of rainfall event that will initiate this type of flow. For example; Trudgill *et al.* (1983) identified an intensity / duration threshold of 3mm/hr for at least 2 hours as necessary to invoke interflow from a well-structured, calcareous woodland soil. Overall, the potential significance of lateral migration, both in the soil zone and unsaturated zone of chalk catchments, needs to be better quantified.

MORECS rainfall versus local rainfall

Another potential source of error when applying the MORECS EP value to a small area (the Lambourn groundwater catchment of 168km^2 represents only 10% of MORECS square 159) is the difference between estimated MORECS rainfall and local observed rainfall. To assess the significance of this influence, weekly rainfall data from East Shefford rainfall station, located close to the centre of the Lambourn catchment, were compared with MORECS rainfall data for the period April 1978 to December 1993, the results being given in Table 4.1.

Parameter **Dataset**	**Mean** (mm)	**Standard deviation, SD** (mm)	**Coefficient of variation** (SD/Mean)	**Median** (mm)	**Minimum** (mm)	**Maximum** (mm)
MORECS	13.6	13.1	0.96	10.2	0	82.0
East Shefford	13.2	13.8	1.05	9.0	0	76.8

Table 4.1 Summary statistics on MORECS and East Shefford weekly rainfall

The parameters in Table 4.1 show that the two datasets are very similar, but it should be noted that as both datasets are non-normally distributed, the values of mean

and standard deviation might not be representative of the magnitude and variability of the datasets. However, the median values, which may be more representative, are also similar.

There is a strong positive correlation between the two datasets, with MORECS rainfall being 102% of East Shefford rainfall, the relationship having an R^2 value of 0.88, although the coefficient of determination must be treated with caution due to the non-normal distributions of the base data. Overall, it can be concluded that MORECS rainfall adequately represents the rainfall in the Lambourn catchment and that it does not contribute significantly to the systematic underestimate observed when comparing MORECS EP with catchment discharge.

4.2.4 Correlating monthly EP with catchment discharge

Weekly MORECS EP data was used to calculate EP to the nearest month, and was then compared with the total monthly catchment discharge in millimetres. The initial assessment used linear regression analysis to compare monthly total EP with monthly total discharge, the latter being lagged over a period of zero to five months, with the results presented in Table 4.2.

Discharge delay (months) **Regression parameter**	**0**	**1**	**2**	**3**	**4**	**5**
Multiplier	0.17	0.32	0.36	0.30	0.17	0.04
Offset	24.2	21.3	20.6	21.9	24.3	26.7
R^2	0.12	0.42	**0.52**	0.33	0.10	0.01

Table 4.2 Results of linear regression correlation between monthly MORECS EP and monthly total catchment discharge

From Table 4.2 it is apparent that the best correlation is provided by discharge lagged two months behind the EP, with approximately 50% of the variance in discharge being explained by the variance in EP. This suggests that the most frequently occurring (modal) duration, from infiltration of precipitation at the ground surface to discharge from the catchment, is two months, and that the greatest influence upon the discharge in any single month *M* is the rainfall in *M-2*. One striking element of the various regression equations is the uniformity in the offset, which varies from 21 to 27mm. This indicates that when EP is zero, as it is for most summer months, discharge in the following months is around 25mm/month. This equates to an instantaneous discharge of around 1.6

cumecs, which closely approximates the long-term average discharge of 1.7 cumecs, suggesting that the regression equations are at least representative on an order of magnitude scale.

To extend these relationships, values for moving average EP, over periods of two to twelve months, were plotted against catchment discharge, both with and without a delay period. The results of the moving average correlations with no delay are given in Table 4.3, whilst the R^2 values for the various correlations are presented graphically in Figure 4.6, with the R^2 values of equivalent relationships having a one month delay shown for comparison. Using a delay of two months or greater generally resulted in a poorer correlation, and these are not shown.

EP moving average period (months) / **Regression parameter**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Multiplier	0.35	0.50	0.63	0.75	0.85	0.93	1.00	1.05	1.10	1.12	1.15
Offset	20.8	17.9	15.5	13.3	11.5	10.1	8.8	7.8	7.0	6.5	6.1
R^2	0.35	0.57	0.71	**0.77**	0.75	0.68	0.58	0.49	0.40	0.35	0.32

Table 4.3 Results of linear regression correlation between various monthly moving averages of MORECS EP and monthly total catchment discharge

The pattern of R^2 values revealed in Figure 4.6 shows that the optimum correlation is achieved for a five month moving average with no delay, closely followed by a six month moving average with no delay and a three month moving average with a delay of one month. Both the delayed and undelayed correlations display a similar pattern, with a gradual rise to a peak value followed by a gradual descent. The peak R^2 value in both cases (delayed and undelayed) is significantly higher than that achieved from any single month (shown in Table 4.2), which demonstrates the 'smoothing' influence of aquifer storage, buffering recharge variability over a number of months.

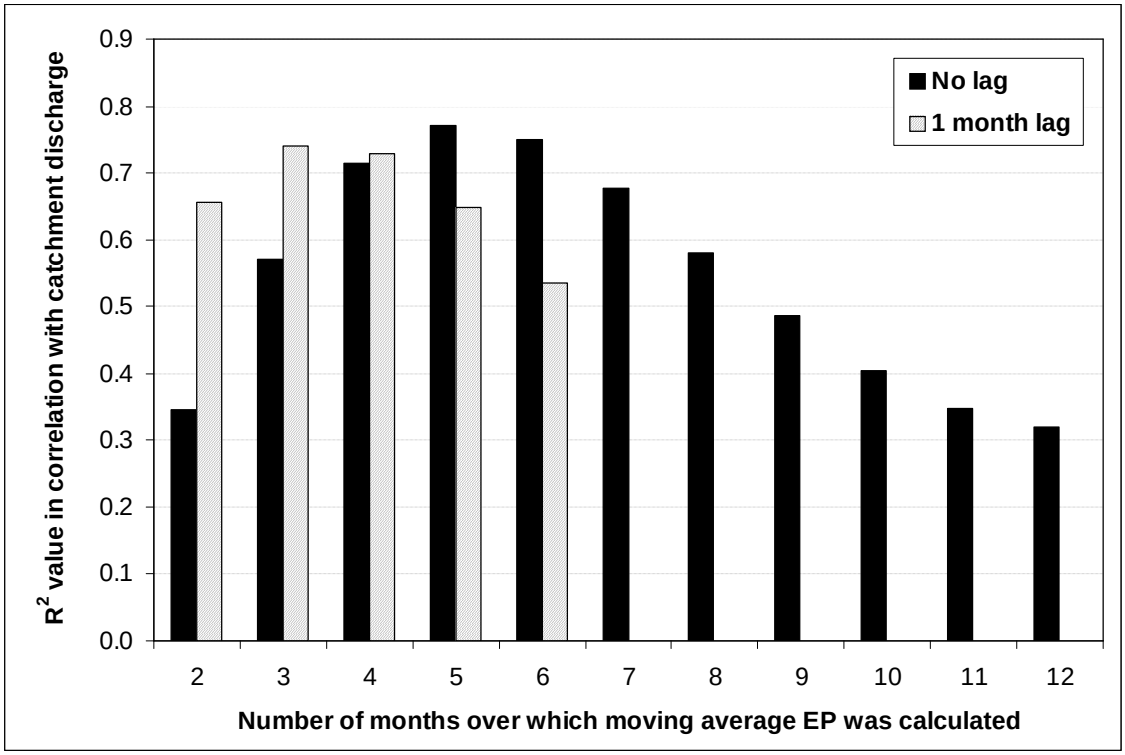


Figure 4.6 Correlation results from linear regressions between MORECS EP moving averages and monthly catchment discharges for the period April 1978 to February 2001

Calculation of a synthetic catchment discharge record based upon EP

To assess the effectiveness of estimating catchment discharge from EP, the linear regression relationship with the highest coefficient of determination (R^2 =0.77) was used to calculate a synthetic record of catchment discharge. The equation is given below and the resulting synthetic record is shown in Figure 4.7, with the actual record of catchment discharge for comparison.

Synthetic discharge was calculated from:

$$Q = \{0.75 \times EP_{5Mma}\} + 13.3 \qquad \text{Equation 4.2}$$

Where:

Q	=	catchment discharge (mm)
EP_{5Mma}	=	Five month moving average EP (mm)

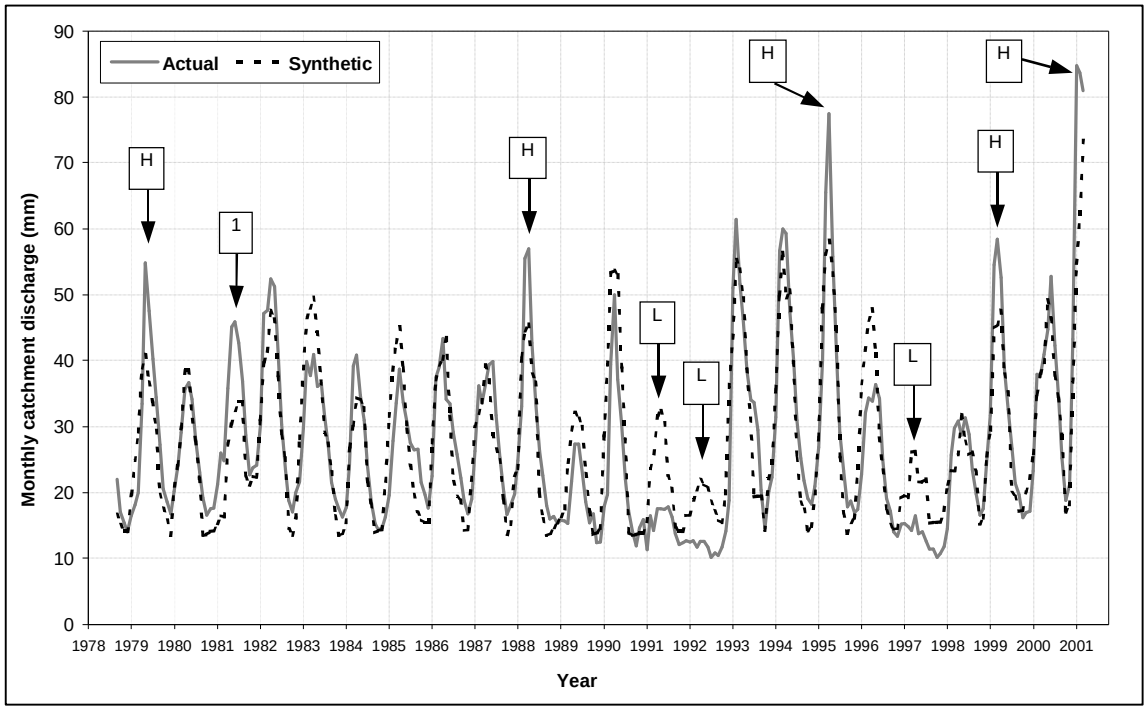


Figure 4.7 Comparison of recorded monthly catchment discharge and synthetic discharge calculated from the five month moving average of MORECS EP
(see text for explanation of annotation)

It is apparent from Figure 4.7 that the synthetic record generally represents average hydrological years successfully, both in terms of timing and magnitude. This indicates that the five-month moving average value realistically represents the recharge – discharge time lag under average conditions. However, the modelled record is less accurate in portraying more extreme circumstances. In years with high peak monthly discharges (> 50mm, annotated '**H**'), such as 1978/79, 1987/88, 1994/95 and 1998/99, the modelled record tends to underestimate the peak values. However, the converse is true for hydrological years with low peak (and total) recharge (annotated '**L**'), such as 1990/91, 1991/92 and 1996/97, where the modelled value is significantly higher than the recorded one. Overall, the synthetic dataset shows much less variability than the observed record.

This pattern is partly due to deviations from the calculated best fit EP_{5Mma}-to-discharge multiplier of 0.75 (Equation 4.1), upon which the synthetic series is based. For example in 1980/81 ('**1**' in Figure 4.7), the modelled value of peak discharge is well short of the actual value, although the peak is not particularly high. However, it was in

this year that MORECS EP was only 47% of catchment discharge (see Section 4.2.2), which equates to the maximum underestimate of true recharge by MORECS, and thus the EP-based model underestimates the discharge.

Overall, this illustrates the effects of variability in the EP-to-discharge ratio and demonstrates that MORECS based estimates of EP are at their least accurate during low recharge years. This is in accordance with the known shortcomings of the system that are recognised by The Met. Office (1992); "All errors are likely to be higher…in very dry summers".

4.2.5 Conclusions on monthly recharge and discharge correlation

If there were no lag in the recharge – discharge system, akin to the scenario in an impermeable catchment, we would expect discharge to be best approximated by the EP of the present month. If a spatially consistent delay mechanism influenced the catchment then we would expect the best correlation to be achieved by the EP value of a single month, delayed by a certain period. The fact that the best overall approximation of catchment discharge is provided by a monthly moving average indicates that there are spatially variable lag times within the system.

The pattern of R^2 values in Figure 4.6 illustrates the influence of time lags on the recharge – discharge sequence. If we consider the relative influence of individual months on the discharge in any month *M*, then we know from Table 4.2 that EP in month *M* itself has a very weak correlation, whilst the correlation is much stronger for *M-1* and the correlation peaks at *M-2*, before weakening at *M-3* and at greater time lags. This suggests that *M-2* represents the modal delay and thus a reasonable estimate for the average lag time would be two months.

Consequently, we might expect that the optimum moving average correlation would be achieved over a three-month period, lagged by one month, and indeed this does produce a strong correlation with an R^2 value of 0.74. However, this is slightly weaker than the R^2 value of 0.77 achieved using a five-month moving average (with no delay), as shown in Figure 4.6, which demonstrates that approximately 77% of the variance in the record of catchment discharge can be accounted for by the variance in the five-month moving average of EP.

The inclusion of each additional month in the moving average, from a two-month moving average ($2M_{ma}$) to a $5M_{ma}$, improves the correlation with catchment discharge (i.e. for months *M* to *M-4* inclusive), but from a $6M_{ma}$ onwards (i.e. including *M-5* and beyond) the correlation deteriorates. This indicates that the majority of recharge appears as catchment discharge within five months (i.e. from the beginning of *M-4* to the end of *M*), and that recharge with a transit time of greater than five months probably represents less than 25% of the total. However, identifying an **effective** maximum transit time (proposed as the duration over which, for example, 95% of recharge emerges as catchment discharge) is not possible using simple linear regression statistics. To overcome this, multiple linear regression was used to correlate catchment discharge with EP from months *M* to *M-10* jointly, with each additional month being added separately. This approach produced ten separate linear regression models, and subsequently ten values for the coefficient of determination. These are presented in Table 4.4, with the change in R^2 value being presented graphically in Figure 4.8.

Monthly EP range	*M*	*M to M-1*	*M to M-2*	*M to M-3*	*M to M-4*	*M to M-5*	*M to M-6*	*M to M-7*	*M to M-8*	*M to M-9*	*M to M-10*
R^2	0.12	0.42	0.66	0.75	0.79	0.80	0.81	0.82	0.83	0.83	0.83
Change in R^2		0.304	0.238	0.092	0.036	0.016	0.009	0.008	0.006	0.003	0.000

Table 4.4 Results of multiple linear regression between monthly EP and catchment discharge

It is apparent from Figure 4.8 that there is a break in the profile of R^2 increase between the models of *M to M-9* and *M to M-10*. Although the actual incremental change between these two months is exaggerated by the logarithmic scale, a change in behaviour seems to occur at this point, indicating that over timescales greater than ten months (from the beginning of *M-9* to the end of *M*), no effective increase in correlation between EP and discharge occurs. Thus, ten months appears to be a representative estimate for the maximum transit time, from infiltration to discharge, through the active zone of the chalk aquifer (Section 3.2.3), comprising the uppermost 60m below the average water table.

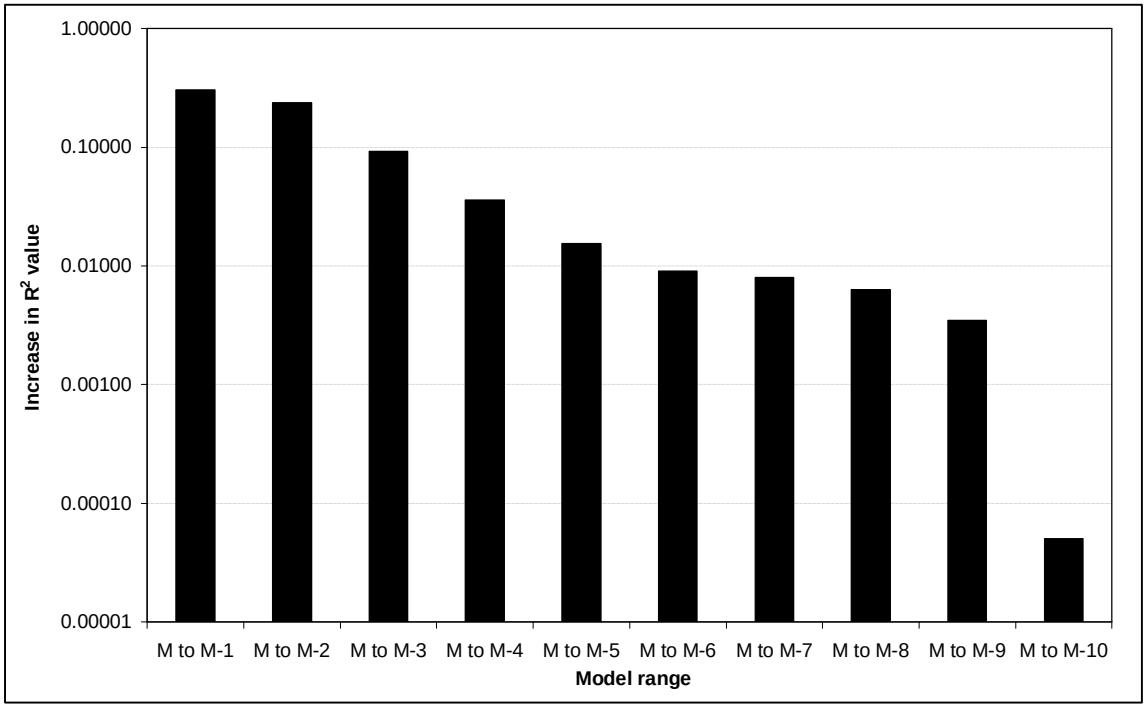


Figure 4.8 Change in R^2 values with inclusion of additional EP months in multiple linear regression models

The actual value of ten months as the effective maximum transit time is important as it suggests that significant recharge (in terms of infiltration reaching the water table) may be occurring throughout the year. Figure 4.3 showed that average MORECS EP was less than 5mm/month from May to September inclusive, indicating that summer recharge was effectively insignificant. However, if a delay of up to ten months is taken into account, then significant recharge may be occurring during the summer. This has ramifications for calculations of chalk storage that use baseflow recession techniques, such as the study undertaken by Lewis *et al*. (1993), which was re-evaluated by Price *et al.* (2000). These studies assumed that no recharge was occurring during the recession period, and that all water was being derived from saturated storage. If this assumption is found to be invalid, then the defined values of storage may overestimate the actual values. However, the proportion of total recharge having a travel time between five and ten months is probably less than 25%, and so the degree of any overestimates in storage parameter will be limited.

The estimate of five months for the period within which around 75% of recharge appears as discharge has implications itself, and two end-member scenarios can be envisaged for this time lag:

1. Normal water year maximum discharge in April, occurring at the end of the recharge season
2. Normal minimum discharge in October, at the end of a period of flow recession

In the first scenario, the maximum water year discharge will be estimated from the moving average EP of the preceding five winter months of high recharge, which will have significant inter-annual variability. In the second scenario, the minimum discharge will result from the normal absence of recharge over the summer months, and will thus tend towards a common value regardless of whether the maximum discharge, at the onset of recession, is high or not. Essentially the higher starting point of the recession period is compensated for by a higher rate of recession during the period. This is an important aspect in terms of water resource management, as it suggests that reduction of groundwater abstraction in the winter will not improve late summer low flows, as the water is lost naturally from the system anyway (Rushton, 2002).

However, in addition to the recharge – discharge processes operating on timescales of months, from careful examination of discharge hydrographs there is evidence that a small proportion of rainfall reaches the river very rapidly, on a scale of hours and days, and this rapid response element is the focus of the following section.

4.3 RAPID CATCHMENT RESPONSE TO RAINFALL

4.3.1 Occurrence

Rapid fluvial response to rainfall in the Lambourn catchment is shown by the minor discharge peaks that coincide with significant rainfall events (exceeding 15mm/d), which are superimposed upon the seasonal pattern of the discharge hydrograph. Whilst almost insignificant in terms of the gross catchment water budget, these peaks are illustrative of a little known facet of chalk stream hydrology, and may be ecologically significant, for example in terms of the mobilisation of fine sediment. These peaks are best illustrated using a dataset of fine temporal resolution, such as that recorded at 30-

minute intervals from East Shefford gauging weir during this study, which is presented together with locally recorded daily rainfall in Figure 4.9. A number of small magnitude, short duration discharge peaks are highlighted in Figure 4.9, and these result from intense rainfall events, generally with magnitudes exceeding 20mm/day. The rapid catchment response to such events was investigated by Gasquoine (1978), who sought to understand the processes controlling the 'fast response' to certain rainfall events. Gasquoine was able to establish a credible relationship between riparian (floodplain) extent and volumes of peak flow (above baseflow) generated from the 17 rainfall events that she studied, but was unable to define a reliable predictor for the proportion of rainfall from any event that appeared as 'fast runoff'. Her approach was inevitably restricted by having no access to high temporal resolution data for shallow groundwater levels in floodplain areas. This shortfall has been overcome in the current study, as 30-minute interval data for both a shallow piezometer and river stage (discharge) were recorded at West Shefford monitoring site, with river temperature and conductivity also being recorded (Section 3.4.2). The use of these datasets to characterise a rapid response event is described in the following section.

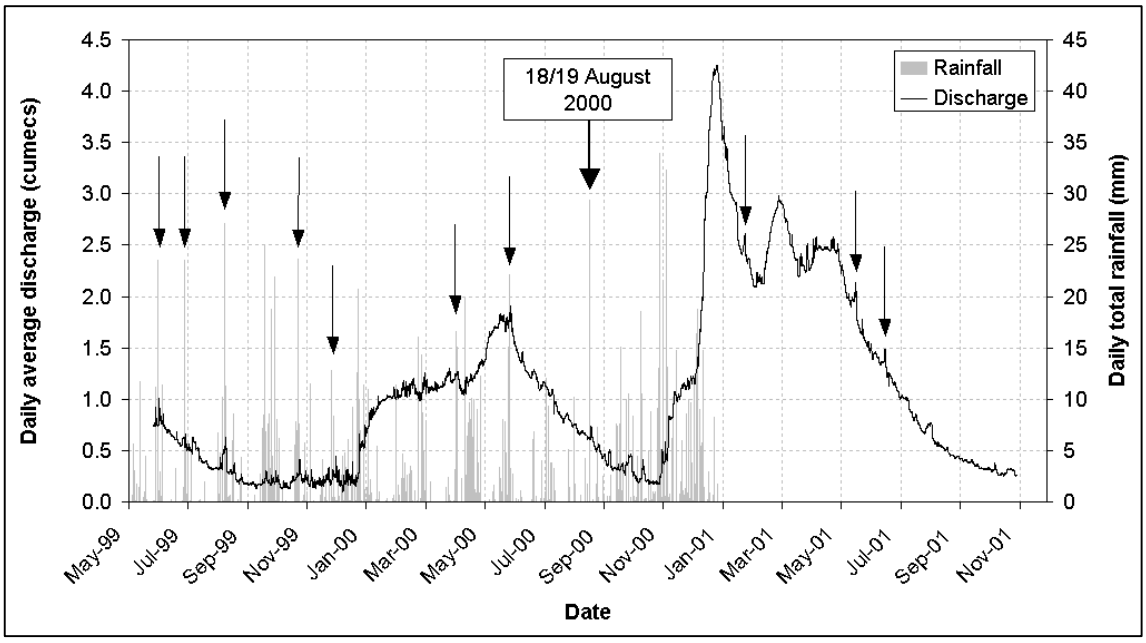


Figure 4.9 The 30-minute interval hydrograph from East Shefford gauging weir, with some rapid responses to rainfall events highlighted
(NB Local rainfall data is only available to 31/12/00)

4.3.2 Characterisation of a rapid response event

To define accurately the timescale of the catchment's rapid response to rainfall, a well-defined (high magnitude/short duration) rainfall event is required, such that a discharge peak can be reliably associated with the event. During the monitoring period for this study, the optimal circumstances occurred on only one occasion, the morning of 18th August 2000.

Between 0900 on 18th August and 0900 on 19th August 2000, 29.4mm of rainfall was recorded at East Shefford rainfall station, located 1.7km south-east of West Shefford monitoring site. No significant rainfall was recorded for two weeks prior to this event, or in the week immediately following it. This event produced the highest rainfall recorded for a summer day (April to September inclusive) in the period from October 1998 to December 2001, and was the fourth highest daily total during this period, regardless of season.

The MORECS data for the week of the 16th to 22nd of August show a rainfall total of 8.6mm, indicating that the Lambourn event was localised, and thus more likely to be convective than frontal in nature. The Meteorological Office Monthly Assessment for August 2000 states: "More thundery rain affected the Midlands, Wales and East Anglia, especially on the 18th " (The Met. Office, 2000). This also suggests that the event was convective in nature, probably lasting no more than an hour, and with a rainfall intensity of around 30mm/hour.

The MORECS EP value for the week of the 16th to 22nd is 0.5mm, which is similar to the value from the six preceding weeks, indicating that even at this late stage in the summer, a significant soil moisture deficit (SMD) had not developed, and that even small amounts of rainfall could produce recharge.

Even if a SMD had been present, the intensity of the rainfall may have been sufficient to overcome it. Jones & Cooper (1998) report that a single rainfall event of 42.5mm in June 1985, at a site on the Middle Chalk in Cambridgeshire, was sufficient to overcome a significant SMD and produce rapid recharge to a depth of 5m within 24 hours, whilst other events, with over 20mm of rainfall, produced no recharge under similar antecedent conditions. Thus, a rainfall event of 30mm appears to lie close to the

threshold of rainfall intensity (for a chalk catchment) that may produce recharge even when a significant SMD exists.

Shallow groundwater and river discharge response

Figure 4.10 shows the reaction of the shallow groundwater level and the river discharge at West Shefford to the rainfall event of 18th August 2000. Both parameters had started to rise by 10:00 on the 18th, suggesting that the start of the rainfall event commenced only a few minutes after the reading of the rain gauge at 09:00. Both parameters peaked at 12:00 on the 18th, giving the duration from rainfall onset to peak response as less than three hours. The river returned to its pre-event discharge within twelve hours of its peak level, but the shallow groundwater took about three days to recede.

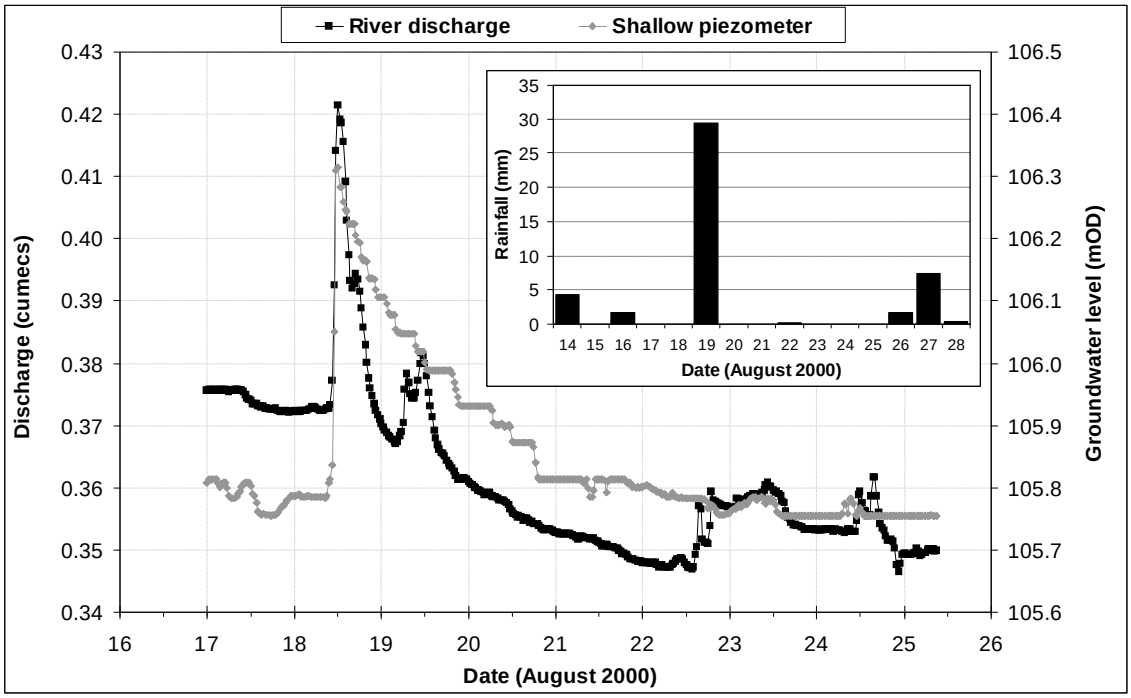


Figure 4.10 River discharge and shallow groundwater level at West Shefford with local rainfall data (inset)
[Rainfall is for the 24-hour period up to 09:00 on the given date]

A small additional discharge peak occurred on the 19th, and this may indicate a small amount of rainfall at the end of the 24-hour period to 09:00 on the 19th, but is more likely to be discharge from the main rainfall event that had been delayed in transit. Additionally, there is a small (0.10 – 0.15 cumecs) but sustained increase in river

discharge from 12:00 on 22nd August to 22:00 on 24th August. This shallow peak was not due to a local rainfall event, as no further rainfall had been recorded at the local rain gauge since 09:00 on the 19th. However, it could possibly have resulted from rainfall occurring upstream of the monitoring site, but there are no available records from up-catchment rain gauges to verify this. Alternatively, it is possible that this delayed peak represented rainfall from the original event that had fallen on non-saturated floodplain areas, and had taken about two days to infiltrate to the water table and move laterally before being discharged into the river channel. An examination of the physico-chemical data, which are described below, gives some evidence to support this explanation.

Physico-chemical parameter response

Physico-chemical parameters can help identify the contributions of different water sources to river discharge at a detailed timescale, especially during extreme events such as periods of intense rainfall (e.g. Crandall *et al*., 1999; Redwine & Howell, 2002). In Figure 4.11, river temperature, river electrical conductivity (EC), temperature-corrected EC and discharge from West Shefford are presented to compare the timing in their patterns of response.

It is apparent that the rainfall event influences both temperature and EC, each of which has a well-defined diurnal pattern. Logged values of EC are influenced by temperature, which is internally corrected by the logging programme (Section 3.4.2), but an external calibration for temperature was also required during data verification. In order to clarify the influence of temperature upon EC, it is also presented in a form that has been corrected for diurnal temperature variability.

Considering first the river temperature time series, the principal discharge peak coincides with a bench in the normal diurnal temperature cycle, indicating that there has been an input of colder water to the system. This is consistent with either the rapid runoff of cool, convective rainfall or the discharge of cold groundwater. The influence of this cool input is also apparent in the daily maximum temperature, which is 1 to 1.5°C lower than preceding days and occurs about four hours later than for adjacent days. The minor discharge peak on the 19th appears to have little effect on the temperature profile, as does the small, sustained peak on the 22nd – 24th.

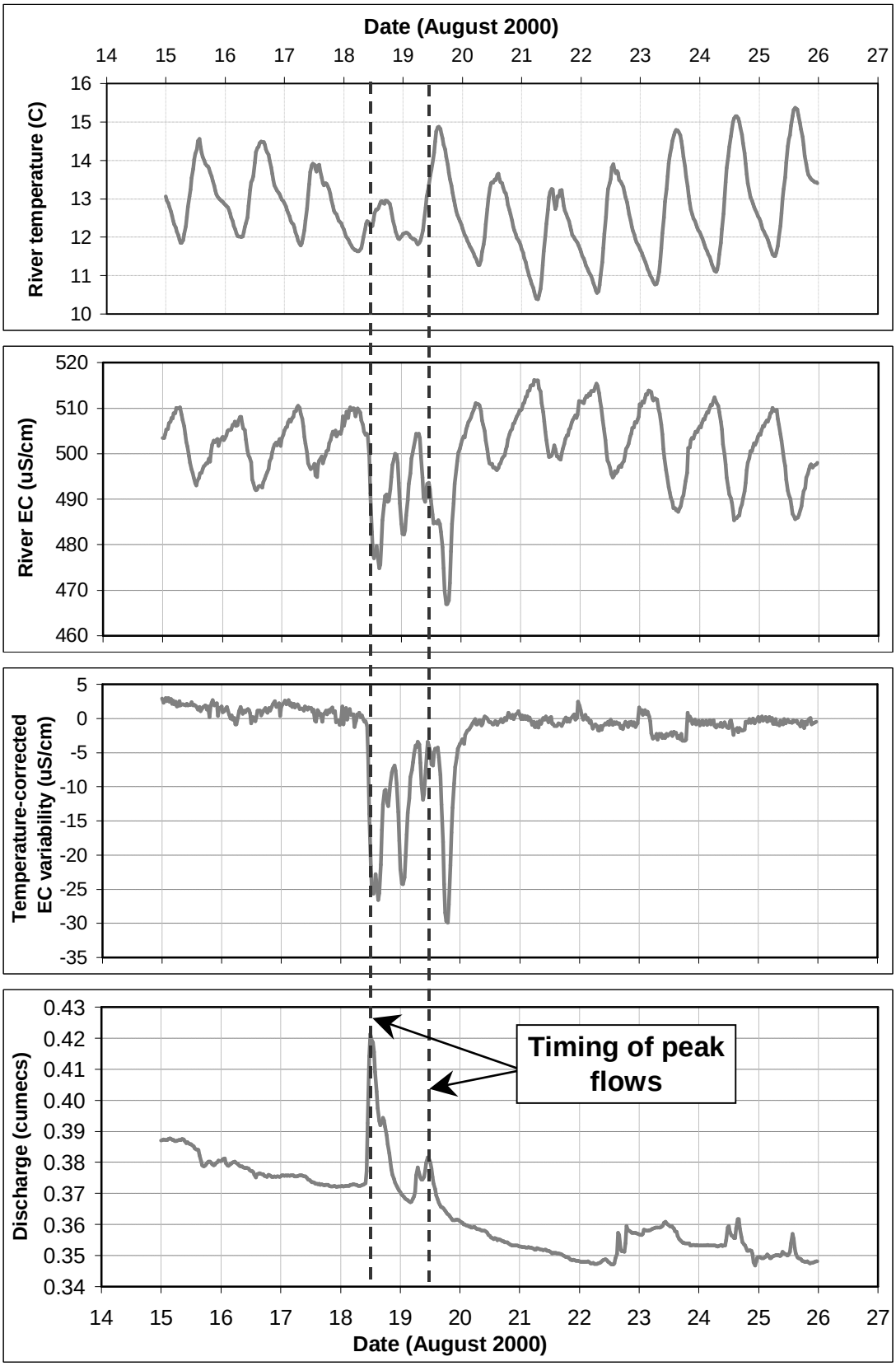


Figure 4.11 River temperature, river EC, temperature-corrected EC and discharge from West Shefford for a period in mid-August 2000

The temperature-corrected EC profile shows the influence of the rainfall event more clearly than the uncorrected profile, and it appears as three distinct troughs, indicating that there were several phases of dilute inputs to the river. The first trough, showing an EC reduction of around 25µS/cm, coincides with the principal discharge peak. A simple mixing calculation, based upon 1 part rapid response water to 7.5 parts 'original' water at 500µS/cm (the ratio derived from the pre-event discharge of 0.373 cumecs and the increase in discharge of 0.050 cumecs), indicates that the EC of the rapid response water was around 280µS/cm. A value for the mean EC of rainfall from an upland catchment of 25µS/cm (Wilkinson *et al.*, 1997) is used here to represent rainfall, whilst chalk spring water in the Lambourn catchment is estimated at 480µS/cm, based upon field results derived from this study.

Using these values, we can infer that the rapid response water could comprise around 44% rainwater and 56% chalk groundwater. However, this takes no account of the EC of shallow groundwater in the alluvial deposits, for which no information is available. There is no soluble matter in the local shallow alluvial material that is likely to increase the EC of alluvial water above that of chalk groundwater, and so this water is likely to comprise a mixture of pre-event rainwater, river water and chalk water, which together would not exceed the EC value of chalk water alone, and could thus approximate the EC value of the rapid response water.

The second trough in the temperature-corrected EC profile does not coincide with any peak in the discharge record, but to the point of return to approximate baseflow conditions following the principal discharge peak, whilst the third EC trough coincides with the return to baseflow conditions following the secondary discharge peak. From this behaviour, we can conclude that EC conditions were not consistent for the duration of the discharge peaks, with the rising limb of the peak having lower EC than the receding limb. This indicates that there was an initial flush of relatively dilute water (with a high rainfall component), followed by a receding component with higher EC, probably with a greater proportion derived from chalk groundwater.

The small sustained discharge peak from 22nd to 25th August is reflected in a subdued manner in the temperature-corrected EC profile, which displays a minor but distinct trough on the 23rd, showing an EC reduction of about 3µS/cm, whilst there is no

perceptible impact on the temperature profile. From this, we can infer that the water input for this peak had equilibrated with ambient temperature, but that it comprised a proportion of dilute water (rainfall) causing the reduction in EC. This lends some weight to the suggestion that it is rainfall from the original event on the 18th, which has taken a longer flow path and been delayed in transit.

In summary, it is apparent that the River Lambourn can respond rapidly to intense rainfall events with daily totals exceeding 15mm. It appears that the reaction occurs on a timescale varying from a few hours to a few days and that the rapid response component of discharge is derived from floodplain areas.

4.4 CONCEPTUALISATION OF THE RIVER – AQUIFER SYSTEM

Based upon the findings of the preceding sections concerning the relationships between rainfall, recharge and discharge, we can conceptualise the movement of water through the system as following two broad pathways, dependent upon the spatial location of the recharge. These are presented schematically in Figure 4.12.

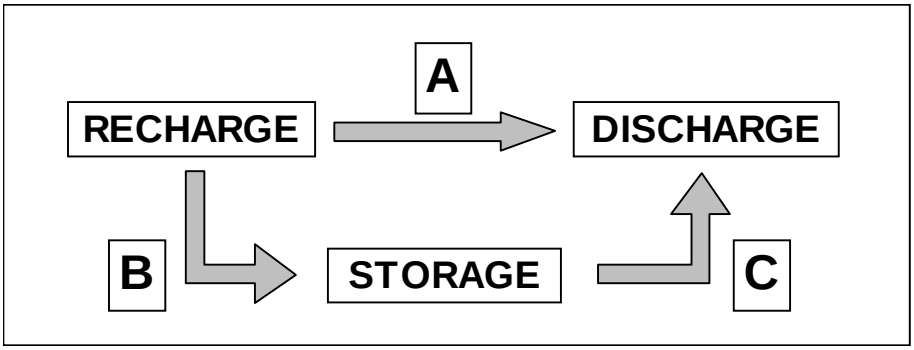


Figure 4.12 Conceptual elements of recharge transmission

A = Rapid discharge of precipitation falling upon floodplain and near-floodplain areas, characterised by shallow groundwater levels and no significant unsaturated zone (average depth to water table < 5m). Discharge is via direct runoff, interflow or rapid infiltration and shallow groundwater flow.

B = Vertical movement of water from the ground surface to the water table, through the unsaturated zone, in non-valley and interfluve areas with average depth to water table > 5m.

C = Lateral movement of water, from interfluve areas to the river valley, through the saturated zone.

From the estimates of recharge lag times detailed in Section 4.2.5 we can now start to quantify time components A, B and C. Based upon a plot of average depth to water table we can estimate that the area of the Lambourn groundwater catchment where component A is dominant (defined as an average unsaturated zone thickness of less than 5m), is 18% of the catchment area. Thus, the area where components B and C take place (which occur in series, not in parallel), cover 82% of the catchment.

Both the average recharge-to-discharge lag time (transit time) of two months and the effective maximum transit time of ten months will be dependent upon the travel times for each component, and the proportion of total flow that is utilising each route.

Thus, we can state that:

$$(0.18A_{av}) + 0.82(B_{av}+C_{av}) = 2 \text{ (months)} \qquad \text{Equation 4.3}$$

and:

$$(0.18A_{max}) + 0.82(B_{max}+C_{max}) = 10 \text{ (months)} \qquad \text{Equation 4.4}$$

Where:

A, B and C represent the transit times through the aquifer – river system via the routes described above and the '$_{av}$' and '$_{max}$' suffixes relate to average and maximum transit times respectively.

This derivation alone is of limited use, but inserting values for the component parameters allows it to become it become a functional tool for assessing the bulk response of the catchment to recharge.

From work in Section 4.3, which investigated the rapid response of the catchment to rainfall, we can derive estimates for parameter A. The minimum value for pathway A is only a few hours and it appears that there may be a secondary value of two to three days. From these defined values, we can conservatively estimate A_{av} to be about one week (0.25 months) and A_{max} to be about two weeks (0.5 months), although as the dominant timescale for Equations 4.3 and 4.4 is in months, they will not be sensitive to

imprecision in estimation of parameters A_{av} and A_{max}. Thus from Equation 4.3, we can state that:

$$(0.18 \times 0.25) + 0.82(B_{av}+C_{av}) = 2$$

$$0.82(B_{av}+C_{av}) = 1.96$$

$$B_{av}+C_{av} = 2.4 \text{ (months)} \qquad \text{Equation 4.5}$$

In addition, from Equation 4.4, we can state that:

$$(0.18 \times 0.5) + 0.82(B_{max}+C_{max}) = 10 \text{ (months)}$$

$$0.82(B_{max}+C_{max}) = 9.91$$

$$B_{max}+C_{max} = 12.1 \text{ (months)} \qquad \text{Equation 4.6}$$

Values for parameter B are estimated in the section below and this allows values for C to be calculated.

4.5 VARIATION IN GROUNDWATER LEVELS AND CATCHMENT DISCHARGE

Whilst the preceding sections considered the start and end points of the recharge–storage–discharge sequence, the approach is limited in its effectiveness, as no account is taken of storage. The degree of storage being utilised at any point in time can be considered as the level of the water table across the catchment. In order to assess this influence on a catchment-wide basis, a representative measure for catchment-wide groundwater levels is required and this is provided by the Mean Groundwater Stage [MGS] (Brettell, 1971). Calculation of this parameter has been described in Section 3.5.3, and the following sections describe the correlation of catchment discharge and MORECS EP with monthly MGS, and the refinement of the timing parameter equations described above, which elucidate some temporal characteristics of the recharge – storage – discharge sequence.

4.5.1 Average annual patterns of MGS and catchment discharge

The annual patterns of catchment groundwater levels and catchment discharge are given in Figure 4.13, which shows that the two parameters display a similar pattern.

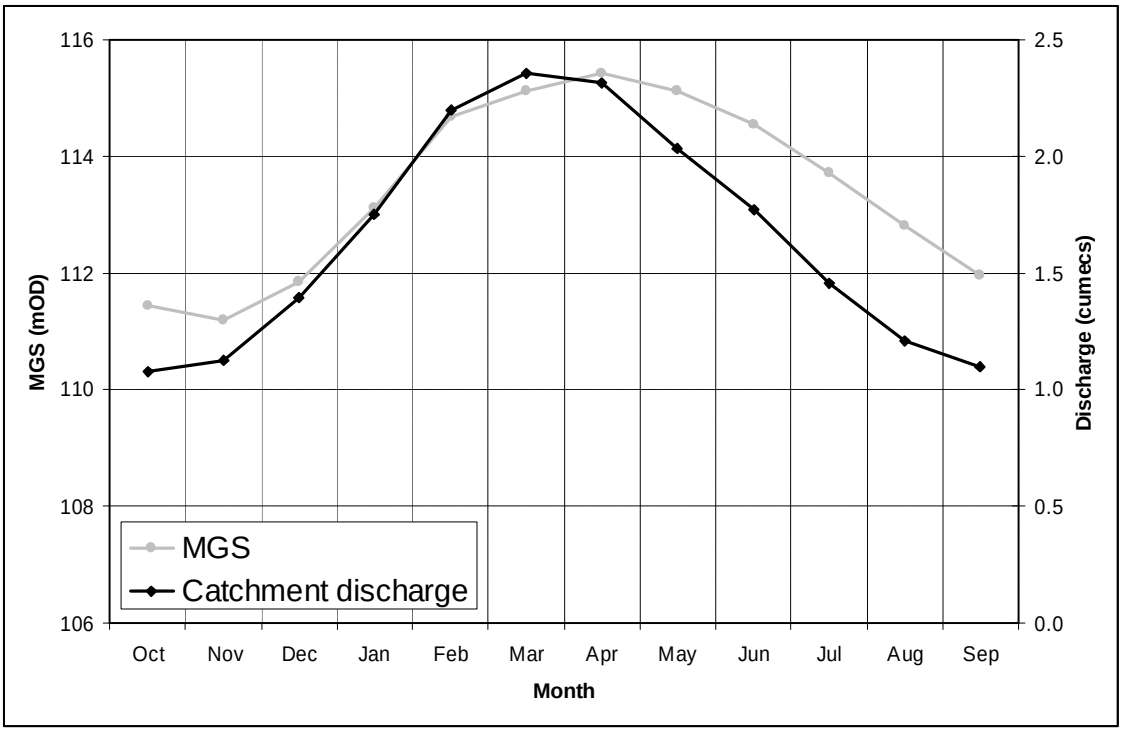


Figure 4.13 Monthly average values of MGS and catchment discharge for the period September 1975 to December 1993

Both MGS and catchment discharge commence the water year at a low level, with the minimum discharge occurring in October and the minimum MGS in November. The peak MGS level also occurs a month after the peak discharge, in April and March respectively. The main difference between the two parameters occurs during the receding limb of the hydrograph, with the MGS receding at a lower and more consistent rate than the discharge, which has a more exponential form.

The data presented in Figure 4.13 are plotted in Figure 4.14, with linear and exponential regression relationships. Owing to the dissimilar numerical scales of the two variables, a proxy value of MGS (MGS – 106m) has been used, and this provides a more viable exponential relationship. This proxy measurement represents a catchment groundwater storage parameter.

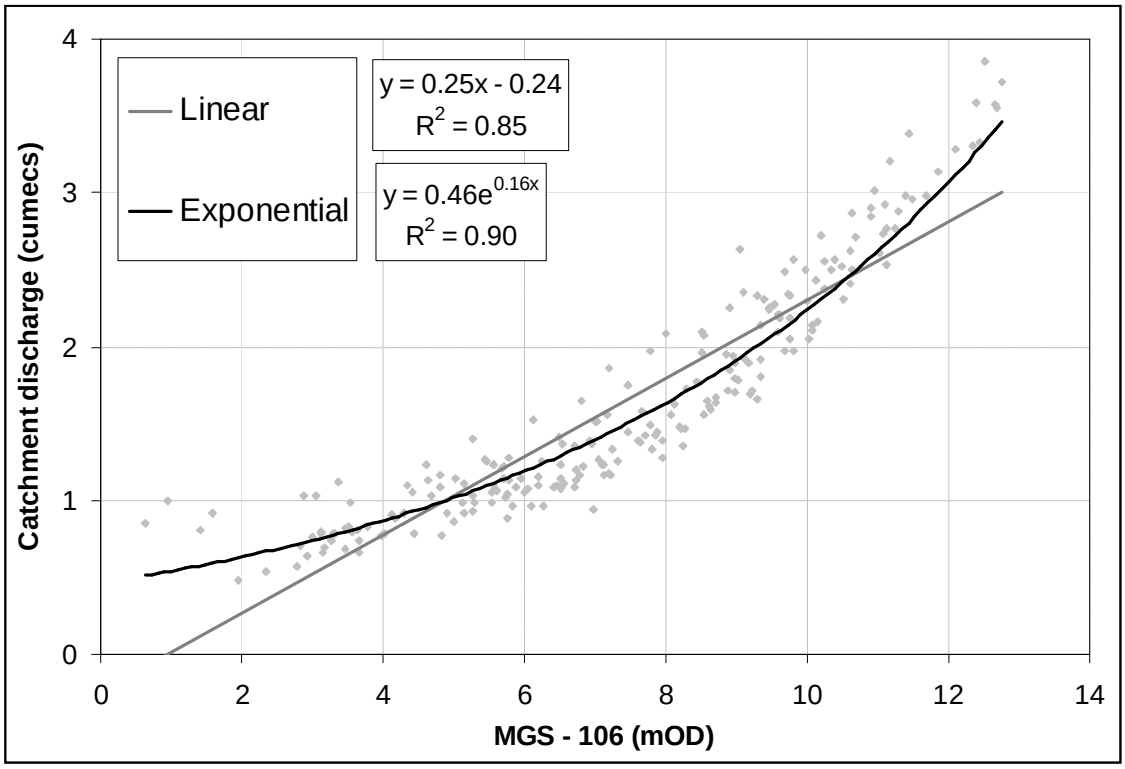


Figure 4.14 Monthly average catchment discharge versus MGS proxy for the period September 1975 to December 1993

We can see from Figure 4.14 that while the linear relationship has a strong correlation (R^2 = 0.85), the data series has a clear concave shape, suggesting that the data are better represented by an exponential relationship (R^2 = 0.90). The form of the relationship suggests that catchment storage invokes increasing influence on discharge at higher groundwater levels. It appears that the curve approaches a maximum value for storage (as it becomes vertical), at which point storage remains fixed, but discharge increases infinitely. However, if the curve is extrapolated it shows that no such limiting value for storage is reached within realistic values of the parameters. However, we can recognise that the gradient becomes increasingly steep and thus the increase in discharge per unit increase in storage is also rising.

If the system were functioning as a true linear reservoir, both discharge and storage volume (represented here by the MGS proxy parameter) would decay exponentially against time at the same rate. Discharge would be directly proportional to storage volume, and thus:

$$Q_t \alpha S_t \quad \text{and} \quad Q_t = c\, S_t \quad \text{and} \quad c = Q_0 / S_0 \qquad \text{Equation 4.7}$$

Where:

Q_t = discharge at any time 't'
S_t = storage volume at any time 't'
Q_0 = initial discharge at onset of recession
S_0 = initial storage volume at onset of recession
c = a constant (in units of time^{-1})

As the relationship between discharge and storage is exponential in form, it demonstrates that the system does not function as a perfect single, linear reservoir. However, the high correlation for the linear relationship between discharge and storage indicates that the system can be effectively approximated as a linear reservoir, except where low flows are of critical importance.

4.5.2 Correlating monthly EP and MGS by linear regression

In order to identify average and maximum transit times for water to pass through the unsaturated zone, moving average and lagged MORECS EP were correlated with month-to-month changes in MGS using linear regression, with the results presented in Table 4.5.

Delay to change in MGS (months) **Regression parameter**	**0**	**1**	**2**	**Number of months moving average EP** **Regression parameter**	**2**	**3**	**4**
Multiplier	10.85	15.95	7.42	**Multiplier**	13.40	11.40	8.35
Offset	17.79	17.53	17.37	**Offset**	17.66	17.57	17.45
R^2	0.28	**0.63**	0.14	**R^2**	**0.63**	0.57	0.39

Table 4.5 Selected results of linear regression between monthly MORECS EP and month-to-month change in MGS value

It was found that the optimum (modal) lag time of EP was one month, with an R^2 value indicating that around 63% of the variability in MGS change in month *M* could be

explained by EP in month *M-1*. From the much weaker correlations with EP in months *M* and *M-2* it is clear that the majority of recharge takes between one and two months to pass through the unsaturated zone. This was confirmed by comparing the change in MGS with moving average EP, where the two-month moving average (the average of EP in months *M* and *M-1*) produced the strongest correlation, which was also 0.63. These findings suggest that a representative value for B_{av} would be one month.

From the linear regression analysis described above, we can estimate a value for B_{max} as three months. To verify this, multiple linear regression was undertaken to assess the relationship between monthly EP (for periods of *M* to *M-12* months) and change in MGS, with a selection of the resulting statistics presented in Table 4.6.

Monthly EP parameter	**Unstandardised coefficients**	**Standardised (Beta) coefficients**	**Correlations**	
			Zero order (R equivalent)	Partial
M	0.008	0.161	0.520	0.262
M-1	0.032	0.643	0.787	0.731
M-2	0.005	0.098	0.352	0.161
M-3	-0.010	-0.206	-0.051	-0.321
M-4	-0.007	-0.140	-0.267	-0.223
M-5	-0.004	-0.077	-0.370	-0.128
M-6	-0.004	-0.076	-0.382	-0.126

Table 4.6 Selected parameters from multiple linear regression between monthly EP and MGS
(see Appendix 9 for full results and explanation of terms)

Table 4.6 demonstrates that the EP parameters beyond *M-2* are characterised by negative coefficients and correlations, indicating that there is no meaningful relationship between EP and MGS on these timescales. From this, we can conclude that the value for B_{max} of three months estimated above is valid, and is an accurate representation of the effective maximum transit time through the unsaturated zone. These values for B_{max} and B_{av} are consistent with transit times through the unsaturated zone used in groundwater modelling by Bullock *et al.* (1995) for 'peripheral' and 'middle' areas of the Lambourn catchment.

The values of B_{av} and B_{max} can now be substituted into Equations 4.5 and 4.6 in order to derive values for C:

$B_{av}+C_{av} = 2.4$ (months) [Equation 4.5]

$1+C_{av} = 2.4$

C_{av} = 1.4 months

And:

$B_{max}+C_{max} = 12.1$ (months) [Equation 4.6]

$3+C_{max} = 12.1$

C_{max} = 9.1 months

The implications of these values for parameter C are explored in the section below.

4.5.3 Calculations based upon the derived values for parameters B and C

The values of parameter B, representing the travel time of recharge through the unsaturated zone of the aquifer, were compared with figures for unsaturated zone thickness to estimate the vertical unsaturated velocity. The 21 boreholes used to calculate the MGS value provided information on unsaturated zone thickness, resulting in a catchment average value of 28m and an effective maximum value of 80m. When used with the values of B_{av} (one month) and B_{max}, (three months) the resulting vertical velocities were both c. 0.9m/d, with the equally high velocities apparently occurring where the unsaturated zone is thickest, in the interfluve areas. Such values have been rarely reported in the literature, but these correspond well to time lags put forward by Oakes (1981) in a discussion by Calver (1997b).

To test the implications of the derived values for parameter C, it was assumed that C_{max} represented the transit time of recharge travelling via the longest groundwater flow paths in the catchment, from the catchment divide to the river. Nine such flow paths were defined, based upon contours of average groundwater levels across the catchment, and these are shown in Figure 4.15. The length of each flow path was measured and the hydraulic gradient from the groundwater divide to the perennial river channel was calculated; the resulting values are presented in Table 4.7.

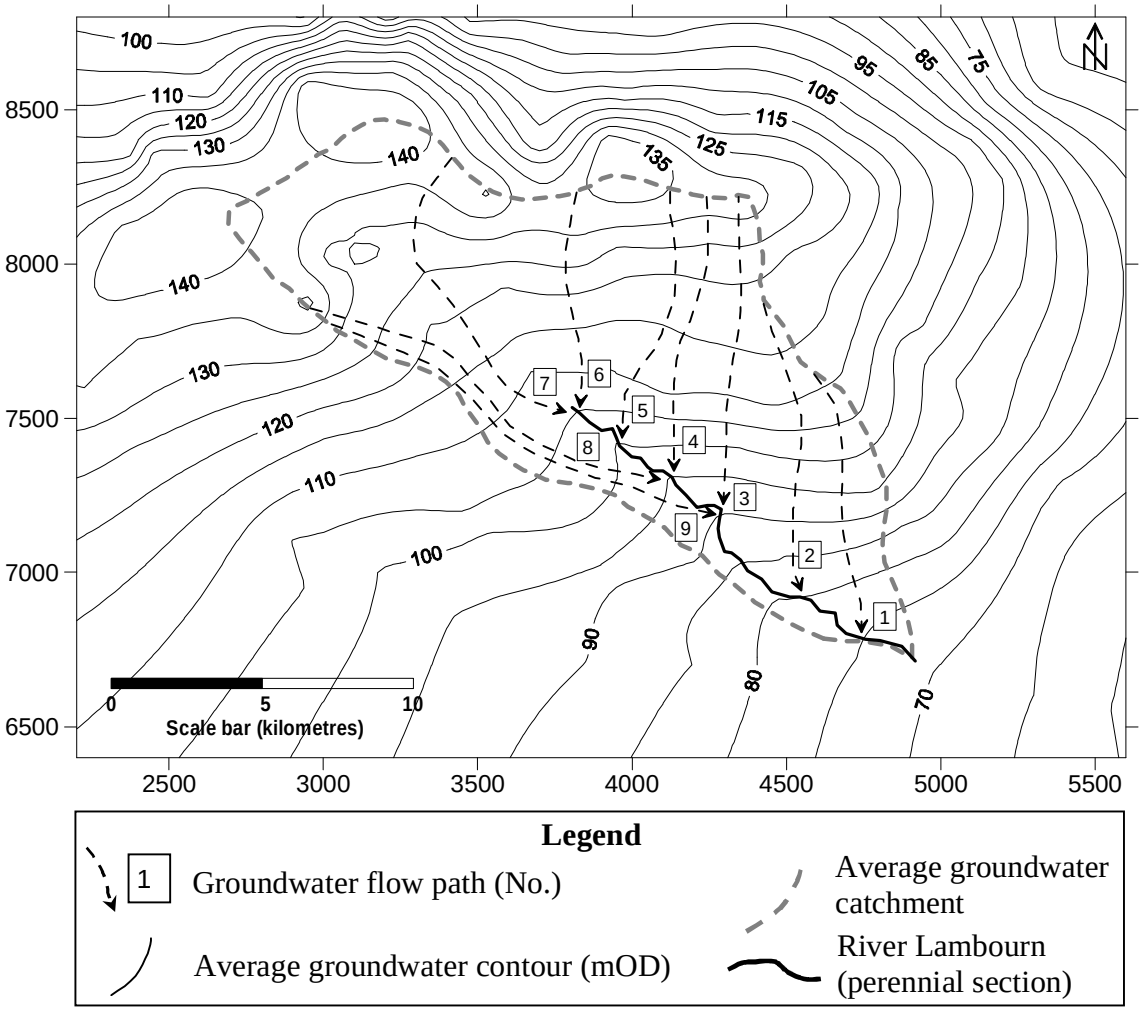


Figure 4.15 Groundwater contour map showing 9 defined groundwater flow paths to the River Lambourn
(The axis labels are Ordnance Survey *Landranger* co-ordinates for square SU, with units of 10's of metres, giving major axis intervals of 5km)

Flow path no. / Parameter	1	2	3	4	5	6	7	8	9
Catchment divide groundwater level (mOD)	112	118	131	133	135	134	138	140	132
River level (mOD)	75	80	90	95	100	105	100	95	90
Elevation change (m)	37	38	41	38	35	29	38	45	42
Flow path length, L (m)	9000	8600	10000	10000	10000	8900	12900	13900	14300
Gradient, i	0.0041	0.0044	0.0041	0.0038	0.0035	0.0033	0.0029	0.0032	0.0029

Table 4.7 Details of groundwater flow paths defined for assessment of C_{max}

An expression was then derived for C_{max} in terms of aquifer parameters based upon Darcian principles, assuming that the chalk aquifer at the catchment scale could be

represented by an equivalent porous medium analogy, i.e. that it acted in the same manner as an intergranular aquifer. This approach is valid providing groundwater flow remains laminar, but would be invalid if turbulent flow took place. Thus, we can state that:

$$v = L / C_{max} \qquad \text{Equation 4.8}$$

Where:

v = groundwater flow velocity (average linear velocity, *sensu* Freeze & Cherry, 1979; p. 71)
L = maximum flow path length (m)
C_{max} = temporal duration of flow path (277 days [9.1 months])

And:

$$v = K\, i / n_e \qquad \text{Equation 4.9}$$

Where:

K = hydraulic conductivity (m/d)
i = hydraulic gradient (the negative sign has been omitted for convenience)
n_e = Effective porosity (here assumed to be analogous to unconfined storage coefficient, Sy)

Thus:

$$L / C_{max} = K\, i / Sy$$

And:

$$L\, Sy / i\, C_{max} = K \qquad \text{Equation 4.10}$$

As C_{max} is known, and an estimate for the catchment-average value of Sy has been defined (1.56% by Brettell, 1971; p. 73), values of L / i for the nine flow paths in Table 4.7 can be used to estimate the bulk hydraulic conductivity of the Lambourn catchment. These values are given in Table 4.8 (including additional estimates based upon Sy from 0.5% to 2.0%), and compared to values from the literature in Section 4.7.

Estimated Sy (%)		**Flow path number**									**Mean**
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	
0.5	**Flowpath average K (m/d)**	40	35	44	48	52	49	79	78	88	57
1.0		79	70	88	95	103	99	158	155	176	114
1.56		123	110	137	148	161	154	247	242	274	177
2.0		158	141	176	190	206	197	316	310	352	227

Table 4.8 Estimated values of catchment-average hydraulic conductivity (K)

4.6 CORRELATING RECHARGE, STORAGE AND DISCHARGE USING MULTIPLE LINEAR REGRESSION

The preceding sections have established strong, individual correlations between EP parameters and catchment discharge, and MGS and catchment discharge. In this section, multiple linear regression techniques are used to identify the optimal parameter set that best represents catchment discharge, and the resulting synthetic discharge time series is compared with recorded data.

Initially, all derived EP and MGS parameters, for the period September 1975 to December 1993, were used in multiple linear regression with catchment discharge, but after a number of runs of the regression model an optimal set of four parameters were identified, and these are shown in Table 4.9.

Parameter	**Description**	**Regression coefficient**	**Standardised (Beta) coefficient**
mgs.lev	MGS level (mOD)	0.21	0.702
ep.4m.ma	4 month moving average EP (mm)	1.24×10^{-2}	0.281
ep.m-1	EP from preceding month (mm)	2.30×10^{-3}	0.095
rte.chng	Rate of change of MGS (m/month/month)	-2.47×10^{-2}	-0.041

Table 4.9 Characteristics of the optimal regression parameters
(Additional information on the regression statistics are given in Appendix 9)

The four parameters in Table 4.9 produced a regression equation with an R^2 value of 0.94, indicating that the calculated values of catchment discharge were able to model around 94% of the variability in the actual record of discharge. It is clear from the Beta coefficients (representative measures of comparative contribution), that the MGS level is the single most important control on catchment discharge, followed by the four-month moving-average EP, which represents about 40% of the contribution made by the MGS level. The regression equation based on the four parameters described above (and the defined regression constant of -21.962) was used to produce a synthetic time series of catchment discharge, which is presented in Figure 4.16.

It is clear from Figure 4.16 that this synthetic discharge record is a close representation of the recorded pattern of discharge from the catchment, and is a significant improvement on the synthetic equation based solely upon the five-month moving-average of EP (Figure 4.7). The only period when the synthetic record significantly breaks down is during the drought of 1990/91, when the peak is

overestimated. This water year was marked by the two lowest monthly MGS levels, in December 1990 and January 1991, and as these months lie on the margin of the MGS range they are unlikely to be as accurately simulated as values closer to the centre of the range. It is probable that the poor representation of the MGS – discharge relationship was responsible for the reduced accuracy in modelling of the peak discharge, because of the importance of the MGS level to the overall regression relationship.

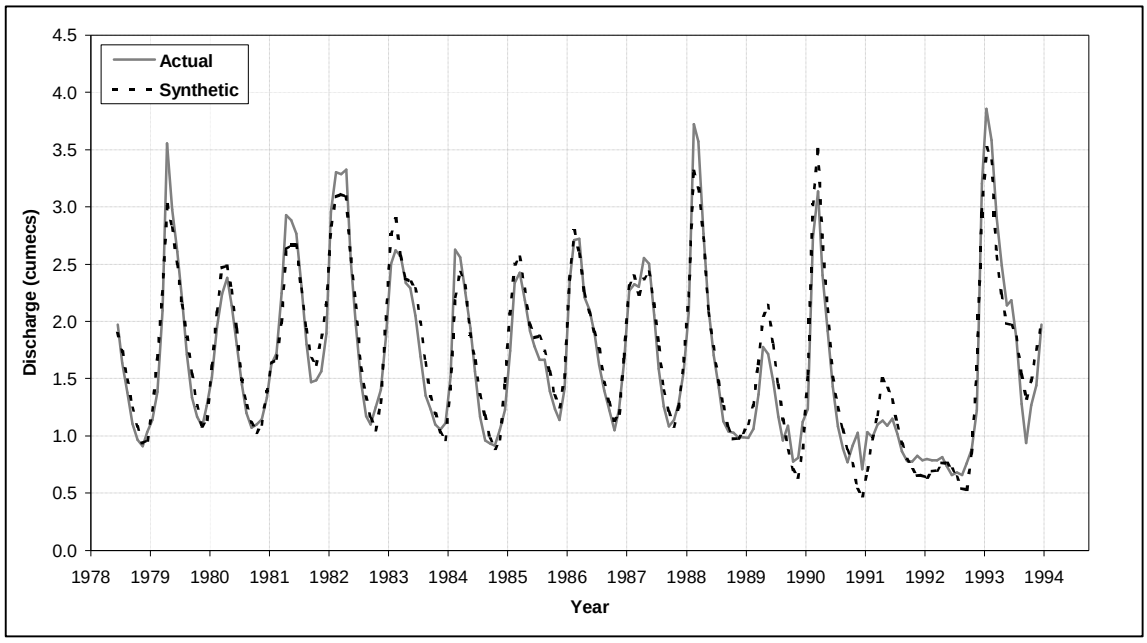


Figure 4.16 Time series of recorded catchment discharge and synthetic discharge based upon a four-parameter multiple linear regression equation

This relationship shows that the record of discharge from a chalk catchment can be accurately represented, even for extreme events, using a relatively simple regression technique and a limited number of parameters.

4.7 IMPLICATIONS OF C_{MAX} BASED ESTIMATES OF CATCHMENT AVERAGE HYDRAULIC CONDUCTIVITY

The estimated values of K in Table 4.8 are significantly higher than the bulk estimates of chalk parameters given by MacDonald & Allen (2001), who produced the definitive assessment of chalk properties derived from pumping tests in the UK. For example, using data from the Kennet Valley province, they report a median value for transmissivity (T) of 830m^2/d (which produces a K value of 14m/d using a thickness of 60m) and a median value for storage coefficient of 0.0075 (0.75%). This K value is

between four and sixteen times smaller than the values in Table 4.8. However, it has been recognised that the Lambourn catchment is unrepresentative of the wider Kennet Valley area, possessing enhanced permeability (Owen, 1981), and so it may be more realistic to compare the calculated K values with aquifer parameters defined within the Lambourn catchment. Pumping tests undertaken in the catchment for the Lambourn Valley Pilot Scheme (LVPS) gave an average transmissivity (T) value of 1490m^2/d (Brettell, 1971; p.168), which can be compared with T values calculated from this study, based upon a range of thicknesses (Table 4.10). However, the average T value from the LVPS is likely to be unrepresentative of the catchment as a whole, as it was derived from relatively short duration pumping tests (lasting 20 days) undertaken on individual abstraction boreholes. Over such short durations, the tests would have only evaluated the aquifer in the immediate vicinity of each borehole, which were all located in the Lambourn valley or in major dry valleys. Thus, the calculated average value for T is heavily biased towards the elevated permeability values known to occur in these types of locations.

Estimated Sy (%)	**Average K (m/d)***	**Estimates of transmissivity, T (m^2/d) based upon an effective thickness of:**				
		20m	**40m**	**60m**	**80m**	**100m**
0.25	28	560	1120	1680	2240	2800
0.5†	57	1140	2280	3420	4560	5700
1.0	114	2280	4560	6840	9120	11400
1.56	177	3540	7080	10620	14160	17700
2.0	227	4540	9080	13620	18160	22700

Table 4.10 Estimated values of catchment-average transmissivity
*Based upon the mean from the 9 flow paths given in Table 4.8
†Catchment average storage coefficient given by Owen & Robinson (1978)

Considering that the LVPS average T of 1490m^2/d is likely to be an overestimate for the bulk transmissivity of the catchment, the figures in Table 4.10 (derived from the C_{max} value) appear far too high to be representative of the catchment average permeability, unless very small values for bulk storage and/or effective thickness are used. This suggests that there is a breakdown in the methodology, which could be in the use of the porous medium analogy to describe the chalk (dominated by secondary permeability). However, when assessed at the catchment scale, the chalk should approximate an intergranular aquifer, and the margin of error appears too large to be

solely due to this factor. In addition, there is a problem with defining groundwater flow velocities in interfluve areas of the chalk (which these estimates are essentially based upon) via any alternative means.

The only independent method of evaluating flow velocities is through groundwater tracer testing, but this is usually carried out in valley or dry valley locations where the enhanced (sub-karstic) permeability can produce very high flow velocities, for example over 5km/day from a test in the catchment of the River Pang, adjacent to the Lambourn catchment (Banks *et al.*, 1995). There appear to be no records of any tracer tests carried out in the interfluve area of a chalk catchment, and so no independent estimates of groundwater flow velocities in these areas are available.

If the porous medium analogy is not the main weakness in the approach, then the only other source of potential error is the flow path definition, which was based upon contours of average groundwater levels. There does not appear to be a major discrepancy in the general morphology of the contours, as the pattern is similar to that shown on the hydrogeological map of the area (Institute of Geological Sciences, 1978), albeit for contours of minimum rather than average level. However, there is a possibility that the defined flow paths *are* inaccurate, if the principal control is litho-structural rather than hydraulic in nature, due to anisotropic development of subsurface permeability causing groundwater flow to deviate from the theoretical flow direction (perpendicular to the groundwater contours). This behaviour was identified during a tracer test undertaken on the chalk in Hertfordshire (Price *et al.*, 1992), when the observed direction of groundwater flow towards the confluence of the Rivers Ver and Colne deviated by a significant angle (around 35°) from the expected flow orientation, based upon the groundwater contours.

If we now consider the scenario of groundwater flow diverging from orientations based upon regional hydraulic gradients, we can conceptualise this in two ways. Firstly, the entire flow path from the groundwater catchment divide to the river could be orientated perpendicular to the direction of the river valley; or secondly, an initial segment of each flow path could be orientated perpendicular to the local groundwater contours, before intersecting a zone of enhanced permeability, which then imposes a

second segment perpendicular to the river valley. Schematic representations of these scenarios are illustrated in Figure 4.17.

To test the influence of the newly defined divergent flow paths upon the derived bulk aquifer properties, a similar approach was undertaken as described previously with the original flow paths. To evaluate the effect of Scenario 1, nine flow paths from the groundwater catchment divide to the river were defined, at an orientation perpendicular to the river, and these were then used to produce estimates of the bulk aquifer permeability (based upon the C_{max} value of 9.1 months), which are given in Table 4.11.

A similar approach was undertaken to evaluate scenario 2, for which it was necessary to identify the spatial frequency of the hypothetical zones of enhanced permeability, in order to evaluate their influence on the divergent flow paths. The influence of the spatial frequency manifests itself as the ratio between the length of conventional flow path (via bulk permeability) and the length of divergent flow path in the enhanced permeability zone. The results of this analysis, essentially estimates of bulk aquifer permeability, are also presented in Table 4.11.

Flow type	**Average K (m/d)**	**Estimates of transmissivity, T (m^2/d) based upon an effective thickness of:**				
		20m	**40m**	**60m**	**80m**	**100m**
Normal	90	1800	3600	5400	7200	9000
Divergent Scenario 1	74	1480	2960	4440	5920	7400
Divergent Scenario 2	1* (bulk) 11000†					

Table 4.11 Comparison of catchment average transmissivity values based upon normal flow and divergent flow scenarios (using Sy=1%)
*Estimated from the literature as representative for interfluve areas (Allen *et al.*, 1997)
†Enhanced zone value calculated using a zone spacing of 500m

The calculations for the normal and scenario 1 flow types use a single bulk value for Sy of 1%, while for scenario 2 a bulk Sy value of 0.1% is used and an enhanced zone Sy value of 100%, to approximate the zone as a single fissure, in the same manner as Price (1987; p.146). It appears that scenario 1 does not achieve a significant decrease in the catchment average transmissivity, and would only be realistic if the effective thickness of the aquifer across the whole catchment was very small, which is contradictory to field evidence from test pumping (Brettell, 1971) and geophysical logging (e.g. Tate *et al.*, 1971).

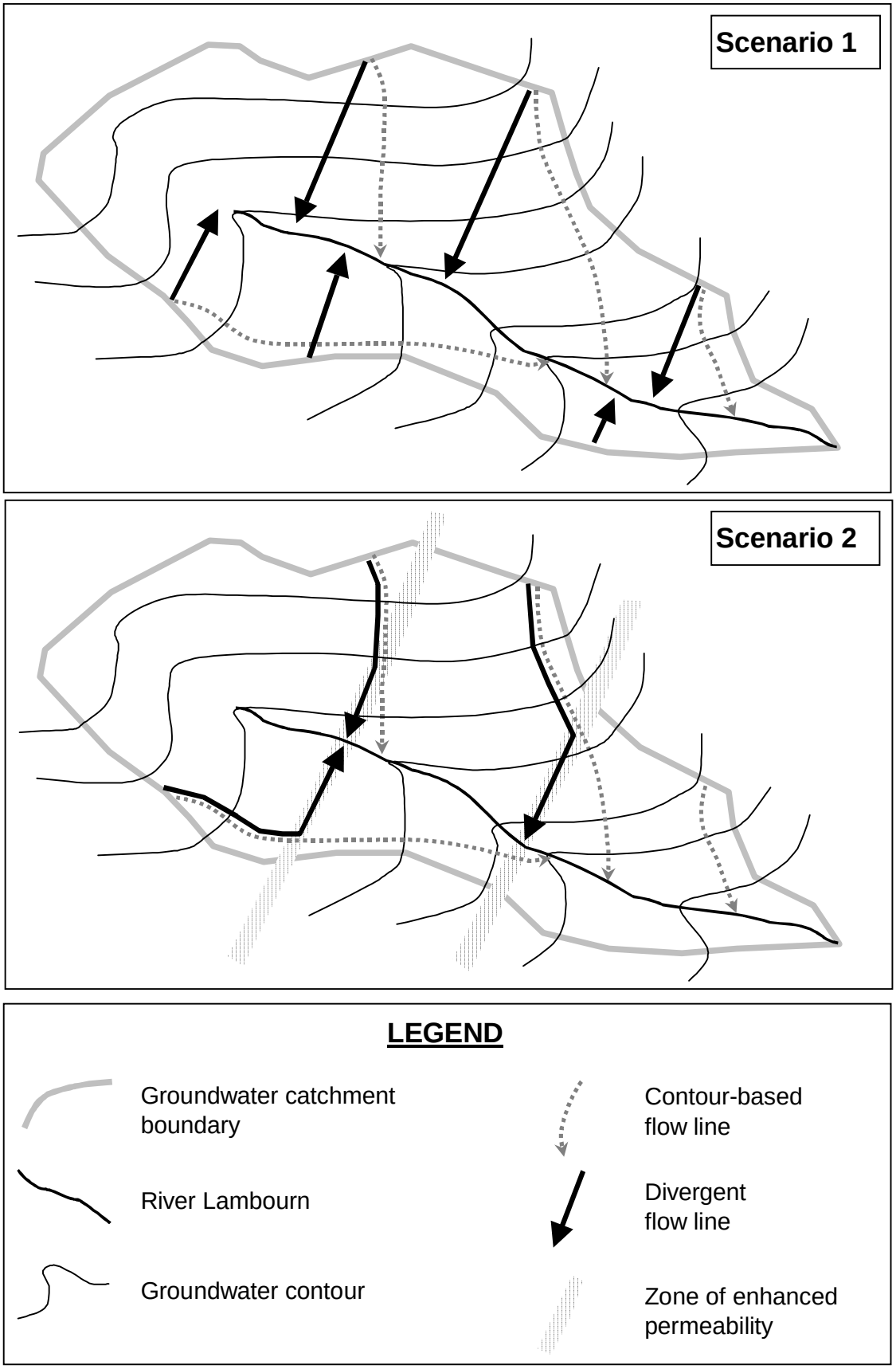


Figure 4.17 Two conceptual scenarios showing divergent groundwater flow paths

Scenario 2 uses a very small bulk permeability value and very large enhanced zone value, which is problematic for calculating an average value for the transmissivity of the catchment. However, the calculated K value can be used to approximate the properties of an enhanced K zone, if it is assumed to represent a single fissure. Using the approach of Price (1987; Equation 2), the width of a smooth, plane parallel fissure with a K value of 11 000 m/d can be calculated as 0.45mm. Thus the observed durations of flow in the saturated zone could be the result of a network of sub vertical fissures, with a width of ~ 0.5mm, spaced at 500m intervals perpendicular to the river.

4.8 SUMMARY

This chapter has sought to characterise the elements of the recharge – storage – discharge sequence by examining their inter-relationships in the temporal dimension. By correlating recharge and discharge on a long-term water year basis it was possible to assess the accuracy of MORECS EP as a recharge measure. Over a period of 22 years it was found that MORECS EP accounted for only 69% of catchment discharge, varying between annual extremes of 47% and 96%. This consistent underestimate was not due to differences between local rainfall and rainfall used in MORECS calculations.

Correlating first recharge and discharge, then recharge and MGS, both on a monthly basis, allowed average and maximum values for the unsaturated zone (B parameter) and saturated zone (C parameter) components of the recharge – discharge time lag to be estimated: B_{av} = 1 month, B_{max} = 3 months, C_{av} = 1.4 months, C_{max} = 9.1 months. These parameters allowed unsaturated and saturated flow rates to be estimated, which were higher than published values. The significance of these finding is discussed in Chapter 7.

Finally, multiple linear regression analysis was used to identify the importance of various controls on the temporal pattern of catchment discharge, and catchment storage level (MGS) was found to be most important. A hydrograph of synthetic discharge was created, based upon an analytical model incorporating the identified controls, and was found to be very effective at simulating catchment discharge.

Chapter 5 Spatial and temporal patterns of river – aquifer exchange along the River Lambourn

5.1 INTRODUCTION

Conceptualisation

The occurrence of water exchange between rivers and aquifers requires that two conditions be satisfied. Firstly, there must be a hydraulic gradient between the two water bodies; secondly there must be an appropriate pathway to permit flow to occur. The latter may take a number of forms but it must be continuous between the aquifer and the river (or floodplain surface), and of sufficient permeability to transmit a significant volume of water. If the pathway is discontinuous, of limited spatial extent, or of only moderate permeability, then some transfer will occur but the site will not be a recognised location of focused water exchange. The potential for water exchange to take place at any given location is a product of the gradient and the pathway transmission capacity. In an idealised aquifer this product is represented by the transmissivity (aquifer saturated thickness multiplied by hydraulic conductivity), which is normally applied to areas where groundwater flow is sub-horizontal. Given the highly variable orientation and morphology of flow paths through valley floor deposits, use of the term transmissivity is less valid. To overcome this difficulty, when considering flowpaths through valley floor deposits we will use the term gradient-pathway product (GPP): being analogous to transmissivity, but without the implicit constraints of consistent orientation and morphology.

There are two potential end member scenarios for river – aquifer exchanges, which can be dominated by either diffuse or point source seepage. If the GPP is spatially consistent along the channel, a diffuse exchange pattern will result, regardless of the actual magnitude of the gradient or pathway capacity. If significant spatial variability exists in the GPP, then the system will tend towards a more point source dominated pattern. However, only if the spatial pattern comprises a consistently low GPP, punctuated by occasional, restricted locations with a high GPP, can the system be truly defined as point source in nature.

Data presentation

A critical aspect of investigating river – aquifer interaction involves defining and understanding underlying controls on the spatial pattern of flow accretion. In this respect, flow accretion profiles, produced by plotting cumulative discharge against distance from river source, provide a useful and convenient illustrative tool. However, despite their effectiveness, flow accretion profiles have been generally under utilised in research on chalk aquifer – stream systems, as discussed in Chapter 2.

Whilst a number of studies investigating river – aquifer interaction in chalk catchments have used flow accretion profiles for calibration of groundwater flow models (e.g. Oakes and Pontin, 1976; Connorton & Hanson, 1978; Wilson *et al.*, 1993; Wyness *et al.*, 1994; Wilson & Akande, 1995), none have attempted to explain the irregular patterns of accretion, which strongly diverge from the idealised linear pattern implicitly assumed in most chalk stream research. Only in a study undertaken by Rushton & Tomlinson (1995) on rivers draining the Sherwood Sandstone aquifer in Nottinghamshire, was the pattern of accretion investigated, and here it could be easily correlated with the presence of major public water supply groundwater abstractions located close to the rivers.

Studies have tended to assume linear accretion in chalk streams, which is understandable given the lack of datasets that allow temporally representative, high spatial resolution accretion profiles to be plotted. However, an historic dataset exists for the River Lambourn that enables this analysis to be undertaken. The bulk of these data were collected during groundwater scheme investigations in the late 1960's and early 1970's and these have been supplemented by continuous gauging records from 1966 to 2001, including data collected during the course of this study. The temporal distribution of the datasets that underpin this chapter is illustrated in Figure 5.1.

A limitation of flow accretion profiles is the non-uniform appearance of equal inflows at different locations along a river. For example; a point source inflow to a river of a certain magnitude in its upper reaches will appear more significant than one of equal magnitude in its lower reaches, since in the former location it represents a greater proportion of the total flow and thus a greater deviation from the linear (diffuse) pattern of inflow. The problem of inflow representation is overcome in this study by presenting exchanges on a reach-by-reach basis as standardised inflows per unit length of channel.

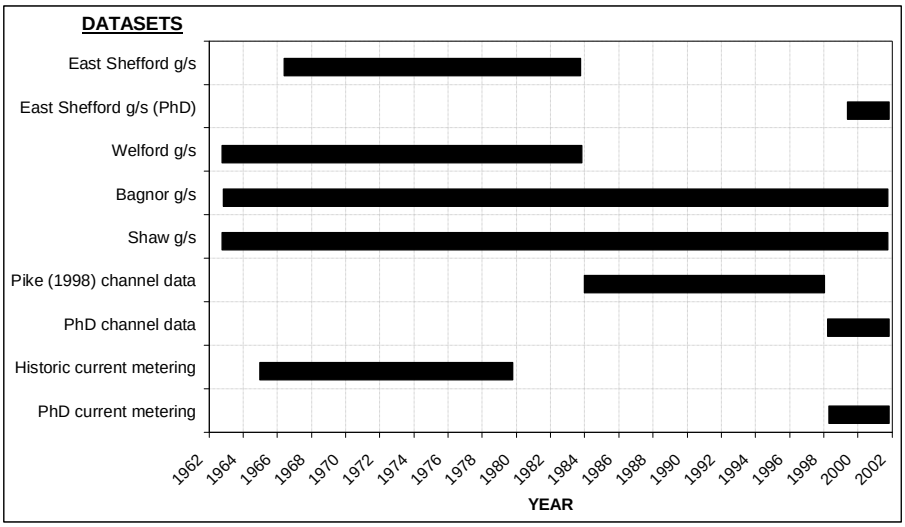


Figure 5.1 Timing and duration of flow accretion analysis datasets
(g/s = Gauging Station with gauging weir)

In this chapter, the pattern of flow accretion is defined at three spatial scales, of increasing resolution, following the staged progression of the investigation. Accretion at the catchment and sub-catchment scale is characterised by continuous datasets from gauging weirs. Catchment average accretion rates over the flowing length of the River Lambourn (which varies seasonally from 14 to 24km) are first calculated from catchment discharge at the lowest gauging station at Shaw, combined with data on the source location from Pike (1998) and the present study. Reach lengths were measured from 1:10 000 scale Ordnance Survey sheets, using the channel centre line.

The spatial resolution of the analysis is then increased as accretion rates are calculated from gauging weir records for the 12.5km length of channel between East Shefford and Shaw, with additional data from Welford (located 3km downstream of East Shefford). Data from this study, covering the period May 1999 to October 2001, are then used (with associated records of flowing channel length) to compare standardised accretion in the seasonal and perennial portions of the channel. Patterns of standardised accretion in the perennial section of the Lambourn are then investigated more closely using gauging weir records for the period 1966 to 1983. Finally, non-continuous data derived from current meter surveys are used to examine flow accretion at a high spatial resolution. Accretion rates from twelve reaches are compared and are shown to display significant spatial variability.

5.2 ACCRETION VALUES BASED UPON CONTINUOUS DATASETS

5.2.1 Catchment average accretion rates

A simple method of calculating spatially-averaged rates of flow accretion (in units such as cumecs/km) uses records of discharge at a known location, divided by the contributing length of channel upstream, providing this is known for any particular point in time. In rivers with fixed channel lengths, this does not present a problem, but it can be problematic on chalk streams, which are characterised by seasonal variation in the length of the flowing channel. Observations of active channel length (or source location) are not normally included in hydrological databases.

For the River Lambourn prior to 1983, data on the location of the river's source are irregular, and limited to occasional observations by the predecessors of the EA (such as the National Rivers Authority and Thames Conservancy), as well as detailed (but short duration) records associated with the groundwater scheme investigations. However, from 1983 to 1998 the rise and fall of the seasonal (and ephemeral) source springs of the River Lambourn were recorded in a consistent manner by an amateur meteorologist in the village of Lambourn, and these were described by Pike (1998). From 1999 to 2001, the record was extended by observations from the present study, and so in total an 18-year record is available. This record, in conjunction with a continuous record of discharge from the gauging weir at Shaw, provided the necessary base data to allow the spatially averaged catchment accretion rate to be defined for the period 1983 – 2001. The results are given in Figure 5.2, which illustrates the variability in catchment average accretion rates, whilst summary statistics for the period December 1983 to September 2001 are shown in Table 5.1. Frequency analysis undertaken on the time series (illustrated in Figure 5.3) shows the temporal duration of accretion rates more clearly.

Statistic	**Shaw g/s discharge (cumecs)**	**Flowing channel length (km)**	**Catchment average flow accretion (cumecs/km)**
Minimum	0.523	13.95	**0.037**
Mean	1.771	19.06	**0.088**
Maximum	6.670	23.35	**0.286**
Standard deviation (SD)	1.019	3.73	**0.039**
SD / Mean*	57.5%	19.6%	**43.2%**

Table 5.1 Summary statistics for catchment average accretion rates
(*represents the coefficient of variation, expressed as percentage of mean value)

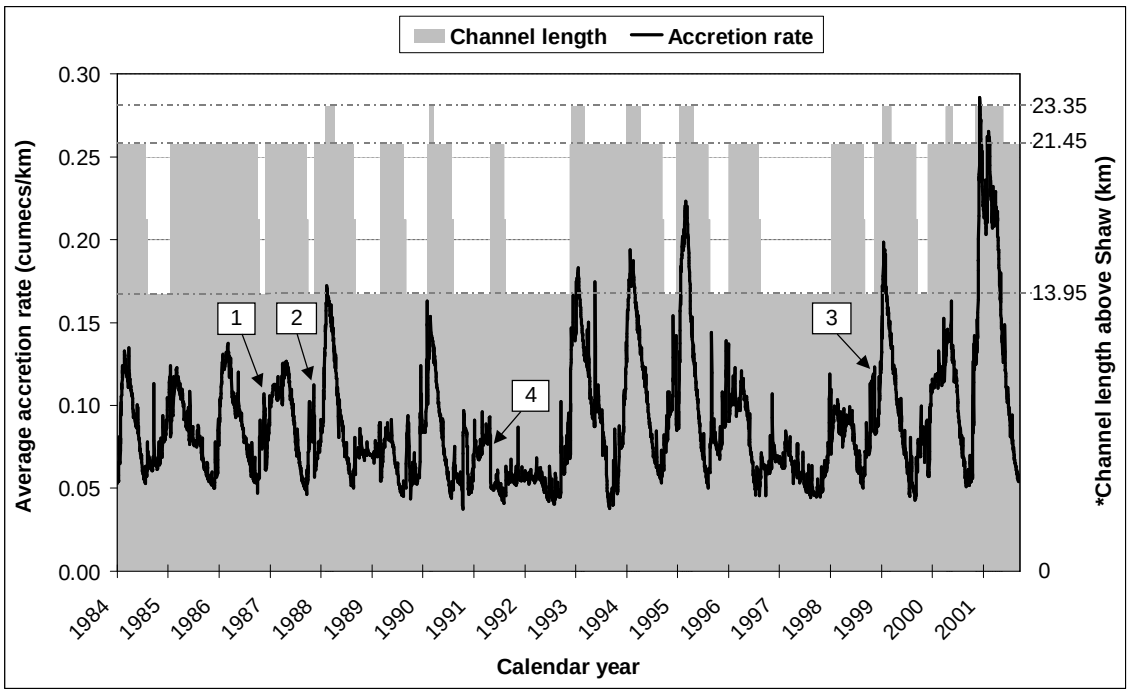


Figure 5.2 Catchment average flow accretion rate and flowing channel length
*13.95km = perennial source; 21.45km = seasonal source; 23.35km = ephemeral source

The time series shows a seasonal pattern related to the flow regime, with some modification to account for changes in channel length, the effect of which acts to attenuate the variability of the record by reducing accretion rates at the highest flows, whilst increasing them at the lowest flows. Peak accretion rates normally occur between January and March, and seldom exceed 0.2 cumecs/km. Peak rates that exceeded this level occurred in the winters of 1995/96 and 2000/2001. In both cases, this resulted from higher than average rainfall. Rainfall in the period September to December 1995 totalled over 350mm, while for the same period in 2000 the total exceeded 460mm. These compare with the long-term average (1964-2000) rainfall of 246mm for the equivalent period. The normal annual minimum accretion rate of around 0.05 cumecs/km is consistent from year to year, indicating a constant baseflow discharge from the perennial section of the channel at minimum groundwater levels. Similar minimum accretion rates also occur during years when flow is maintained from the seasonal source throughout the year, such as 1985/86, 1993/94 and 2000/2001. This suggests that minimum bulk accretion rates in the seasonal section of channel are similar to those in the perennial portion.

The influence of the variability in channel length on accretion rate is relatively subdued but can give rise to secondary peaks such as in late 1986 (1), 1987 (2) and 1998 (3). It can also cause a sudden decline in accretion rate if the drainage network expands rapidly for only a short period, such as in 1991 (4). Evidently, there is a clear relationship between channel length and peak accretion rate. When the uppermost ephemeral section of the channel (above the seasonal source) is activated, the catchment average accretion rate consistently exceeds 0.15 cumecs/km. This relationship demonstrates the inter-connectedness of the system, as the extension of the drainage network is symptomatic of high accretion rates throughout the catchment, not solely near the point where the extension has occurred.

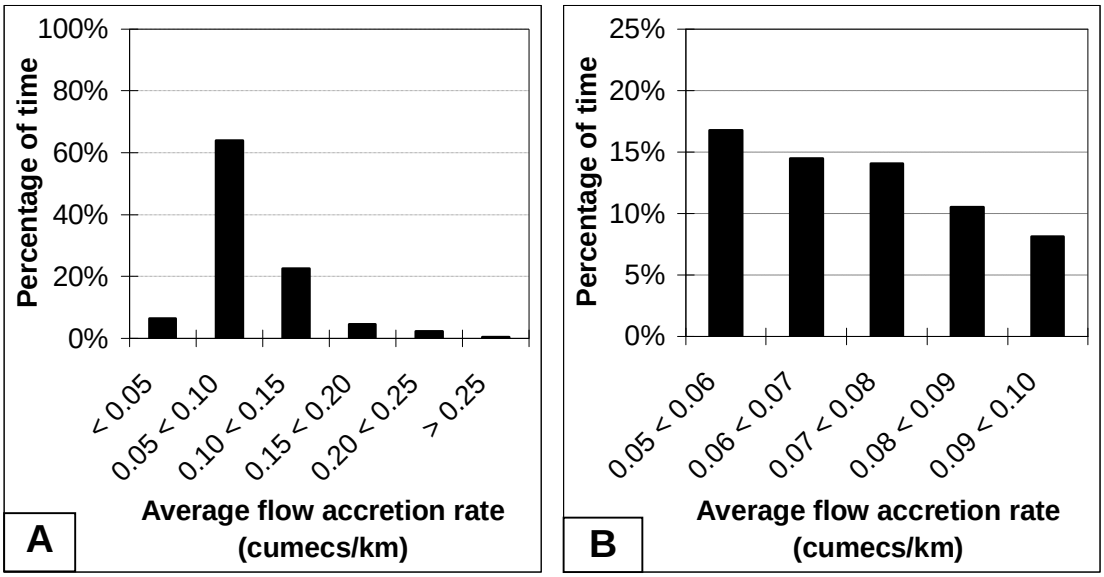


Figure 5.3 Temporal occurrence of catchment average accretion rates (A), with a detailed breakdown for the most commonly occurring rates (B)

The frequency analysis given in Figure 5.3A illustrates the relative stability of the catchment-scale accretion regime, with the accretion rate lying between 0.05 and 0.10 cumecs/km for 64% of the time. The mean value of catchment accretion lies near the top of this range at 0.088 cumecs/km and this figure can be used to characterise accretion on the River Lambourn for comparison with other chalk catchments. At the extremes of the range, accretion rates rarely fall below 0.05 or exceed 0.25 cumecs/km; the two categories combined represent less than 7% of the total record. Figure 5.3B depicts the most frequently occurring category (0.05 – 0.10 cumecs/km) from Figure 5.3A in more detail, showing that within this range, duration gradually declines as the

accretion rate increases. The reason for the step change in occurrence between less than and greater than 0.05 cumecs/km is unclear.

Overall, this simple approach provides baseline information on temporal accretion variability, but cannot assess spatial variability in accretion rates, which is required to improve understanding of the underlying physical processes controlling river – aquifer exchange, and this aspect is considered in the following section.

5.2.2 Comparison of sub-catchment accretion rates from gauging stations

Discharge records from four gauging weirs (described in Section 3.2.2) were used to calculate gross accretion values for discrete channel sections of the River Lambourn for the period June 1966 to September 1983, and summary statistics are given in Table 5.2.

Statistic	**Accretion to East Shefford** (cumecs)*	**Accretion from East Shefford to Welford** (cumecs) *{cumecs/km}*	**Accretion from Welford to Shaw (excl. W.bourne)** (cumecs) *{cumecs/km}*	**Accretion on the Winterbourne Stream to Bagnor**† (cumecs)*
Minimum	0	-0.230 *{-0.078}*	0.068 *{0.007}*	0.008
Mean	0.765	0.294 *{0.100}*	0.562 *{0.059}*	0.183
Maximum	2.460	0.910 *{0.308}*	1.478 *{0.156}*	0.551
Standard deviation	0.547	0.093 *{0.032}*	0.214 *{0.022}*	0.098
Coefficient of variation (% of mean)	71.5%	31.7%	37.3%	53.7%

Table 5.2 Summary statistics for flow accretion data from gauging stations for the period June 1966 to September 1983
**Standardised* accretion rates are not presented, as there is no data on channel length
†Bagnor is located immediately upstream of the confluence with the River Lambourn

The values in Table 5.2 illustrate the variability in accretion for reaches that include seasonal portions, for example from the source of the Lambourn to East Shefford, and for the Winterbourne Stream. The reach to East Shefford displays both the highest and lowest accretion rates, the latter (zero) value occurring for a few days in August 1976 when the actual source of the river migrated downstream of East Shefford. The coefficient of variation (standard deviation divided by mean) gives a standardised measure of variability independent of the magnitude of the accretion. This is an effective measure for distinguishing between wholly perennial reaches (standard deviation < 40% of the mean) and sections including seasonal reaches (standard deviation > 50% of the mean). Using the same dataset, contributions to catchment

discharge from various sections were also calculated for the same period and these are given in Table 5.3.

	ACCRETION AS PERCENTAGE OF CATCHMENT DISCHARGE			
Statistic	**To East Shefford**	**East Shefford to Welford**	**Welford to Shaw (excl. W.bourne)**	**Winterbourne Stream**
Minimum	0%	-8.3%	4.8%	1.0%
Mean	37.2%	20.3%	32.6%	9.9%
Maximum	69.0%	55.6%	63.1%	27.6%
Standard deviation	14.9%	11.1%	7.2%	2.8%
Coefficient of variation (% of mean value)	40.0%	54.6%	22.1%	28.4%

Table 5.3 Summary statistics of gauged discharges relative to catchment discharge for the period June 1966 to September 1983

The values in Table 5.3 are not directly comparable with Table 5.2 as they depend upon the temporal dynamics of catchment discharge. The various reaches of the river fluctuate with differing timescales, which leads to variability in their relative contributions with time. For example, the maximum contributions shown in Table 5.3 cannot occur simultaneously, because the sum of the components would then exceed 100%. This imposed timing control can be seen in the change in coefficient of variation between Table 5.2 and Table 5.3, with values for three of the four sections being reduced and the other section (East Shefford to Welford) increased. The increase in this parameter for this section of the river indicates that the pattern of accretion here is not synchronous with catchment discharge, and this anomalous pattern of behaviour is explored further in Section 5.3.2.

The values discussed in this section give an initial insight into the spatial variability of accretion rates. However, to compare true accretion rates between the portions of river, rates need to be standardised for reach length, and this is described in the following section.

5.2.3 A comparison between standardised accretion rates in the seasonal and perennial reaches from gauging station data

Calculation of standardised accretion rates (i.e. change in discharge/unit length) requires the length of channel over which accretion occurs to be defined. This is only problematic for the seasonal section of a channel, where the channel length varies with time, whereas it remains constant for the perennial section. For the seasonal channel (upstream of East Shefford), the only period when both discharge data and channel

length data are available is for the period of this study (see Figure 5.1). Thus, standardised accretion rates for the seasonal section of the Lambourn are only available for the period from June 1999 to September 2001. This period is illustrated in Figure 5.4, which presents standardised accretion rates for the reaches to East Shefford and to Shaw, with the channel length used in the calculation displayed as a backdrop. This record shows that accretion rates in the seasonal portion of channel are generally similar to the perennial reach, except during the latter period of flow recessions. Additionally, the discharge hydrographs for the two relevant gauging stations are presented in Figure 5.5, and these show a close similarity in shape and magnitude of variability, indicating that at this broad scale the catchment is operating in a spatially consistent manner. The peak rate for the seasonal section occurred in December 2000, when the drainage network had expanded considerably, with flowing channels occupying the base of normally 'dry' valleys, although the calculated accretion rate is based solely upon the length of flowing channel within the main Lambourn Valley.

To place the period of this study in a longer term context, the mean daily catchment discharge for the period was 2.57 cumecs, 47% higher than the long-term average of 1.75 cumecs, and this reflected above average rainfall. No local rainfall data are available from January 2001 onwards, but monthly rainfall totals in 20 of the first 27 months of this study (from October 1998 to December 2000), were higher than the long-term average (1963–2000), and these included some extreme rainfall events. For example, very high rainfall in April 2000 (153mm compared to the long term average of 45mm) produced a high and unusually late peak in the annual hydrograph. Moreover, further heavy and prolonged rainfall at the end of 2000 (the 3-months to the end of the year delivering 388mm of rainfall compared with the long term average for the equivalent period of 181mm) produced the highest discharges recorded at Shaw in nearly 40 years of record, peaking at 6.67 cumecs on 19th December 2000. Comparison of Figure 5.4 and Figure 5.5 indicate that accretion rates are generally proportional to catchment discharge. Clearly, as discharges have been higher than average over the period of field monitoring for this study, then accretion rates calculated for this period may not be representative of long-term average conditions, being biased towards higher values.

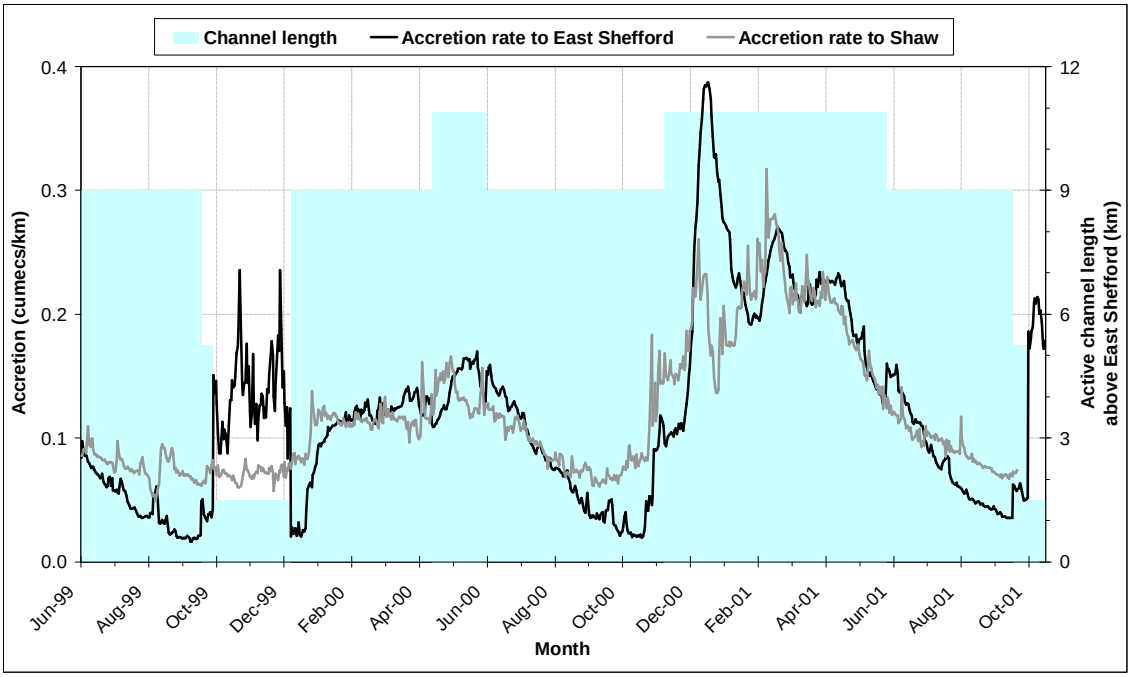


Figure 5.4 Time series of standardised accretions for the sections of river to East Shefford and Shaw

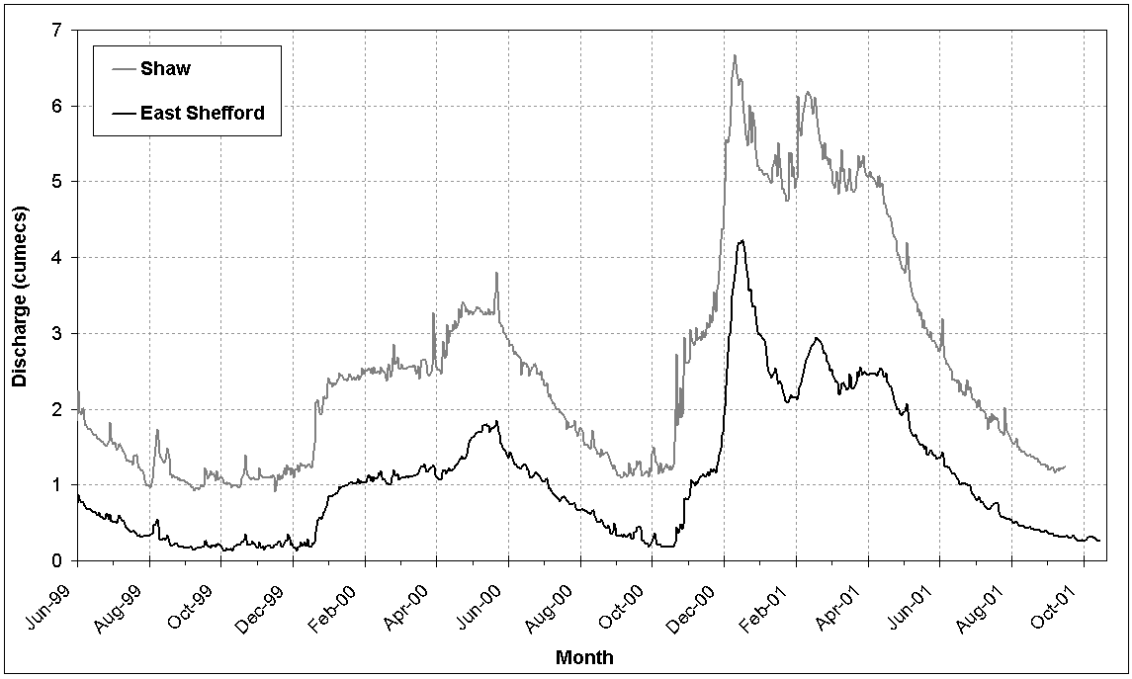


Figure 5.5 Hydrograph of gauged discharges at East Shefford and Shaw

The accretion rate in the seasonal reach is particularly sensitive to variation in channel length when discharge is low, as occurred in October/November 1999, when there was an 83% reduction in the flowing channel length above East Shefford, as the head of the river migrated to the perennial source. Comparing the plots of discharge and accretion at East Shefford for the period of October/November 1999, it is apparent that the migration of the source had no perceptible impact on the discharge. This indicates that for some period prior to the downstream migration of the river's source, the discharge at East Shefford is almost entirely derived from the uppermost 1.5km of perennial channel immediately above the gauging station, with effectively no contribution from the seasonal section of channel upstream. This situation occurs during the latter periods of prolonged recessions.

5.2.4 Standardised accretion rates for the perennial section of the channel at an enhanced spatial resolution

Compared to the rather short record of standardised accretion for East Shefford (extending for 2.4 years from June 1999 to October 2001), a much longer record exists for the reaches between East Shefford and Shaw, covering nearly 20 years from June 1964 to September 1983. The record from these reaches is illustrated in Figure 5.6, which presents 3-monthly moving average plots of standardised accretion for the reaches from East Shefford to Welford and Welford to Shaw, with the daily catchment discharge at Shaw presented for comparison. Accretion calculated here for the Welford to Shaw reach includes a contribution from the Winterbourne Stream, which on average provides around 25% of the total accretion for this reach (from Table 5.2).

Figure 5.6 shows that accretion in the Shaw reach (i.e. from Welford to Shaw) is closely associated with Shaw discharge. This pattern is not simply because accretion from this reach controls the magnitude of the catchment discharge, as Table 5.3 shows that on average this reach contributes only around 33% of the total catchment discharge. Instead, it suggests that the accretion rate in the Shaw reach is associated with a broader pattern of catchment-wide behaviour. In contrast, accretion rates in the Welford reach are generally higher than in the Shaw reach, particularly when the catchment discharge is low. This is the first indication that there are significant differences in accretion rates *within* the perennial section of the river. Indeed, it is evident that, especially over the

period 1977-1980, the pattern of peaks and troughs for the two accretion records are consistently inversely proportional to one another. By extension, this also causes accretion rates in the Welford reach to be out of phase with the record of catchment discharge.

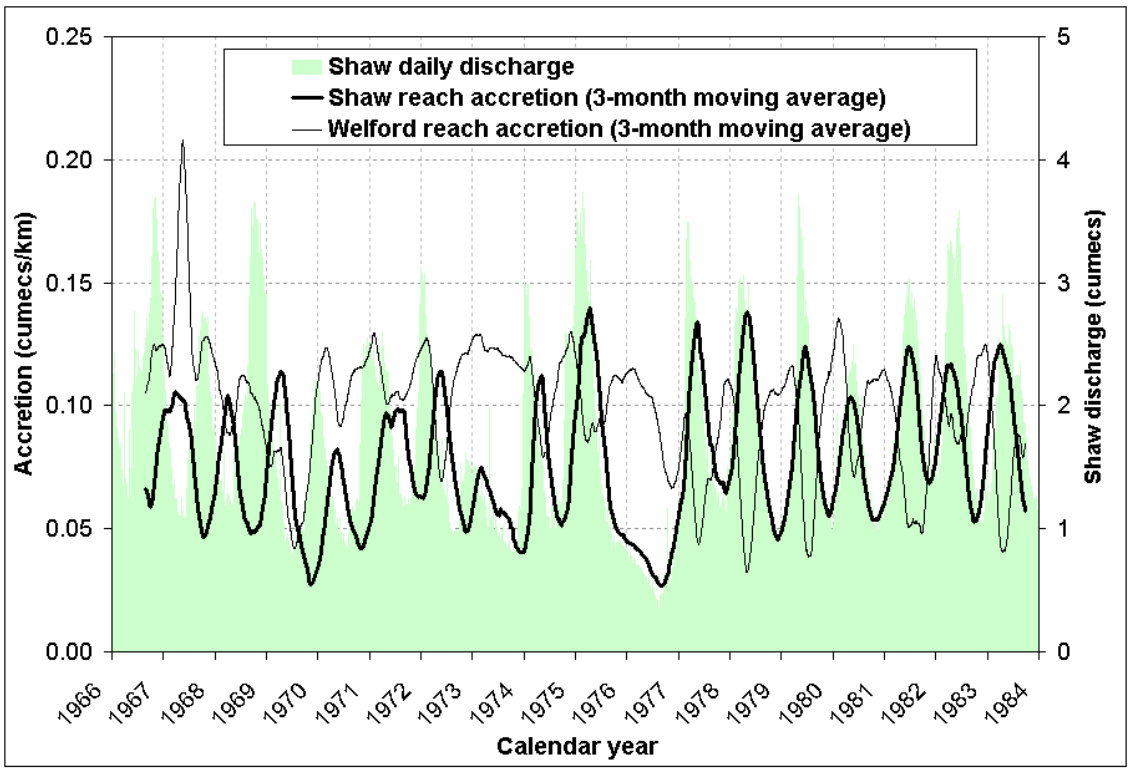


Figure 5.6 Time series of standardised long-term accretion rates for the Welford and Shaw reaches

The record for 1967 is anomalous in that the peak in Welford accretion coincides with the peak in catchment discharge. This may have been influenced by pumping activity related to testing of the Lambourn Valley Pilot Scheme. The gauging weir records used in these analyses have been corrected during the present study for recorded pumped discharges to the river (Section 3.5.4), to account for the artificial variability during the major testing periods. However, a number of minor tests were carried out in 1967 for which no exact timing or discharge information is available, and their influence on the natural discharge regime cannot be adequately assessed.

Figure 5.7 presents the duration of accretion rates in the Welford and Shaw reaches. The distributions of the two datasets are very different in form, with Welford being more highly peaked, with a low rate tail to the distribution, while Shaw is less

peaked and has a high rate tail. The most commonly occurring rate in the Welford reach is around twice that of the Shaw reach.

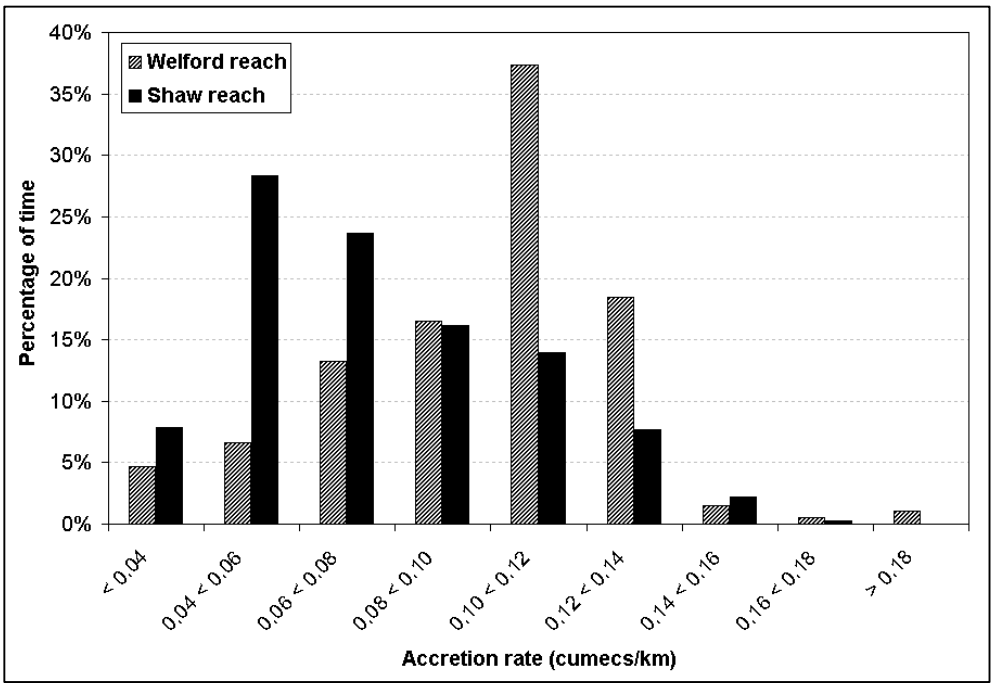


Figure 5.7 Occurrence of Welford reach and Shaw reach accretion rates

The relationship between accretion in individual reaches and catchment discharge is illustrated in Figure 5.8. This shows a strong linear relationship between the Shaw reach accretion rate and catchment discharge but no correlation between the Welford reach accretion rate and catchment discharge, clearly demonstrating that different controls on accretion operate for these reaches. The ratio between the reach accretion rates is plotted against the catchment discharge in Figure 5.9, with the association best represented by an exponential relationship. When discharge at Shaw approaches a minimum (0.5 cumecs), the standardised accretion (accretion/km) in the Welford reach is around three times that of the Shaw reach. However, when the discharge at Shaw reaches four cumecs, the accretion rate in the Welford reach is less than half of that in the Shaw reach. Accretion rates in the two reaches are equal when Shaw discharge is about 2.2 cumecs.

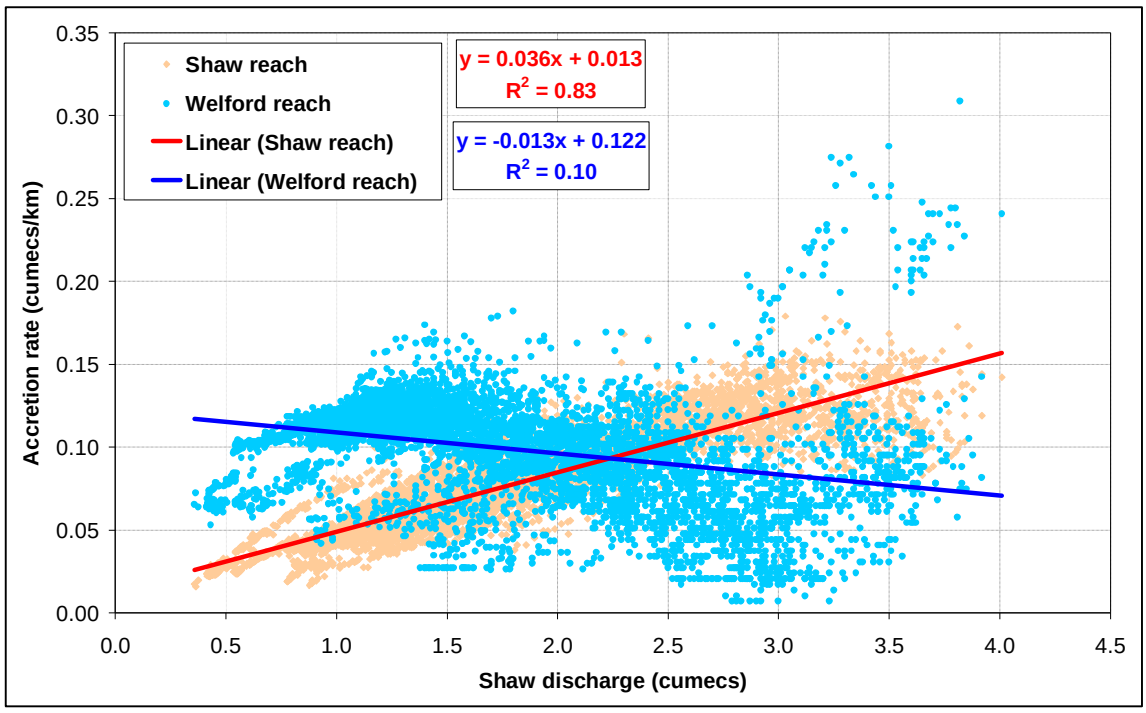


Figure 5.8 Scatter plots of accretion rates versus Shaw discharge

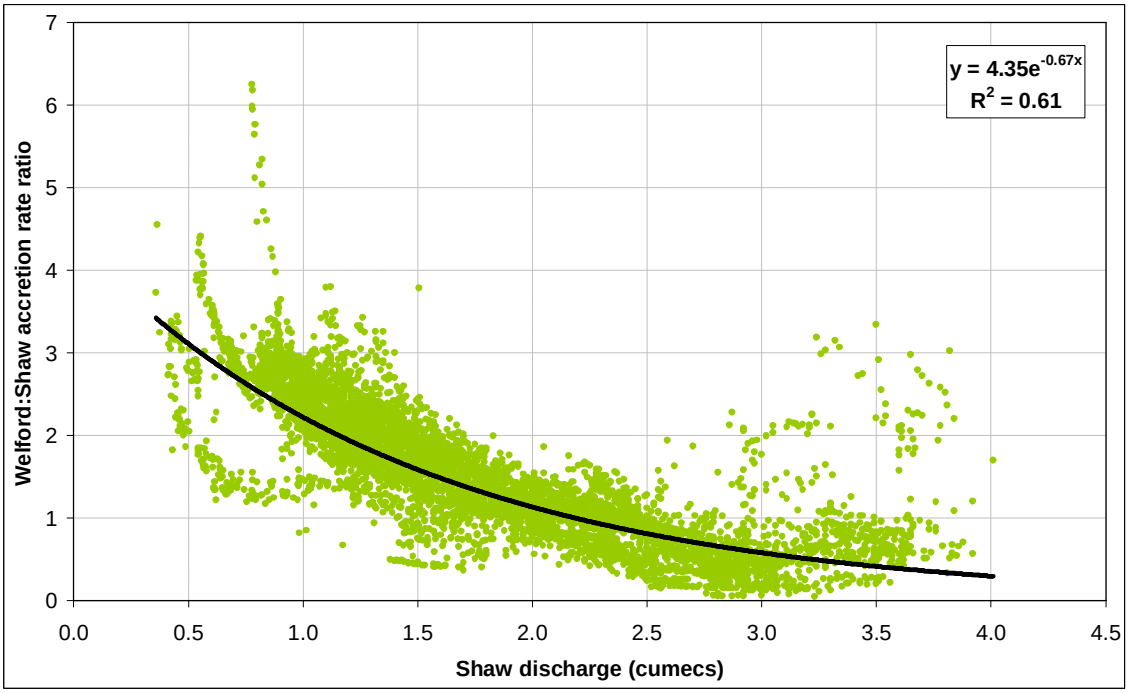


Figure 5.9 The ratio of Welford to Shaw accretion rates versus Shaw discharge

The discrepancy in the behaviour of the two lowest reaches of the Lambourn might be considered a consequence of discharge from the Winterbourne Stream into the Shaw reach. One possibility might be that rapid runoff due to low permeability Tertiary deposits overlying the Chalk in the catchment of the Winterbourne Stream could influence accretion statistics for the Shaw reach. To investigate this, a comparison between the responses of the two watercourses to rainfall events in the summer of 1973 was undertaken, and this is shown in Figure 5.10.

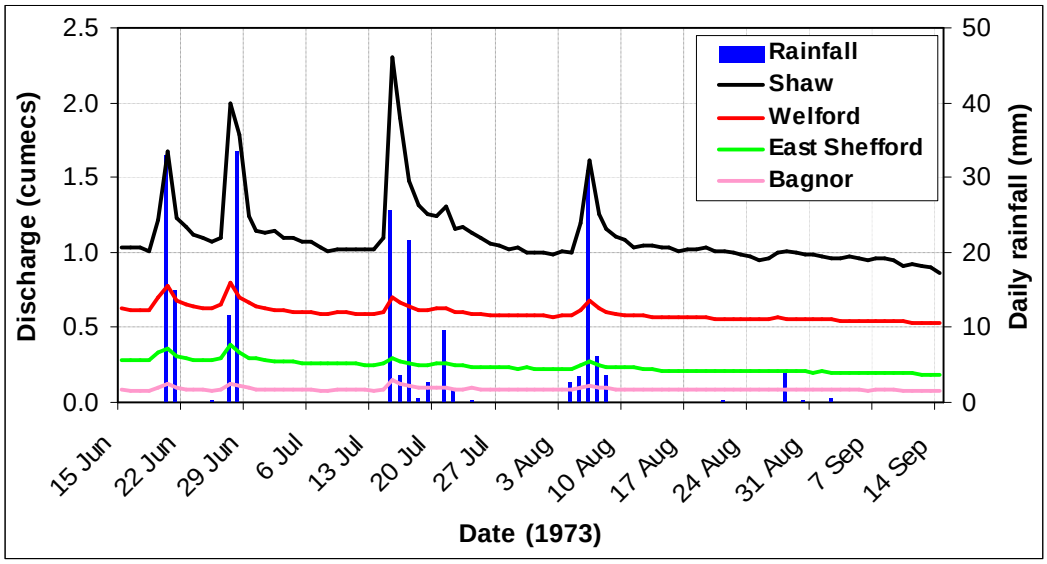


Figure 5.10 Comparison of the response of lower and upper catchment reaches to intense rainfall events

From Figure 5.10 it is apparent that a flashy response is generated from the reach immediately above Shaw, but with only a negligible input from the Winterbourne Stream (gauged at Bagnor). Evidently, the presence of the Tertiary deposits in the lower part of the Lambourn catchment can have a significant (albeit short term) influence on catchment discharge following periods of intense rainfall, such as summer storms. However, under these conditions the contribution from the Winterbourne Stream is insignificant, showing that it is not the cause of the difference in the behaviour between the Welford and Shaw reaches.

5.3 HIGH SPATIAL RESOLUTION ACCRETION RATES FROM NON-CONTINUOUS DATA

5.3.1 Background

The most spatially detailed analysis of flow accretion rates in this study is based upon extensive current meter surveys undertaken during the groundwater scheme investigations, which have been described previously (Section 3.2.4). The complete dataset comprises over 2000 individual discharge records, but for these analyses the dataset was reduced to 505 pairs of readings. These were derived from twelve reaches, varying in length from 1.00 to 2.95km, for which the flow gain or loss was calculated (Section 3.5.4). The locations of the current meter stations from which data have been derived are shown in Figure 5.11 and summary details of the twelve reaches are given in Table 5.4.

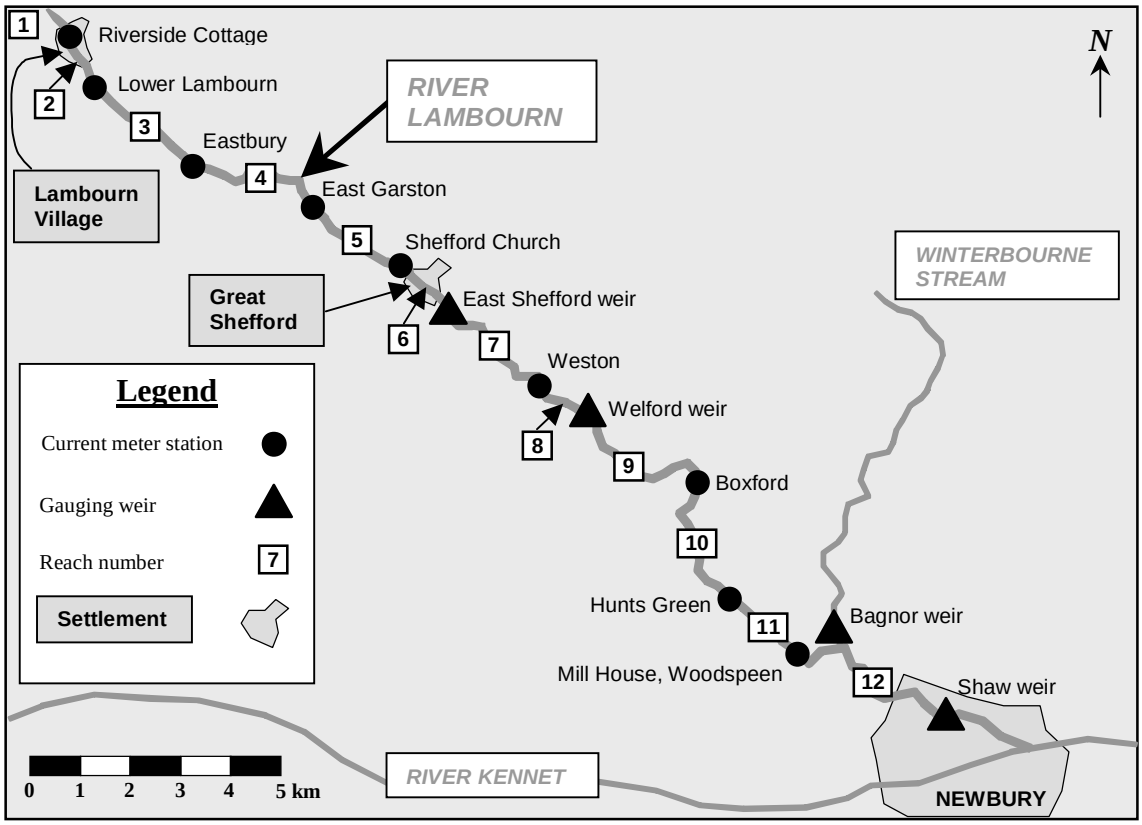


Figure 5.11 Locations of current meter stations and gauging stations used in high spatial resolution flow accretion analysis

From the data given in Table 5.4, the average reach length is 1.78km and each reach has an average of 36 records, representing 36 dates upon which current metering took place at both the upper and lower ends of the reach. The data are not distributed

evenly over time, but are concentrated in specific years, corresponding to periods of intensive investigation for the groundwater schemes.

Reach No.	Start of reach	End of reach	Start (km BHS*)	End (km BHS)	End grid reference†	Length (km)	No. of data
1	1km u/s of Lynch Wood	Riverside Cottage	0.95	1.95	SU 328 792	1.00	72
2	Riverside Cottage	Lower Lambourn	1.95	3.10	SU 333 783	1.15	49
3	Lower Lambourn	Eastbury	3.10	5.10	SU 349 770	2.00	44
4	Eastbury	East Garston	5.10	7.55	SU 367 765	2.45	55
5	East Garston	Shefford Church	7.55	9.40	SU 381 754	1.85	54
6	Shefford Church	East Shefford	9.40	10.90	SU 389 747	1.50	68
7	East Shefford	Weston	10.90	12.85	SU 403 736	1.95	37
8	Weston	Welford	12.85	13.85	SU 411 731	1.00	36
9	Welford	Boxford	13.85	16.50	SU 429 719	2.65	18
10	Boxford	Hunt's Green	16.50	18.65	SU 434 701	2.15	16
11	Hunts Green	Mill House, Woodspeen	18.65	20.40	SU 445 693	1.75	28
12	Mill House, Woodspeen	Shaw	20.40	23.35	SU 470 683	2.95	28

Table 5.4 Summary details of current meter stations and reaches
(*Below Highest Source of the River Lambourn; †from Brettell, 1971)

The distribution of records by year is given below in Table 5.5 and presented graphically in Figure 5.12, showing that the peak year for current meter data was 1966, representing 22% of the dataset, followed by 1967 with 15% and 1975 with 14%. In terms of a cumulative influence, the period 1966-1970, and 1975, represents 80% of the dataset. Clearly, the non-uniform distribution of the dataset over time has implications for its long-term representativeness. In order to assess how representative these six years were likely to be of the record as a whole, catchment discharge was used as a proxy measure. Statistics from the combined six-year record were compared with the long-term discharge statistics from 1962 to 2001, and the results are shown in Table 5.6.

Reach No.	YEAR 19.. (number of readings per year)																Reach totals
	64	**65**	**66**	**67**	**68**	**69**	**70**	**71**	**72**	**73**	**74**	**75**	**76**	**77**	**78**	**79**	
1	0	0	11	10	9	10	5	5	1	3	7	7	0	3	0	1	72
2	0	0	11	9	10	10	5	0	0	0	0	4	0	0	0	0	49
3	0	0	9	9	9	8	5	0	0	0	0	4	0	0	0	0	44
4	0	0	10	11	9	8	5	3	0	0	0	7	0	1	0	1	55
5	0	0	10	10	7	9	6	1	1	0	0	7	0	1	1	1	54
6	1	5	12	10	7	9	7	2	5	0	0	7	0	1	1	1	68
7	1	5	12	12	1	0	0	0	0	0	0	6	0	0	0	0	37
8	1	5	12	11	1	0	0	0	0	0	0	6	0	0	0	0	36
9	0	0	0	0	0	0	2	5	1	0	0	7	0	1	1	1	18
10	0	0	0	0	0	0	2	3	2	0	0	6	0	1	1	1	16
11	0	5	11	0	0	0	0	1	1	0	0	7	0	1	1	1	28
12	0	5	11	0	0	0	0	1	1	0	0	7	0	1	1	1	28
Year totals	3	25	109	76	52	54	37	21	12	3	7	71	0	10	6	8	***505***

Table 5.5 Annual occurrence of current meter data

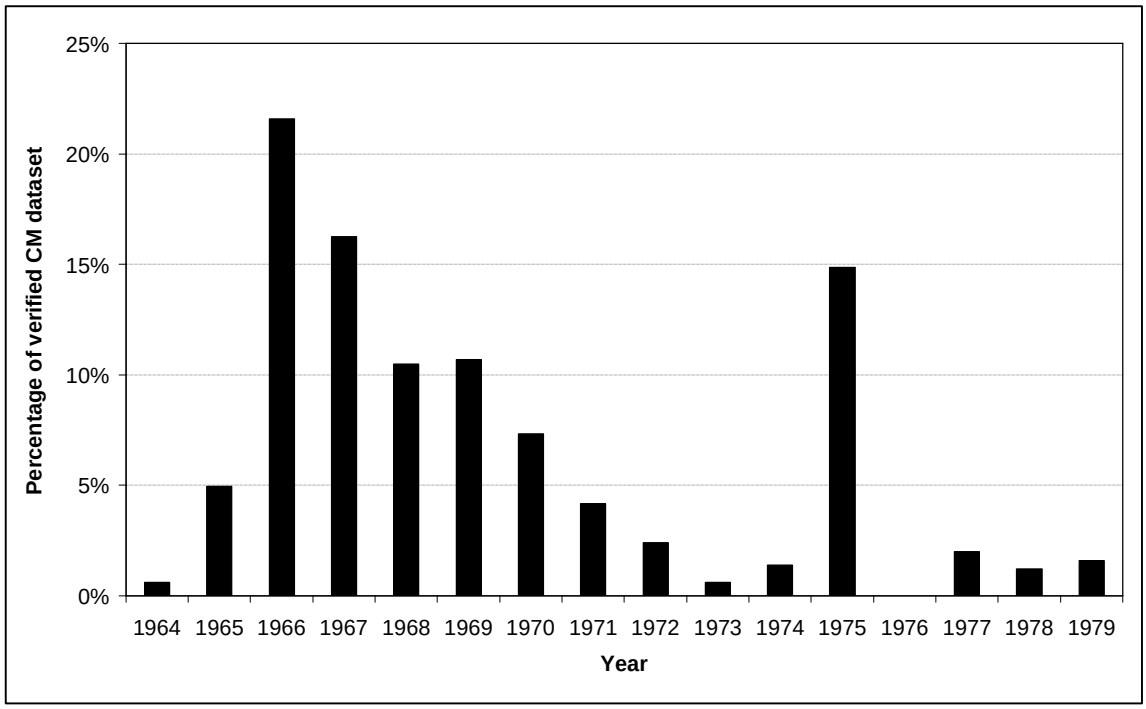


Figure 5.12 Annual frequency of current meter data

Table 5.6 indicates that the current meter dataset period is characterised by generally higher discharges than the long term average, shown by the mean and percentile values, which range from 28% higher for the Q10 figure, to 9% higher for the Q90 figure. However, as the majority of current metering was undertaken during summer and autumn, when flows were not at their peak, any bias in accretion rates will

tend more towards the Q90 value of being c. 10% greater than LTA, than the Q10 figure.

	Timescale		Percentage of 1962 - 2001value
Parameter	**1966 - 70, 1975**	**1962 - 2001**	
Mean (cumecs)	1.98	1.75	113%
Minimum (cumecs)	0.78	0.41	189%
Maximum (cumecs)	4.01	6.67	60%
Standard deviation (cumecs)	0.77	0.88	87%
Coefficient of variation	39%	51%	77%
Q10 (10% percentile; cumecs)	1.09	0.85	128%
Q25 (1st quartile; cumecs)	1.30	1.08	120%
Median (2nd quartile; cumecs)	1.87	1.51	124%
Q75 (3rd quartile; cumecs)	2.51	2.26	111%
Q90 (90% percentile; cumecs)	3.16	2.91	109%
Inter-quartile range (Q75 – Q25; cumecs)	1.21	1.18	103%

Table 5.6 Assessment of the representativeness of the reduced current meter dataset

5.3.2 Results

Summary statistics for the twelve current meter reaches are given in Table 5.7 and are presented graphically in Figure 5.13. The data in Table 5.7 from the seasonal section of the channel (reaches 1 to 5) are derived solely from periods when there was active flow occurring in this portion of the channel. However, this approach takes no account of the duration of seasonal no-flow periods, and hence upwardly biases the average accretion rates. To correct for this bias, the mean rates calculated for the seasonal reaches were multiplied by 0.75, as on average flow occurred in the seasonal section of channel for nine months per year, over the period 1983 – 2001.

The minimum and maximum accretion rates in Table 5.7 and Figure 5.13 should be treated with caution as they could reflect the gauging of an exceptional flow event, or might represent a single poor gauging that has distorted the value. Overall, the average values are likely to be most representative of the true variability in the spatial pattern of inflows. Although a number of reaches show a negative accretion (i.e. flow loss) on the plot of minimum rates, only a single reach (from Hunts Green to Woodspeen) shows an average accretion rate of less than zero.

It is apparent from Table 5.7 and Figure 5.13 that the detailed pattern of flow accretion is far from spatially uniform. The highest accretion rates occur at the upstream and downstream limits of the river, and close to the midpoint of its length, with lower rates occurring in the intervening sections. A prominent feature of the accretion rate

profile is its gradational variability, which roughly approximates a sinusoidal pattern. The variable, but non-random, distribution of accretion rates suggests that their dominant control exists on a large (near-catchment) scale, being locally overprinted by smaller scale influences. Some potential controls on this pattern are discussed in Chapter 7. Mean reach-based accretion rates are compared graphically with the long-term catchment mean accretion rate in Figure 5.14, being presented in the form of a cumulative flow accretion profile.

Reach No.	**End of reach**	**Minimum rate (cumecs /km)**	**Mean rate (cumecs /km)**	**Maximum rate (cumecs /km)**	**Standard Deviation (SD)**	**Coefficient of variation (% of mean)**	**No. of data**
1	Riverside Cottage	0	0.129	0.480	0.091	70.5%	72
2	Lower Lambourn	0	0.086	0.383	0.064	74.4%	49
3	Eastbury	-0.090	0.020	0.115	0.026	130.0%	44
4	East Garston	-0.004	0.024	0.135	0.024	100.0%	55
5	Shefford Church	-0.049	0.063	0.195	0.036	57.1%	54
6	East Shefford	-0.014	0.211	0.560	0.129	61.1%	68
7	Weston	0.072	0.139	0.338	0.052	37.4%	37
8	Welford	-0.080	0.123	0.490	0.082	66.7%	36
9	Boxford	-0.045	0.068	0.162	0.053	77.9%	18
10	Hunts Green	-0.042	0.054	0.251	0.073	135.2%	16
11	Mill House, Woodspeen	-0.217	-0.019	0.114	0.073	N/a	28
12	Shaw	0.018 *0.002*†	0.152 *0.084*†	0.380 *0.236*†	0.089 *0.060*†	58.6% *71.4%*†	28

Table 5.7 Summary statistics for current meter reaches
†with the discharge component from the Winterbourne Stream removed for comparison

The catchment discharge based upon the catchment average accretion rate (1.97 cumecs) is found to be higher than that of 1.86 cumecs, based upon cumulative average reach accretions. This contradicts the assessment made in Section 5.3.1 (based upon data in Table 5.6), that the current meter dataset was likely to overestimate accretion rates by between 10 and 30%. In fact, the cumulative discharge, based upon the average reach accretion rates, is 6% less than that based upon the catchment average accretion rate. This suggests that although the current meter dataset was derived from years with

above average discharges, the months during which the data were recorded were mainly low rather than high flow months, thus compensating for the annual bias.

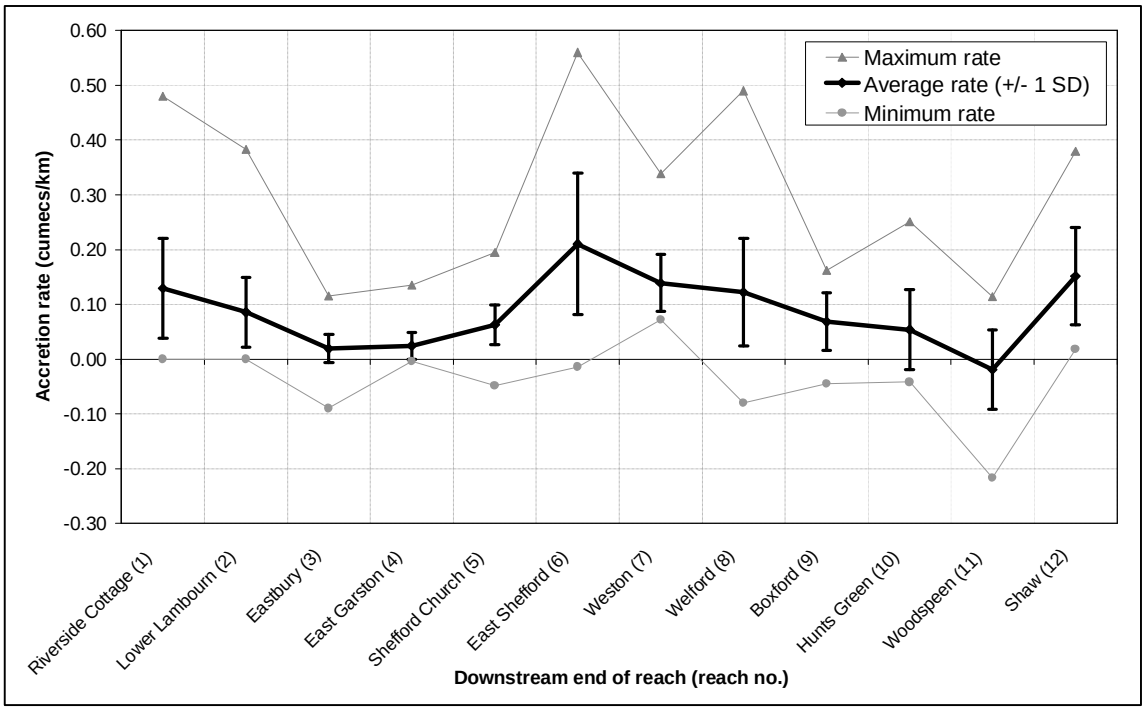


Figure 5.13 Ranges of accretion rates from current meter reaches

Comparing the gradients of the two time series in Figure 5.14, it is clear that a number of the reaches (3 Eastbury/ 4 East Garston/ 10 Boxford/ 11 Woodspeen) have rates that are well below the catchment average. There are also a number of reaches (6 East Shefford/ 7 Weston/ 12 Shaw) whose average inflow is significantly higher than the catchment average. A number of flow accretion profiles from specific days are presented in Figure 5.15, and these serve to illustrate the small day-to-day variability in accretion rates from individual reaches.

The volumetric significance of the average input from each reach to the catchment discharge is shown in Figure 5.16, which includes representation of reach length, and the data are also presented in Table 5.8. The area of each reach-based block can be compared to assess their volumetric significance. Figure 5.16 clearly shows the contrast between the peak accretion rate of reach 6 (East Shefford) and the maximum volumetric input from reach 12 (Shaw).

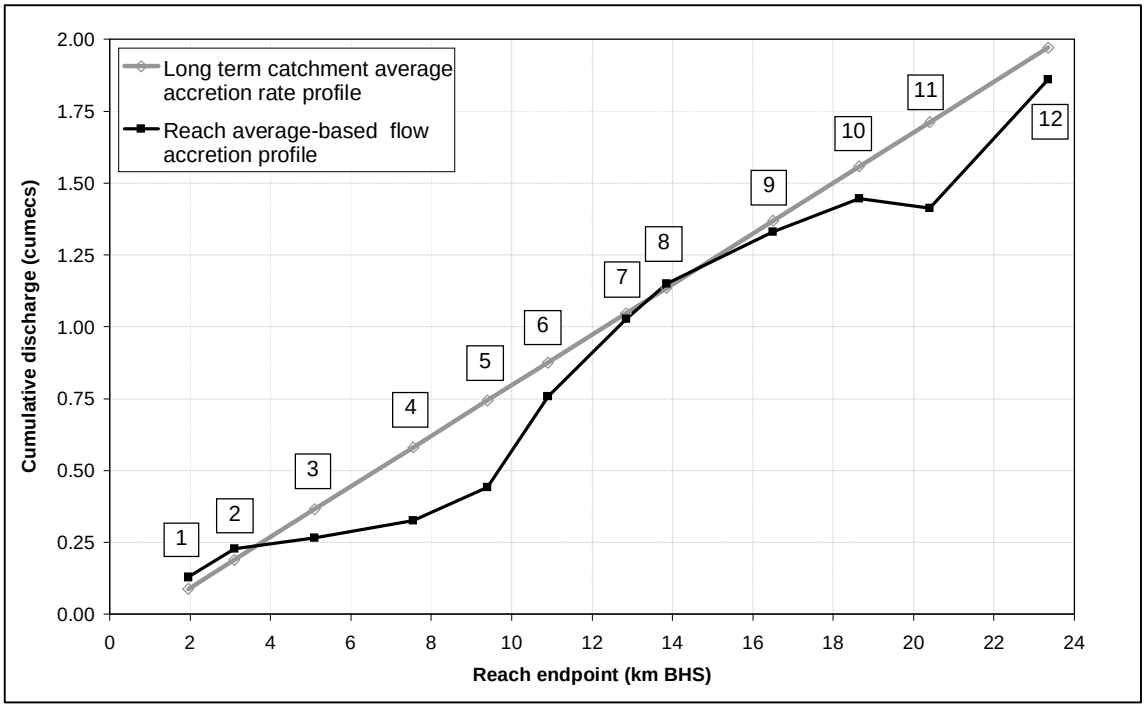


Figure 5.14 Flow accretion profile based upon catchment mean accretion rate and mean reach accretion rates
[Numbered boxes refer to reach numbers]

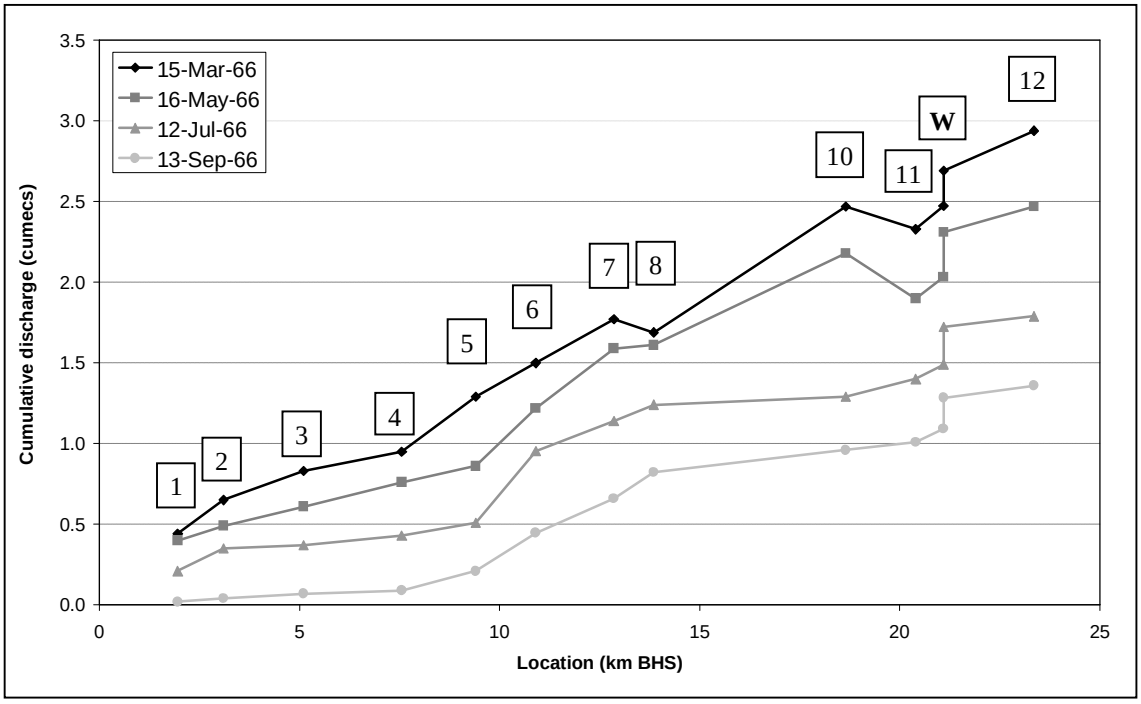


Figure 5.15 Flow accretion profiles from individual days during a period of flow recession in 1966
[**W** corresponds to the input from the Winterbourne Stream. NB values for the reach to Boxford {9} are absent]

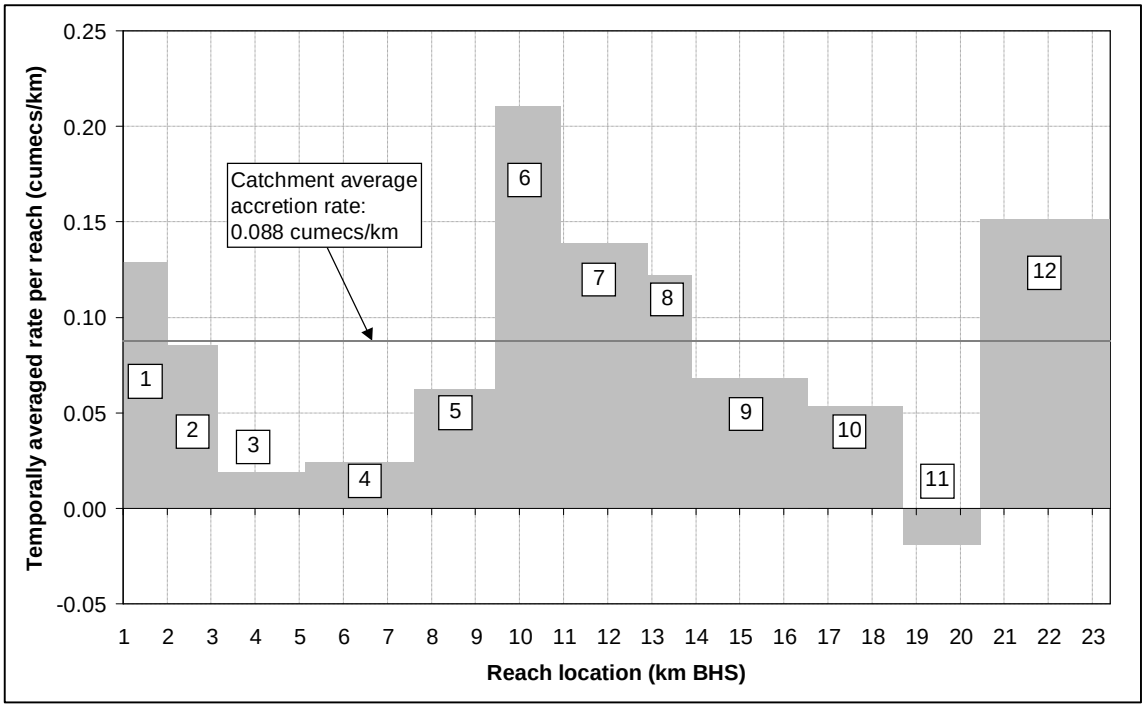


Figure 5.16 Spatially distributed reach-based inflows

Reach No.	Reach end:	Length (km)	Average accretion rate (cumecs/km)	Average accretion per reach (cumecs)	Contribution to catchment discharge	Cumulative Discharge (cumecs)
1	Riverside Cottage	1.00	0.129	0.129	7%	0.129
2	Lower Lambourn	1.15	0.086	0.098	5%	0.227
3	Eastbury	2.00	0.020	0.038	2%	0.266
4	East Garston	2.45	0.024	0.060	3%	0.325
5	Shefford Church	1.85	0.063	0.116	6%	0.442
6	East Shefford	1.50	0.211	0.316	17%	0.757
7	Weston	1.95	0.139	0.270	15%	1.028
8	Welford	1.00	0.123	0.122	7%	1.150
9	Boxford	2.65	0.068	0.181	10%	1.330
10	Hunts Green	2.15	0.054	0.116	6%	1.446
11	Woodspeen	1.75	-0.019	-0.033	-2%	1.413
12	Shaw	2.95	0.152	0.447	24%	1.860

Table 5.8 Volumetric reach accretions and contribution to catchment discharge

5.3.3 Variability in reach contributions with catchment discharge

Whereas tables and figures in the previous section give some indication as to the gross variability of the inflows from the various reaches, they give no information concerning the temporal pattern of variability within each reach. As the current meter dataset was very unevenly distributed over time, it was not appropriate to plot it as a simple time series. Instead, the data were used to calculate a Flow Accretion Index

(FAI), a unit-less parameter that was then plotted against catchment discharge, which acted as a proxy timescale. The FAI was calculated from:

$$FAI = \frac{\text{reach gain / reach length}}{\text{Shaw discharge / total length}} \qquad \text{Equation 5.1}$$

Thus:

$$FAI = \frac{\text{standardised reach accretion}}{\text{catchment average accretion}}$$

However, this can also be represented by:

$$FAI = \frac{\text{reach gain /Shaw discharge}}{\text{reach length / total length}}$$

Thus:

$$FAI = \frac{\text{reach flow contribution}}{\text{reach length contribution}} \quad \begin{matrix}\text{(as fraction of catchment discharge)} \\ \text{(as fraction of total channel length)}\end{matrix}$$

From these two representations of the same parameter, it can be seen that the FAI is a useful value for characterising the relative contribution of each reach to the catchment discharge. If inflows were spatially constant (at any point in time) and were proportional to catchment discharge, then the FAI would be constant with a value of 1 for all sites. However, from the selected plots of the FAI against Shaw discharge presented in Figure 5.17, inflows are seen to be neither spatially constant nor consistently linked to the catchment discharge. The linear regression correlations between Shaw discharge and FAI are summarised for all reaches below in Table 5.9.

Reach No.	**Reach end location**	**Regression relationship**		
		Multiplier	**Offset**	**R^2**
1	Riverside Cottage	Logarithmic relationship		0.49
2	Lower Lambourn	0.34	0.451	0.12
3	Eastbury	0.14	-0.039	0.18
4	East Garston	0.25	-0.298	0.46
5	Shefford Church	0.12	0.062	0.12
6	East Shefford	0.13	2.283	0.01
7	Weston	Power relationship		0.60
8	Welford	Logarithmic relationship		0.41
9	Boxford	0.10	0.601	0.02
10	Hunts Green	-0.08	0.824	0.004
11	Mill House, Woodspeen	0.08	-0.349	0.004
12	Shaw	0.01	1.892	0

Table 5.9 Details of linear regressions between Shaw discharge and FAI

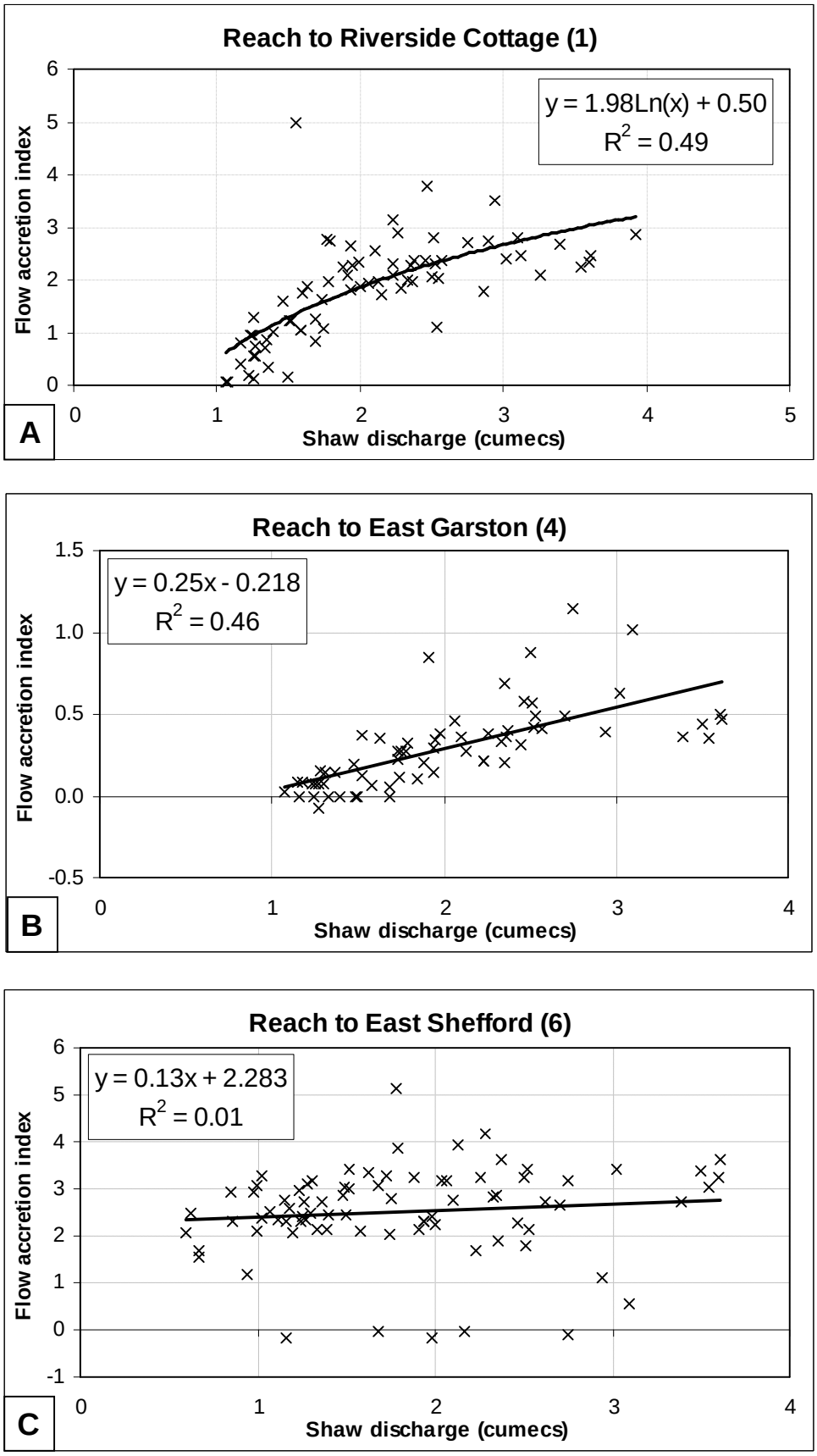
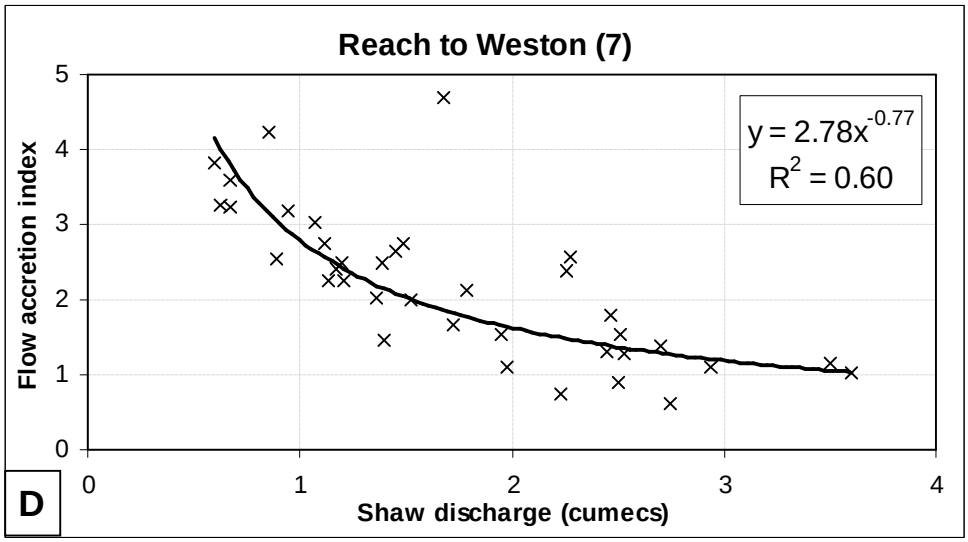
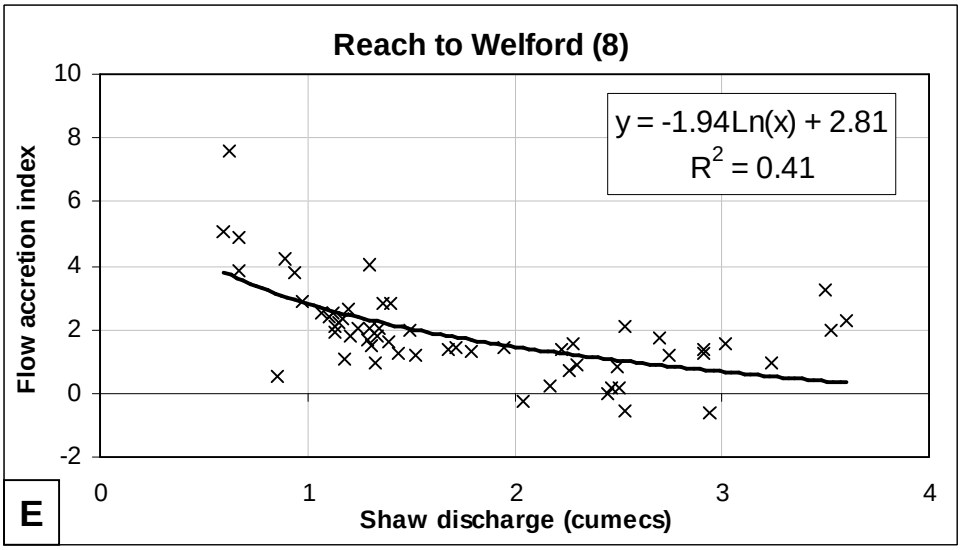


Figure 5.17 Variability in FAI versus Shaw discharge for selected reaches





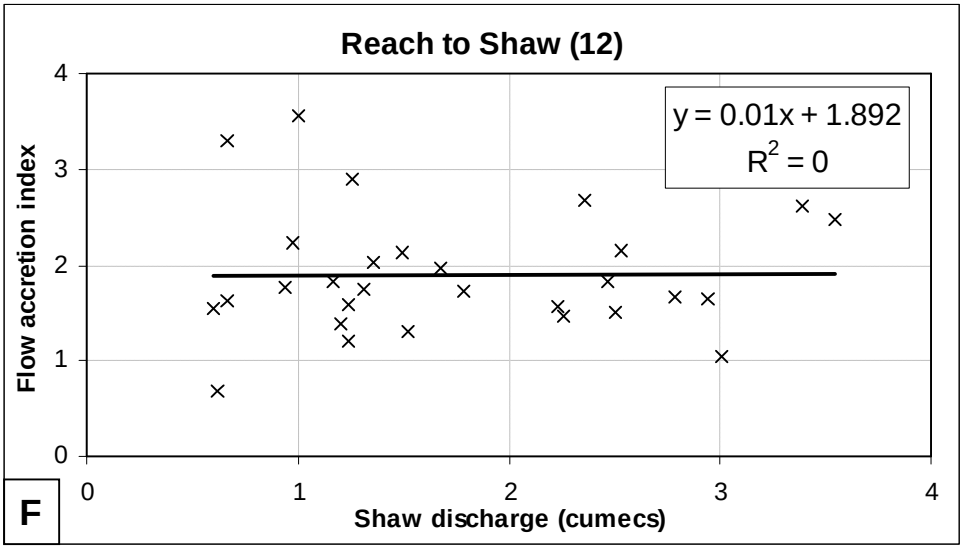


Figure 5.17 Variability in FAI versus Shaw discharge for selected reaches (cont.)

It is apparent from Table 5.9 that few of the reaches show a strong correlation between FAI and catchment discharge, the exceptions being reaches 1, 4, 7 and 8. The upper two of these reaches have a positive correlation, indicating that accretion in these reaches is proportional to catchment discharge. Both of these reaches are strongly reliant for their accretion upon point source inputs from well-defined springs. Discharge from these springs tends to be closely related to the catchment average water table (MGS), which itself exerts a strong control on the catchment discharge, thus acting to link accretion from these reaches with catchment discharge.

Whereas reaches 1 and 4 have positive correlations with Shaw discharge, reaches 7 and 8 have strong negative correlations, showing that accretion in these reaches is inversely proportional to the catchment discharge. This is the same behaviour recognised for the Welford gauging station reach in Section 5.2.4 (which includes the Weston and Welford reaches defined here). The additional data presented here confirm the anomalous nature of the Welford reach, and also serve to define the key portion of this reach with greater spatial precision. Of the remaining reaches, numbers 2, 3 and 5 in the seasonal section of channel all show weak positive correlations with catchment discharge, whereas reaches 6, 9, 10, 11 and 12 show no significant correlation. The pattern of correlation, like the pattern of accretion rates, appears to be gradational in form, and values of correlation coefficient (R) derived from the R^2 values and the sign of the multiplier (from Table 5.9) are plotted against location in Figure 5.18, with the pattern of average reach accretion rates also plotted for comparison.

From Figure 5.18 there appears to be a systematic pattern in the variation of correlation coefficient with location. All the strongest positive correlations are located in the uppermost 8km of the river, which coincides with the seasonal section of channel. There is no effective correlation with any sites in the perennial section of the river, with the exception of the two sites with strong negative correlations (Weston and Welford). It has been recognised previously that accretion in the Weston / Welford area does not operate synchronously with catchment discharge, and controls on these patterns of behaviour are discussed in Chapter 7. The observed pattern of flow recession in the seasonal section of channel, from Lynch Wood to West Shefford, supports the pattern of calculated flow accretion rates, and a detailed description is given in Appendix 10.

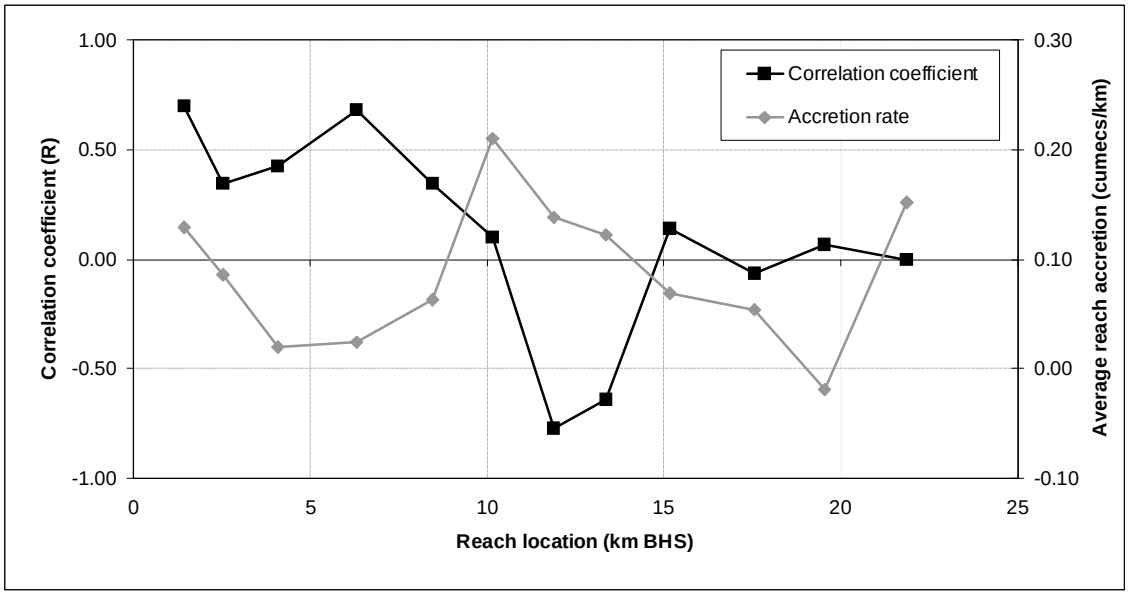


Figure 5.18 Spatial distribution of correlation coefficients for the relationship between reach accretion rate and catchment discharge

5.4 SUMMARY

The aim of this chapter was to present the spatial distribution of flow accretion rates, based upon historical and contemporary field data, with an increase in spatial resolution through the chapter. Initially a long-term (1984-2001) catchment average accretion rate of 0.088 cumecs/km was calculated, and this was put forward as the best single value for comparison of accretion rates with other chalk catchments. The importance of maintaining records of source location for chalk streams was highlighted during the calculation of this value.

Analysis of discharge data from gauging weirs, and the subsequent derived, unstandardised, accretion rates (Section 5.2.2), showed that at this arbitrary sub-catchment scale, the reach from the source to East Shefford was the most volumetrically important, producing on average 37% of catchment discharge. The reach from Welford to Shaw was the next most significant, delivering 33%, whilst the reach from East Shefford to Welford produced 21% and the Winterbourne Stream only 9% of the total.

Standardised accretion rates, based upon contemporary data, were then compared for the seasonal section (upstream of East Shefford) and the perennial section from East Shefford to Shaw in Section 5.2.3. It was found that their rates were broadly similar at this scale, but there were indications that the short perennial section

immediately above East Shefford had a significant influence on the spatially averaged rates for the ‘seasonal’ portion.

Standardised accretion rates for two perennial reaches (East Shefford to Welford and Welford to Shaw) were then compared (Section 5.2.4) and it was found that the reach to Welford behaved in an anomalous manner, being inversely proportional to catchment discharge. It was demonstrated that this behaviour was not due to discharge from the Winterbourne Stream influencing the Shaw reach.

Using historic current meter data, the spatial pattern of accretion was then defined with greater resolution, revealing a complex pattern of spatial variability (Section 5.3.2). The relationships between reach accretion rates and catchment discharge were then examined (Section 5.3.3), and these confirmed the anomalous behaviour of the channel section between East Shefford and Welford described above, which displayed a strong negative correlation with catchment discharge, illustrating the significance of localised influences on flow accretion. The potential significance of some regional and local controls is assessed in greater detail, including use of numerical groundwater modelling, in Chapter 6.

Chapter 6 Characterising and modelling controls on the spatial pattern of flow accretion

6.1 INTRODUCTION

A number of potential controls on flow accretion were identified in the literature review (Chapter 2), and during the analysis of spatial patterns of accretion (Chapter 5). The most significant of these is the hydraulic gradient, and specifically the head differential between the river stage and local groundwater level, as in the absence of a potential gradient there will be no river – aquifer exchange. In any groundwater system, the pattern of hydraulic gradient is intrinsically linked to the distribution of aquifer permeability, as the gradient is dependent upon the water flux in the aquifer, whilst the flux depends upon both the gradient and the permeability.

Differential head levels are the basis of the 2-dimensional 'Rushton-type' conceptual scenarios of groundwater – river interaction (Rushton & Tomlinson, 1979), which are illustrated in Section 2.2. Rushton & Tomlinson's conceptual scenarios provide a context for describing the potential direction and magnitude of river – aquifer exchange at any location, but fail to consider longitudinal variability (the third dimension) arising due to variability in aquifer parameters and valley floor deposits, including both the underlying alluvial deposits and the sedimentary character of the stream bed / banks (specifically their silt / clay content).

Analytical approaches (e.g. using Darcy's law) can be used to assess specific, localised variations in both bedrock and alluvial permeability, but are generally too cumbersome to assess complex patterns at larger spatial scales. However, more complex scenarios can be investigated systematically (albeit with some generalisation of parameter configurations) by using 3-dimensional numerical groundwater models. These also allow the influence of variability in other aquifer parameters (e.g. storage and aquifer thickness) to be assessed in a methodical manner through sensitivity analyses.

From work in this and previous studies, it appears that two scales of influence are operating; regional hydraulic gradients at the catchment scale, and valley floor - related controls at the local scale. The catchment MGS (mean groundwater stage), which can be considered a proxy measure for regional hydraulic gradient, was shown to

be the key control on catchment discharge (Table 4.9). However, in this chapter (Section 6.2.1) the variable relationship that exists between MGS level and reach-scale inflows is demonstrated, indicating the degree to which some reaches are disconnected from the catchment-scale groundwater flow system. This conclusion is supported by a direct assessment using calculated regional hydraulic gradients, the variability in which is insufficient to account for the spatial variability in reach inflows.

To assess the influence of local-scale valley floor controls, an analytical approach is used to estimate valley floor permeability at three locations in the upper half of the River Lambourn. These sites have a similar pattern of water level behaviour, with groundwater levels being higher than river stage, but the sparse detail on the valley floor alluvial deposits limits the interpretation of their specific influence.

Given the lack of available subsurface detail, particularly pertaining to valley floor controls, a groundwater modelling approach was used to simulate various stream – aquifer parameter configurations, and evaluate potential controls on accretion. Initially a catchment scale simulation was undertaken, which was calibrated satisfactorily based upon surface water discharge from the catchment. This baseline simulation then provided the foundation for further simulations focused at reach scale parameter configurations, in order to evaluate valley floor controls. However, these results were of limited value as the reach scale simulations highlighted a number of shortcomings in the model's ability to represent river – aquifer exchanges.

6.2 THE INFLUENCE OF CATCHMENT SCALE HYDRAULIC GRADIENTS ON REACH-SCALE PATTERNS OF FLOW ACCRETION

6.2.1 MGS level as a control on reach-scale accretion rates

Section 4.6 demonstrated that the average groundwater level across the catchment (represented by the MGS value) is the most important control on the catchment discharge. However, from plots of flow accretion index (FAI) against catchment discharge in Section 5.3.3, it is unclear whether the dominant control of the MGS value also applies at the reach scale. To undertake this assessment, simple linear regression analysis between reach scale flow accretions and the appropriate MGS value was carried out, with the results summarised in Table 6.1.

Reach No.	Reach end location	Multiplier	Offset	R^2	Average accretion rate (cumecs/km)	Calculated* accretion rate (cumecs/km)
1	Riverside Cottage	0.059	-6.55	0.82	0.129†	0.117
2	Lower Lambourn	0.034	-3.82	0.56	0.085†	0.022
3	Eastbury	0.012	-1.38	0.40	0.019†	-0.024
4	East Garston	0.014	-1.63	0.63	0.024†	-0.048
5	Shefford Church	0.014	-1.47	0.36	0.063†	0.112
6	East Shefford	0.039	-4.24	0.59	0.211	0.167
7	Weston	0.006	-0.55	0.10	0.139	0.128
8	Welford	0.004	-0.35	0.01	0.122	0.102
9	Boxford	0.014	-1.52	0.50	0.068	0.062
10	Hunts Green	0.005	-0.57	0.04	0.054	0.295
11	Woodspeen	-0.003	0.31	0.01	-0.019	-0.029
12	Shaw	0.024	-2.57	0.65	0.152	0.142

Table 6.1 Results of linear regression analysis between reach accretion rates and MGS level

*Based upon linear regression relationships and the average MGS level of 113mOD

†Signifies seasonal reach; accretion value adjusted for an average 3-month period per annum without flow

It is clear from Table 6.1 that the variability in standardised accretion (i.e. accretion/km) in most reaches can be explained by variability in the associated MGS level, although four of the twelve reaches (7, 8, 10 and 11) have no significant relationship with MGS. However, what is apparent among the reaches with high R^2 values is that there is considerable variability in the nature of the linear regression relationships. Even reaches that appear to have similar relationships, for example 4 and 5, are actually very different, as the range of calculated accretion rates based on a constant MGS value testifies. This indicates that whilst there is a strong relationship between MGS and accretion rate in the majority of the reaches, the actual nature of the relationships is diverse.

6.2.2 Regional hydraulic gradients as a control on reach-scale accretion rates

To assess the relationship between catchment groundwater level and accretion rates in an alternative manner, regional hydraulic gradients were calculated from the groundwater catchment divide to the mid points of the 12 current meter reaches at conditions of maximum and minimum groundwater levels. Accretion rates occurring at periods of maximum and minimum MGS level were then correlated with the hydraulic gradients to assess the nature of the relationship, and the results are presented in Figure 6.1.

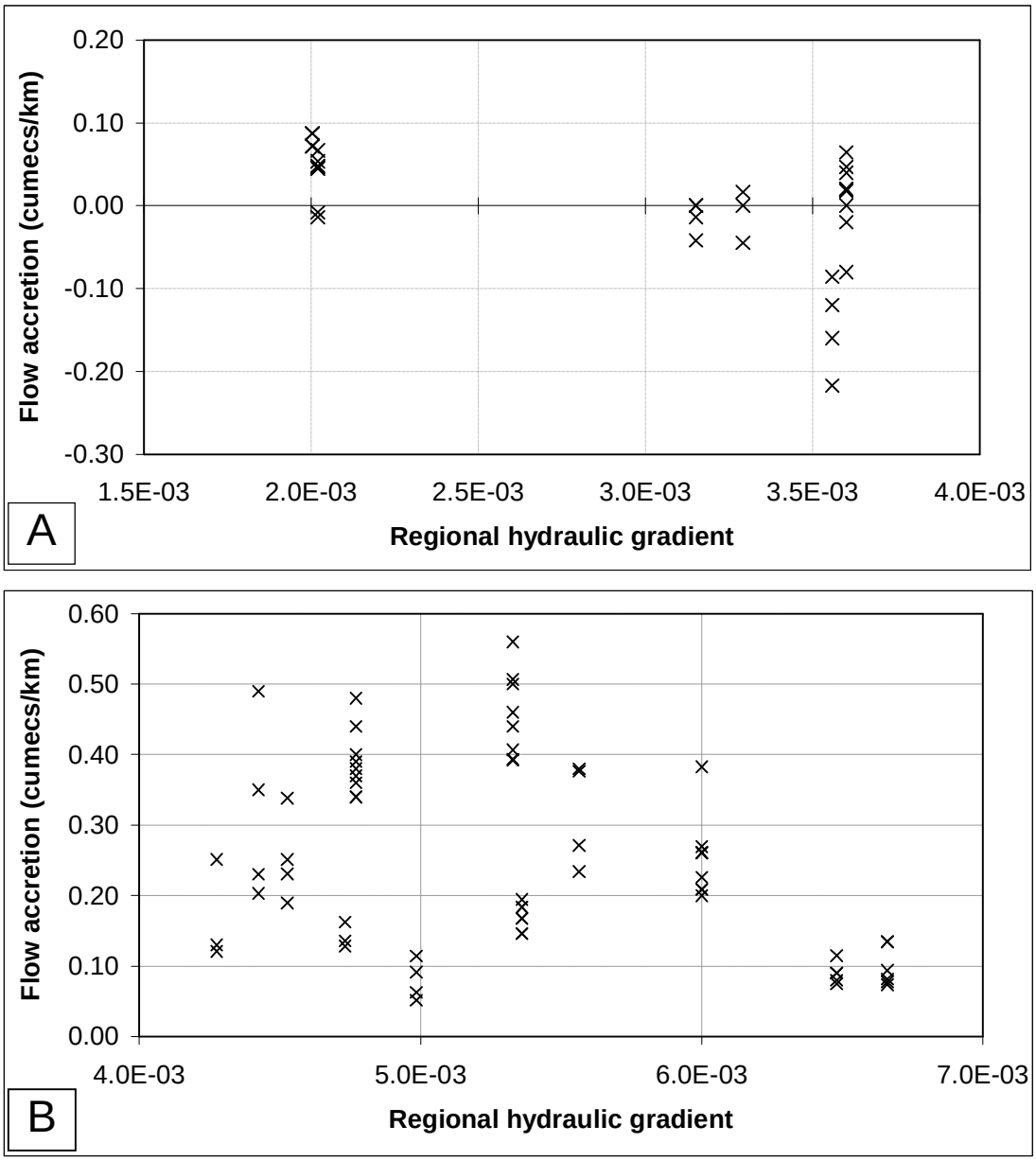


Figure 6.1 Maximum (A) and minimum (B) regional hydraulic gradients versus reach accretion rates

From Figure 6.1 it is clear that there is no systematic relationship between the regional hydraulic gradients and the individual reach accretion rates, suggesting that local-scale features and hence local scale hydraulic gradients determine the reach-scale pattern of flow accretion rates. Thus, the spatially variable pattern of accretion is not simply a manifestation of regional scale aquifer morphology, or regional distribution of aquifer parameters, but represents the influence of local scale features imprinted upon a regional scale backdrop.

6.3 CHARACTERISATION OF VALLEY-FLOOR DIFFERENTIAL HEAD LEVELS ALONG THE RIVER LAMBOURN

At a number of locations along the Lambourn, groundwater levels have been recorded in close proximity to the river channel, both historically and in the course of this study. The patterns of near-channel groundwater levels and hydraulic gradients are defined from three locations in the upper half of the catchment and are compared with the spatial pattern of discharges defined in Chapter 5. The three locations, Bockhampton, East Garston and West Shefford are shown in Figure 6.2.

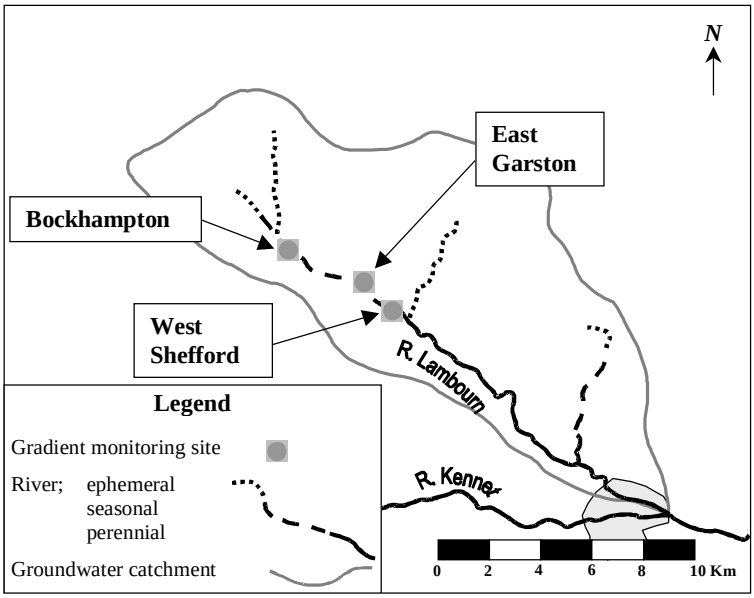


Figure 6.2 Locations of river – aquifer gradient monitoring sites

6.3.1 Bockhampton

Site context

The Bockhampton site is located close to the upstream end of current meter reach 3 (Figure 5.11), 0.45km downstream from Lower Lambourn and 1.55km upstream from Eastbury. The presence and nature of alluvial deposits at Bockhampton are poorly defined, but the location is significant both lithologically and hydrologically. The lithological importance of the site lies in it being close to the outcrop of the Chalk Rock in the floor of the Lambourn valley. The Chalk Rock represents a significant lithological control on groundwater flow at locations further downstream (e.g. West Shefford and Newbury) and may be important here. Hydrologically, Bockhampton is significant because it lies at the junction between the high inflow reaches around

Lambourn village and the low inflow reaches between Eastbury and East Garston (identified in Section 5.3).

Data availability

The monitoring infrastructure at Bockhampton, located 1.6km downstream of the Lambourn's seasonal source at Lynch Wood, consists of an EA observation borehole (reference number SU37/60), which is cased to a depth of 12m and situated c. 20m from the river channel. The datum elevation of the borehole is 121.89mOD and it is 50m deep (based upon EA records), whilst the bed elevation of the adjacent channel is approximately 120mOD, based upon Ordnance Survey topographic data. Discharge was not measured at the site, but the presence or absence of flow for the period from December 1983 to October 2001 can be estimated from the conditions at Lynch Wood springs, recorded by Pike (1998) and during this study. Additionally, discharge has been recorded at Lynch Wood at roughly monthly intervals for this study (from April 1999 to October 2001). The discharge at Bockhampton normally exceeds that at Lynch Wood during winter and spring, when there are flow gains in the vicinity of Lambourn village, but will be lower at other times of the year when groundwater discharge is focused at Lynch Wood springs, and infiltration losses occur downstream.

Patterns of groundwater level variability

The record of flow occurrence at Lynch Wood is compared with groundwater levels at Bockhampton in Figure 6.3, which shows that there is a close relationship between the occurrence of flow at Lynch Wood and the groundwater level at Bockhampton. The dashed lines indicate the maximum and minimum groundwater elevations at which flow commences or ceases at Lynch Wood, and encompass range 'A', from 119.3 to 120.3mOD. From the relative timing of the increases in groundwater level, it is clear that the rises are not simply due to infiltration losses from the stream, as they always pre-empt the occurrence of discharge from Lynch Wood springs. Instead, the groundwater level and springs are reacting to the same stimulus; specifically changes in catchment scale groundwater levels. It is also apparent from Figure 6.3 that the maximum groundwater level is limited to around 121mOD, which suggests that at this elevation there is sufficient gradient to maintain a significant discharge to the river, and thus prevent any additional rise in the water table.

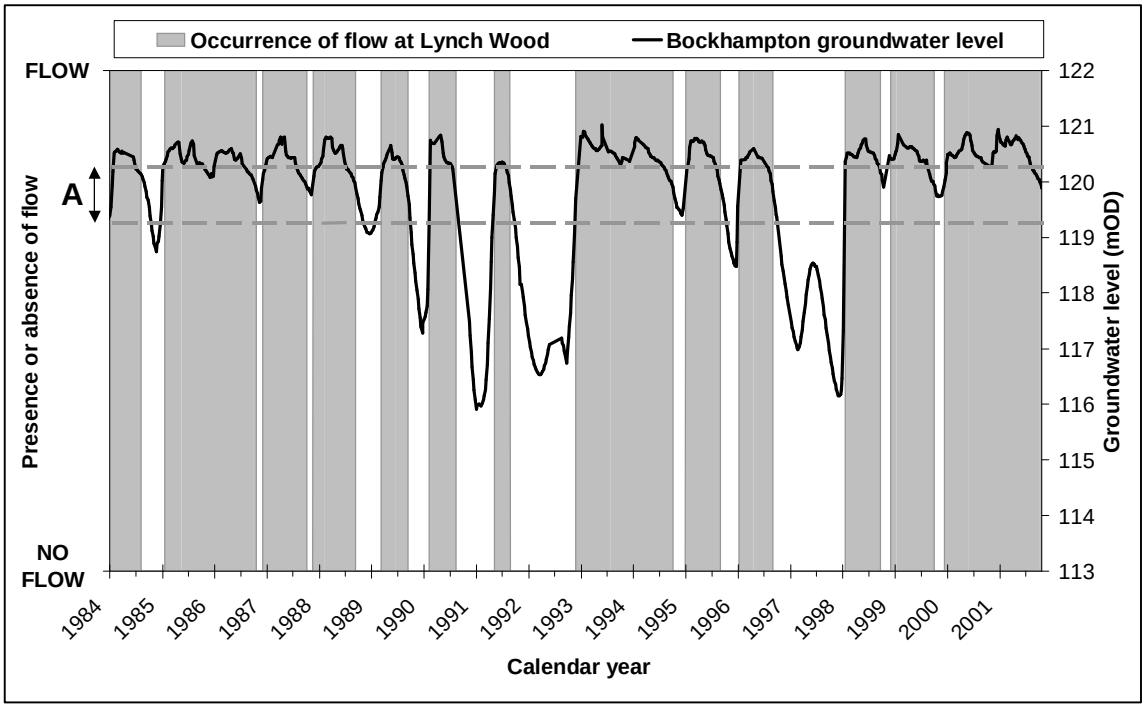


Figure 6.3 Comparison of flow occurrence at Lynch Wood with groundwater level at Bockhampton observation borehole

Variability in lateral gradient and spring discharge

In order to assess the relationship between Lynch Wood springs and the channel at Bockhampton quantitatively, a hydrograph of the lateral hydraulic gradient (calculated from the groundwater level and the local channel bed elevation) at Bockhampton is plotted with discharge from Lynch Wood in Figure 6.4, for the monitoring period of this study.

Figure 6.4 demonstrates the close similarity between the temporal patterns of lateral gradient at Bockhampton and discharge from Lynch Wood, which reinforces the premise of a common control. Point **1** illustrates the short period in the pattern of recession when a small discharge is still occurring from Lynch Wood, but flows are subsequently lost due to infiltration in the first few kilometres downstream, demonstrated by the small negative gradient occurring at Bockhampton. The maximum groundwater level at Bockhampton (and thus the maximum lateral gradient) is limited by the presence of the adjacent channel, whilst there is no such limit on the maximum discharge from the springs. The exceptionally wet autumn of 2000 produced a very high discharge from Lynch Wood springs, but the maximum gradient was constrained by the water level in the adjacent channel, which was little affected by the high discharges, as

the channel is relatively wide and shallow at this location. This caused the two parameters to diverge (**2**). Once the peak discharge had receded at Lynch Wood the two parameters re-converged (**3**) and displayed a very similar pattern of recession. The average lateral gradient at Bockhampton of around 0.02 is almost an order of magnitude higher than the regional scale hydraulic gradient of 0.003.

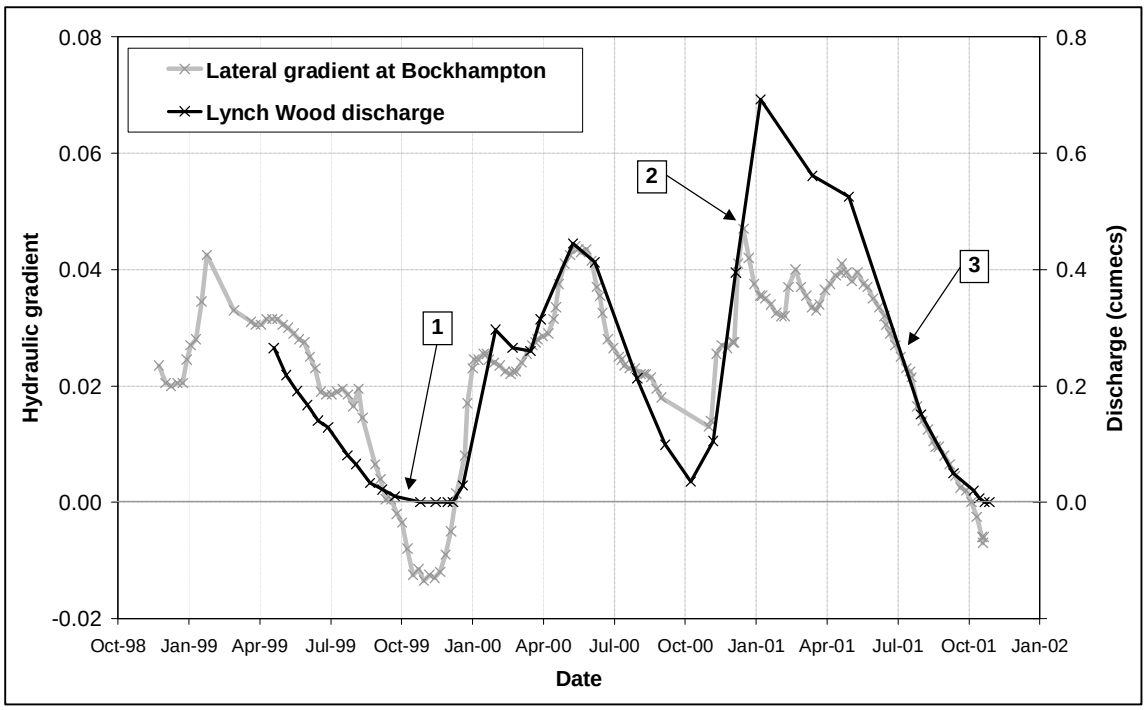


Figure 6.4 Temporal patterns of lateral hydraulic gradient at Bockhampton and discharge from Lynch Wood springs
[See text for explanation of annotation]

Calculation of valley floor permeability

The defined lateral gradient between aquifer and channel provides an opportunity to quantify valley floor permeability, using a simple analytical approach based upon Darcy's Law, applied to a 1km section of river channel:

$$\mathbf{Q = - K\, i\, A} \qquad \text{Equation 6.1}$$

Where:

Q = reach accretion rate (m^3/s/km)

K = gross hydraulic conductivity between borehole and channel (m/s)

- i = hydraulic gradient between borehole and channel

A = area of flow exchange between aquifer and channel (m^2/km of channel)

The site lies in current meter reach 3 and the flow gain in this reach is estimated from the relationship between measured accretion rate and catchment discharge (modified from Section 5.3.3). The lateral hydraulic gradient between the borehole and the channel is plotted against the calculated reach accretion rate in Figure 6.5.

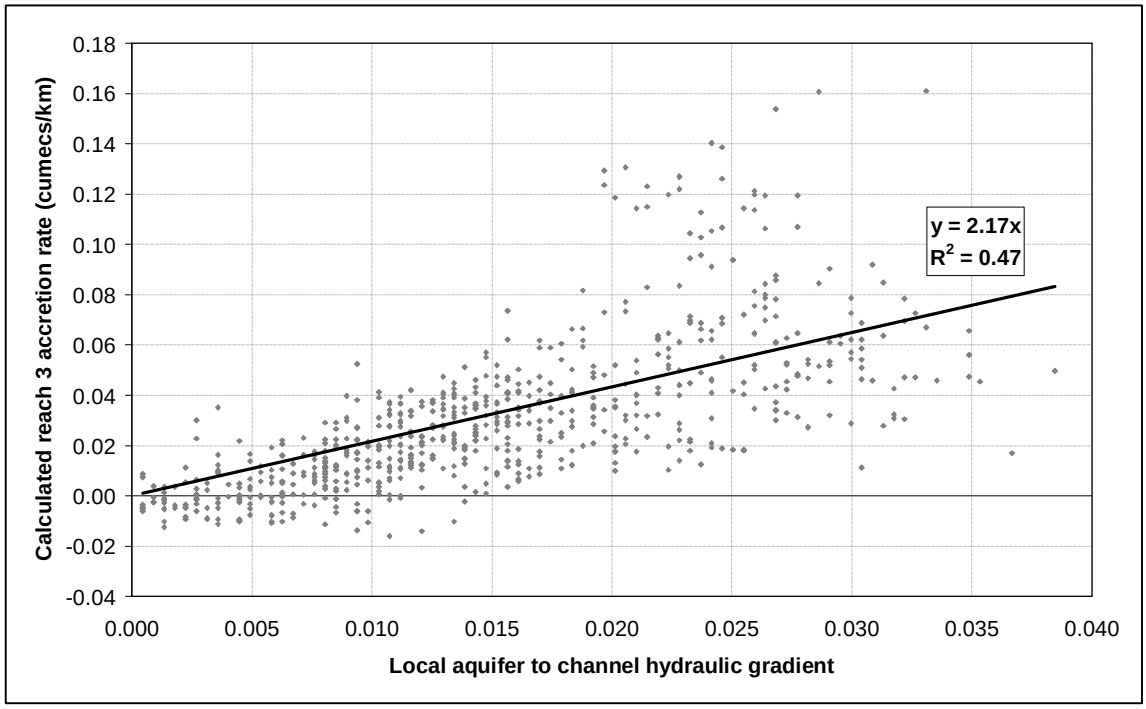


Figure 6.5 Lateral hydraulic gradient at Bockhampton versus calculated accretion rate in reach 3

The linear relationship in Figure 6.5, passing through the origin, allows 'K' to be defined if 'A' is known, as:

$$Q = - X i$$

And:

$$X = K A$$ (based upon Equation 6.1, with the minus sign removed for convenience)

Parameter 'A' was estimated as the average wetted perimeter of the channel, per kilometre length. From a channel survey at Bockhampton the wetted perimeter was found to be 5.7m, giving a value for 'A' of 5700m^2. Using the gradient from Figure 6.5, this produced a 'K' value of 3.8 x 10^{-4} m/s (33m/d) as an estimate for the combined permeability of the chalk, alluvium and channel bed materials in the vicinity of Bockhampton. In terms of the permeability of the chalk, this compares to an average value of 25m/d defined from the Lambourn Valley Pilot Scheme (Brettell, 1971),

calculated here from a transmissivity value using an effective saturated thickness of 60m. In terms of unconsolidated material, the defined value for 'K' could represent medium grained sand to gravel (Domenico & Schwartz, 1990; Table 3.2) but in this case may indicate poorly sorted or partially clogged gravel.

6.3.2 East Garston

Site context

The village of East Garston is located near the downstream end of current meter reach 4 (Figure 5.11), with the Eastbury current meter station situated around 2km upstream and the East Garston current meter station situated on the downstream edge of the village (shown in Figure 6.6). Both reaches 3 and 4 upstream are characterised by low accretion rates, whereas the reaches downstream (5 to 10) display much higher rates of accretion. Thus, East Garston lies at the junction between two significant lengths of the river displaying contrasting rates of accretion.

Although accretion is generally low in the area, there are a number of minor springs present, the most significant of which maintains a small discharge even when the channel upstream is dry (Figure 6.6). This spring appears to discharge from the chalk aquifer, as it displays a characteristic chalk spring temperature and electrical conductivity (EC) signature. This signature consists of low variability and low values for both parameters (relative to river water), with temperature varying from 9.1 to 10.7ºC and EC from 454 to 495µS/cm. Despite this hydrochemical evidence for the chalk provenance for this spring, the exact configuration of local permeability that allows it to maintain its discharge, whilst the adjacent channel is dry, remains enigmatic.

Monitoring infrastructure

There are two shallow piezometers (both approximately 4m deep) located adjacent to the river channel in the village (Figure 6.6), and both have been monitored on a roughly weekly basis since 1992. A plot of water levels from these piezometers is shown in Figure 6.7.

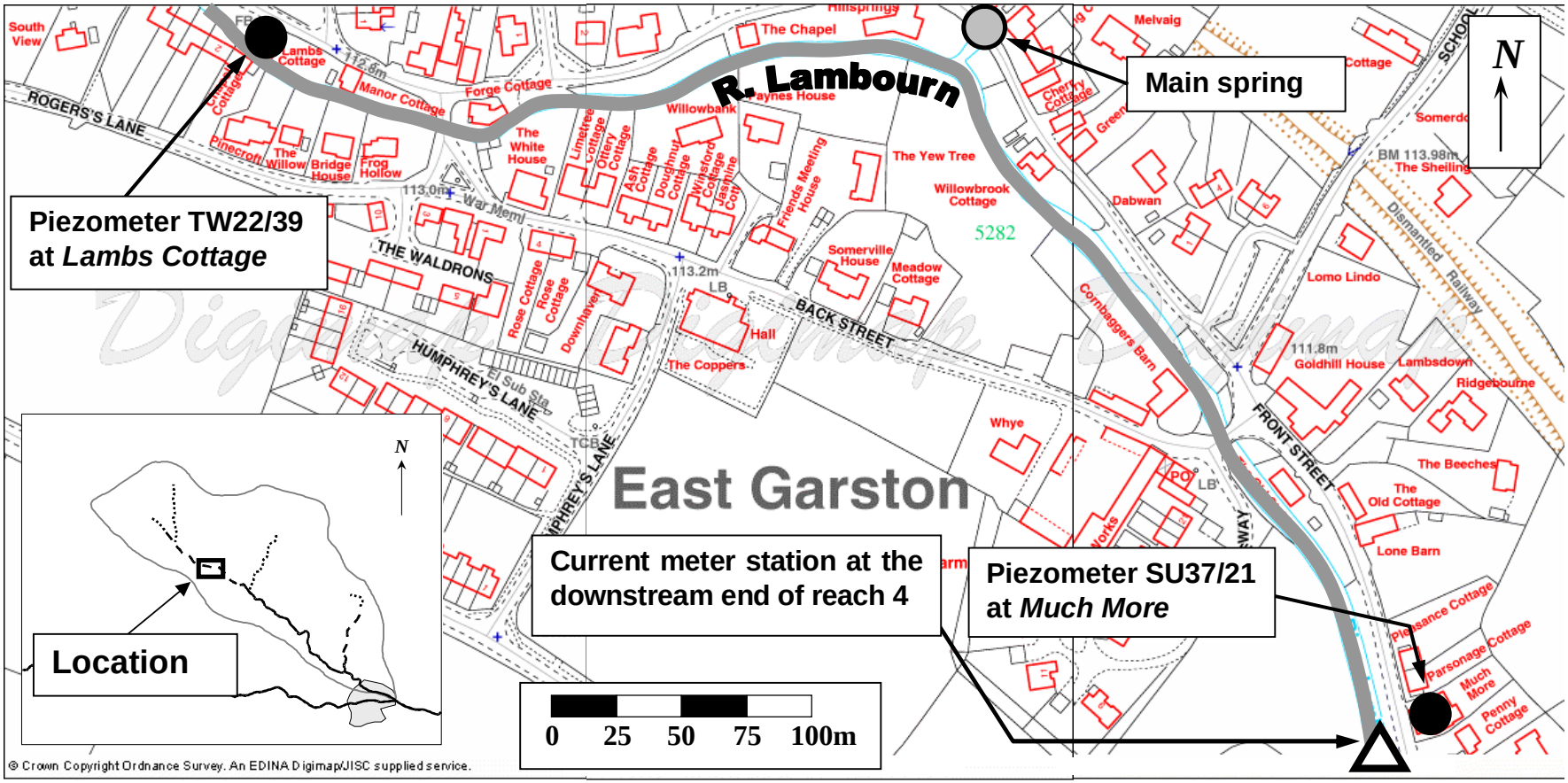


Figure 6.6 Locations of piezometers and other hydrological features in East Garston
[Water level data from the two piezometers are courtesy of Mr Roy Hunt, a local resident, who manually records the levels]

Patterns of groundwater level

Figure 6.7 clearly demonstrates the close association between the two piezometers and also shows their close association with the pattern of flow occurrence at Lynch Wood springs.

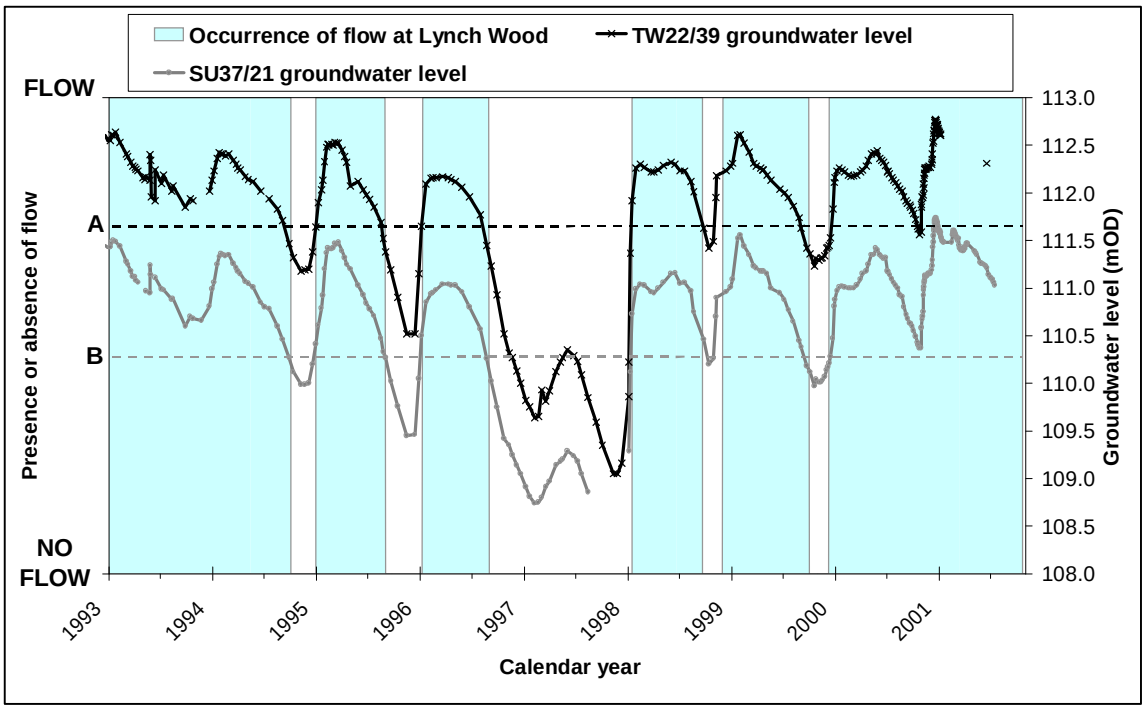


Figure 6.7 Shallow groundwater levels at East Garston, with occurrence of flow at Lynch Wood
[**A** represents channel bed elevation adjacent to TW22/39, **B** adjacent to SU37/21]

The difference in the behaviour of the upstream and downstream sections of the river in East Garston is demonstrated at the base of recession in 2000, where the upper section dried out, but the lower section maintained a small flow.

Derivation of a value for local permeability

Values for local permeability were calculated by the same approach as outlined in the previous section (6.3.1), with the exception of the calculation of values for the local gradient. As the piezometers were so close to the channel, the lateral and vertical components of the hydraulic gradient were of similar magnitude, and to overcome this the true distance (the hypotenuse of the lateral and vertical distances) between the water level measuring point and the channel bed was used to calculate the hydraulic gradient. After plotting the hydraulic gradient against calculated accretion rate (Figure 6.8), the slopes from the resulting linear regression relationships were then used with an estimate

for parameter 'A' (5100m^2/km) to calculate values for 'K' of 15m/d for the upstream site (TW22/39) and 25m/d for the downstream site (SU37/21). These values are still within the same order of magnitude as the value from Bockhampton (33m/d), but show significant variability despite a lateral separation of only 500m. This indicates the composite nature of the accretion rate in a reach at any point in time, which is a function of numerous gradient / permeability combinations over each kilometre of channel. It is thus difficult to assess how representative are the 'K' values defined here, given the very limited number of measurement points, but they appear to be credible values for alluvial gravel, or the chalk aquifer in a river valley.

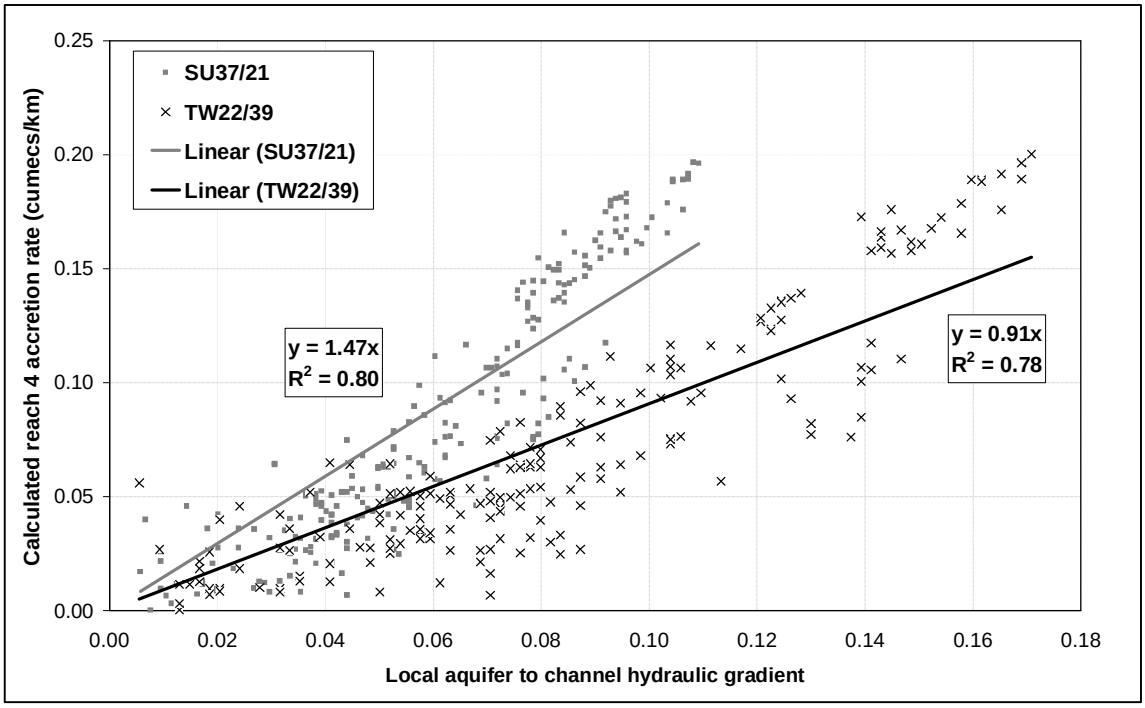


Figure 6.8 Lateral hydraulic gradient at East Garston piezometers versus calculated accretion rate in reach 4

6.3.3 West Shefford

Water level monitoring points

Various valley floor water levels were measured at the West Shefford site during the period of this study. River stage, deep chalk groundwater levels, shallow chalk groundwater levels and alluvial groundwater levels were each monitored. The relative positions of monitoring points, and available subsurface data, are shown in Figure 6.9, which represents a section from south-west to north-east across the floor of the Lambourn valley at West Shefford.

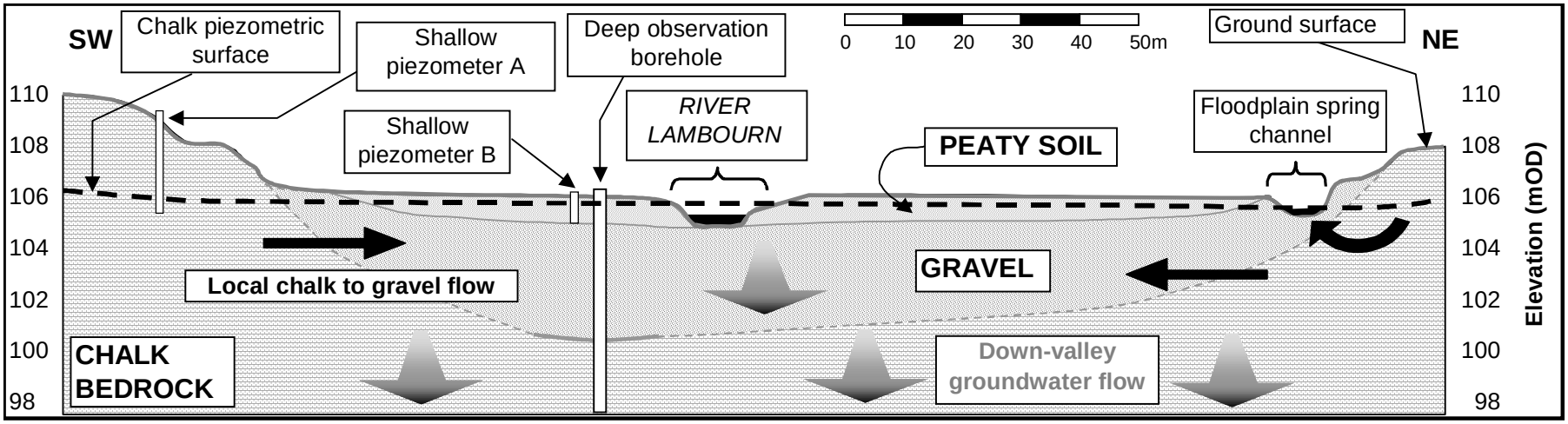


Figure 6.9 Section across the Lambourn valley at West Shefford looking upstream to the north-west
(Vertical exaggeration is 5 x horizontal)

Subsurface morphologies

In Figure 6.9 the morphology of the base of the gravel layer is conjectural, with the exception of parts adjacent to the deep observation borehole, where it is recorded in the drillers logs at 5.5m below ground level (Brettell, 1971). The longitudinal extent of the gravel layer is also poorly defined, but at East Shefford, 1.5km downstream, it is of much reduced lateral extent and thickness, and may be absent altogether. The lithology of the gravel layer is not well known. Material from the base of a hole, augered for installation of shallow piezometer B, comprised clean, coarse flint gravel, similar to that observed in the base of both the main river channel and floodplain spring channel. However, observations recorded during this study from a pit excavated* in the floodplain deposits 30m downstream of the cross-section, showed around 1m of black peaty material (possibly wood peat) overlying cobbles of flint and sarsen (Tertiary silcrete) in a putty chalk matrix. *(not as part of this study)

The morphology of the base of the peaty soil is conjectural, except in the area of shallow piezometer B, where peat was recorded to a depth of 1m during installation of the piezometer for this study. Shallow piezometer A was not part of this study but was one of a pair installed by the local Parish Council in glebe land of the adjacent West Shefford church, in connection with a proposed extension of the churchyard. Water level data from these holes were provided courtesy of Mr Lister Hickson, a member of the Parish Council.

Patterns of water level elevation

A hydrograph showing water level elevations from monitoring points illustrated in Figure 6.9 is presented as Figure 6.10, including deep chalk water levels (deep observation borehole), shallow chalk water levels (piezometer A), alluvial deposit water levels (piezometer B) and river stage. The daily record from piezometer B was very variable and so is presented here as a seven day running mean for clarity.

From Figure 6.10 it is apparent that both lateral and vertical controls influence the recorded water levels. The highest water levels were consistently recorded in piezometer A, which monitored shallow chalk water levels on the lower portion of the valley slope, approximately 80m from the river channel. The ground level at piezometer A was 109.2mOD, around 2.7m higher than at the collar of the deep observation borehole and piezometer B, which explains the highest water levels being recorded at

this location. Despite the differences in water level, it is clear that the levels from all the monitoring points follow a similar seasonal pattern of variation, in terms of both timing and magnitude.

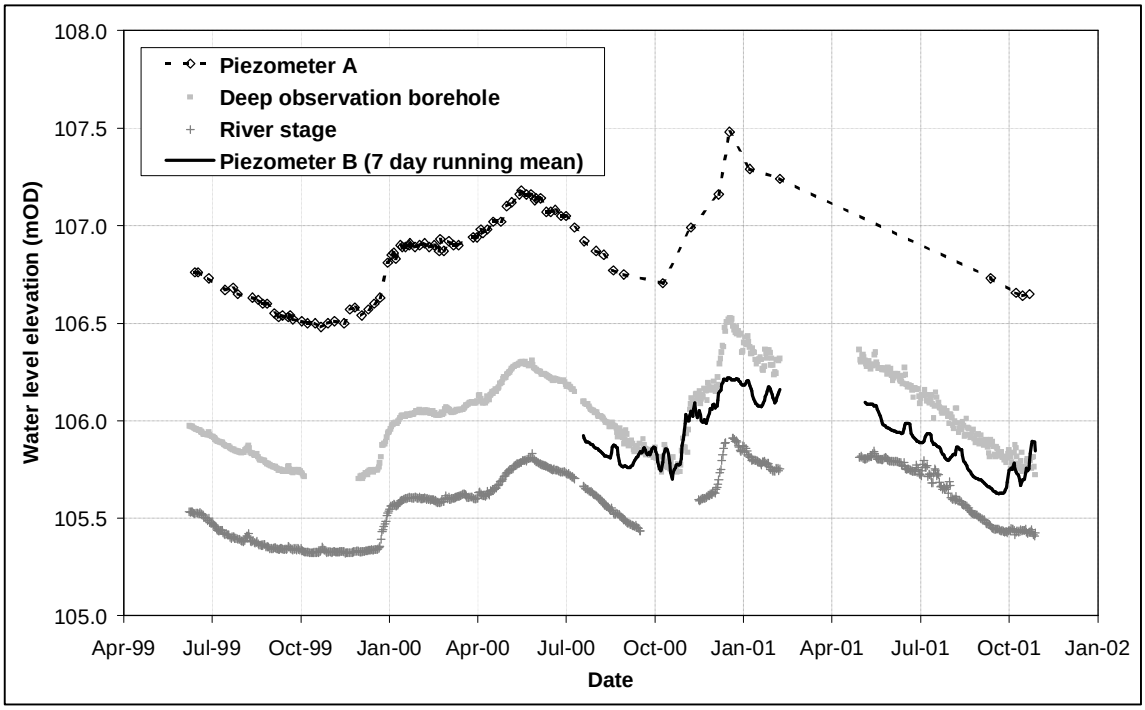


Figure 6.10 Hydrograph of water elevations at West Shefford from four monitoring locations shown in Figure 6.9

Comparing water levels from monitoring points close to the river; i.e. the deep observation borehole (OBH), piezometer B and river stage itself, it is apparent that there is a strong upward hydraulic gradient present beneath the valley floor, indicating a groundwater discharge zone. Deep chalk levels from the OBH are higher than alluvial deposit levels, except for a brief period in the autumn of 2000 which was probably due to the unusually heavy rainfall in this period, and both groundwater level records are consistently higher than river stage.

The presence of a significant upward vertical gradient from the chalk aquifer to the river indicates the potential for discharge from the aquifer into the channel, but evidence from piezometer B suggests that discharge may not occur directly via the alluvial gravels. The base of piezometer B rests upon coarse, flint gravel beneath 1m of low permeability peaty material. The water in the gravel is confined by the peat and rose by around 0.3m when intersected during augering of a hole for the piezometer. The base of the hole is at 105.5mOD, whilst the bed of the adjacent river channel (at the

point of stage measurement) is at 105.2mOD, and also consists of coarse, flint gravel. Considering the similarity in lithology, and the lateral separation (piezometer B is c. 12m from the channel), we might expect that both piezometer B and the channel bed would be located in the same alluvial horizon, and that they would consequently have good hydraulic continuity and exhibit very similar water levels. However, the water level evidence from Figure 6.10 shows that this is not the case, with the level in piezometer B being consistently 0.2 to 0.4m higher than the river stage. This suggests a form of hydraulic barrier exists between the alluvial gravel and the water in the channel, and this is most likely to be present as armouring or cementation of the channel bed, which would significantly reduce its permeability, and would act to restrict direct exchanges of water between the aquifer and the channel. The occurrence of channel bed armouring may have implications for the values of local permeability calculated in the section below.

At West Shefford it appears that instead of direct transfer from the aquifer to the river channel, exchange takes place indirectly via flood plain springs, which form minor channels of their own (as illustrated in Figure 6.9) before discharging into the main river channel. This method of indirect interaction occurs at several locations along the Lambourn valley, most notably between Elton and Weston (1.5km downstream of East Shefford), where a major spring occurs close to the eastern margin of the floodplain, whose discharge forms a minor channel that joins the main river channel 300m downstream.

Calculation of local values for permeability

Using the approach outlined in previous sections, the slopes from linear regression relationships between hydraulic gradient and calculated reach accretion rate, shown in Figure 6.11, were used to calculate values of 'K' for the three groundwater monitoring points, based upon an estimate for 'A' of 8400m^2/km. This produced values for 'K' of 390m/d (piezometer A), 52m/d (piezometer B) and 140m/d (deep OBH). All these values are considerably higher than those calculated from previous reaches, which correlates with the higher average accretion rate for reach 5 compared to reaches 3 and 4. The two chalk aquifer monitoring points (deep OBH and piezometer A) display higher 'K' values than the alluvial monitoring point (piezometer B), but are elevated even for the chalk. However, they may represent a shallow zone of high permeability in

the uppermost 10 to 15m of chalk that is rarely investigated by geophysical logging as it lies in the zone where most chalk boreholes are cased off. The 'K' value from piezometer B could represent gravel or coarse sand (Domenico & Schwartz, 1990; Table 3.2).

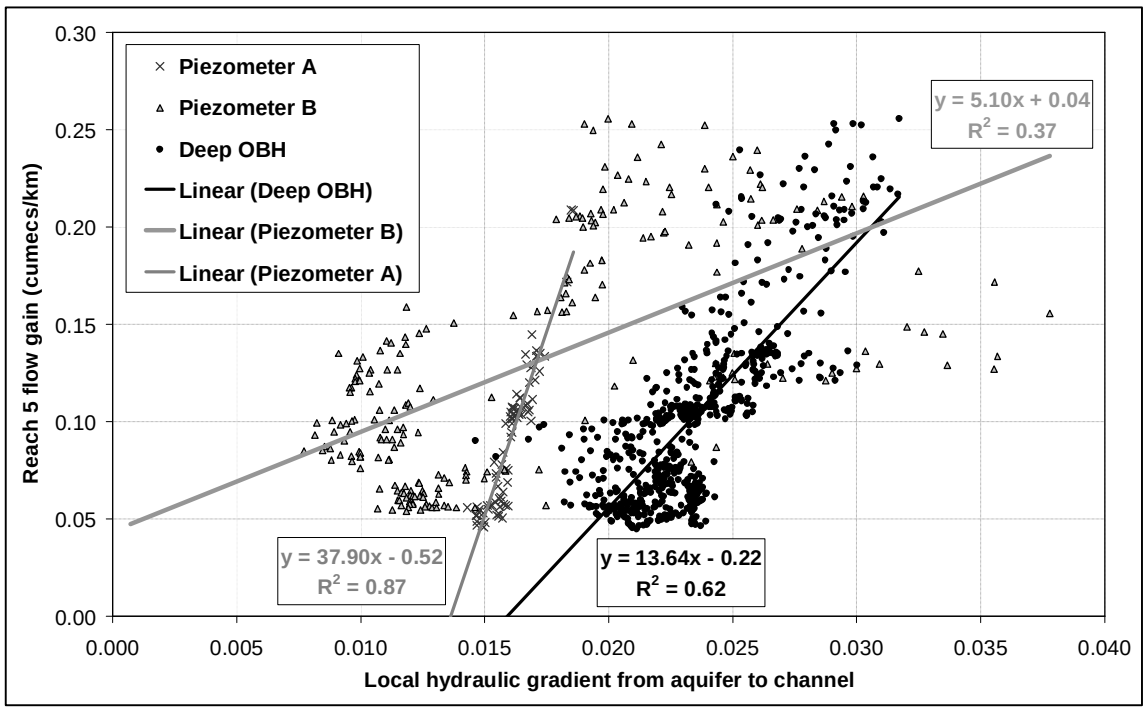


Figure 6.11 Lateral hydraulic gradients from monitoring points at West Shefford versus the calculated accretion rate in reach 5

It is clear from Figure 6.11 that the regression relationships derived for this site are of a different form compared to the two previous sites, particularly as the regression lines do not pass through the origin. This indicates that hydraulic gradients of zero between the monitoring location and the adjacent river stage are not associated with an accretion rate of zero. The regression relationships for both the chalk aquifer monitoring points (deep OBH and piezometer A) suggest an intercept on the x-axis of around 0.015. This positive value suggests that the calculated hydraulic gradient overestimates the true gradient controlling discharge, and that the chalk aquifer discharges to a higher elevation than the adjacent river stage, which could relate to a floodplain spring channel.

However, the regression relationship for piezometer B (monitoring channel-proximal alluvial gravels) intersects the x-axis at -0.009, indicating that discharge from these deposits is to a point of lower elevation than the adjacent river stage. This

suggests that the gravel deposits are not in hydraulic continuity with the channel in the vicinity of the monitoring point, but may be connected to a location some distance downstream, where the river stage is at a lower elevation.

6.4 TESTING CONTROLS ON SPATIAL PATTERNS OF FLOW ACCRETION USING GROUNDWATER MODELLING

6.4.1 Introduction

Evidently controls on the spatial pattern of flow accretion are related to both ground surface and subsurface features. At the surface, variables such as channel bed gradient and channel width are important, whilst in the subsurface, lithological and structural variability in the bedrock aquifer, plus the presence and nature of alluvial deposits, regulate accretion rates. The latter category of controls can only be investigated by a limited range of surface-based techniques (excluding costly drilling). Geophysical methods (such as resistivity and GPR) could have provided useful data on valley floor subsurface morphologies, but were not used in this study as a result of logistical constraints. Qualitative tracer testing, as a means of investigating conceptual subsurface flow paths, was undertaken but no positive results were returned, and thus those elements of the conceptual model could not be confirmed. Within the logistical constraints imposed by this study, groundwater modelling provided a potential alternative for investigating conceptual subsurface scenarios, and their influence on accretion patterns.

This section describes the formation of a groundwater model of the Lambourn catchment, and the results obtained from it. First, the modelling is placed in context by briefly reviewing previous modelling studies undertaken in the area. Next, the model conceptualisation is described and the process of translating the conceptual model into the modelling software is outlined. This section includes a critique on the representation of surface watercourses. The calibration of the model under both steady state and transient conditions is then described before the resultant base case simulation is used in a sensitivity analysis of parameters influencing the spatial pattern of accretion.

6.4.2 The context of the modelling

Numerical groundwater modelling is undertaken using a discretized representation of reality, in which the study area is divided into a number of cells, each

having a defined set of parameter values (such as hydraulic conductivity, storage coefficient, recharge). The groundwater model uses an iterative process to calculate the hydraulic head (groundwater level) in each cell based upon Darcy's flow law and a continuity equation. The latter takes the form of a mathematical statement, which states that when inflow to a cell does not equal the outflow from it, then the difference must equal the net change in storage within the cell.

A number of previous groundwater modelling studies, at both the catchment and regional scale, have simulated conditions in the Lambourn catchment. To provide a context for the current work, these studies are reviewed in Table 6.2. All the studies, except Bullock *et al.* (1995), were undertaken in connection with groundwater resource management and river augmentation issues arising from the various phases of the Thames Groundwater Scheme. Rushton *et al.* (1989) used the most sophisticated model, which incorporated variable transmissivity with depth.

6.4.3 The modelling package

The software selected for the modelling in this study was *Groundwater Vistas* v2, a proprietary, groundwater flow model with pre- and post-processors to simplify the creation of input files, and to display results from output files. At the heart of the model is the MODFLOW (**MOD**ular Three-Dimensional Finite Difference Ground-Water **FLOW** Model) code described by McDonald & Harbaugh (1988), Harbaugh & McDonald (1996). MODFLOW is a block-centred, quasi-three dimensional, finite difference groundwater model developed by the United States Geological Survey (USGS). The vertical dimension is provided using layers to represent different aquifer horizons, with flow between layers controlled by a leakage term (Anderson & Woessner, 1992).

Publication	Model objective	Modelling package	Model set up				
			Time domain	Transient duration	Grid cell size	Model area	Details of aquifer parameters
Oakes & Pontin, 1976	Means of assessing the results of pumping tests in the Lambourn Valley Pilot Scheme area	N/a[1]	Transient	Up to 400 days	1km^2	Groundwater catchment of the Lambourn to Shaw gauging station; defined as ~200km^2	Uniform T* and S*; 1790m^2/d and 0.015
Connorton & Hanson, 1978	Regional modelling of the Thames Groundwater Scheme Stage 1 area using analogue and digital models	N/a	Steady state (preliminary)	N/a	Generally 1km^2	Catchments of the Rivers Lambourn and Pang, and the Aldbourne	Base values for T and S of 1500m^2/d and 0.01 respectively
Morel, 1980	Aid to water resource management in the Upper Thames basin, especially river augmentation during drought conditions	Not specified	Steady state and transient	Up to 6 months	Not specified	Upper Thames Basin: ~2300km^2	Derived by inverse modelling
Rushton *et al.*, 1989	Predictive: regarding groundwater abstraction for river augmentation	Not specified	Transient	10 years	1km^2	Berkshire Downs (~2000km^2)	Used variable T and S with depth
Bullock *et al.*, 1995	Evaluation of the performance of an analytical technique for predicting the impact of groundwater abstraction on stream flow.	ASM[2]	Transient	3 to 25 years	500m x 500m	Topographic catchment of the River Lambourn to Shaw gauging station: 234km^2	T range from 70 to 3500m^2/d

Table 6.2 Summary details of previous groundwater modelling studies relating to the Lambourn catchment

[1]Used code developed by the then Water Resources Board

[2]Aquifer Simulation Model

*T = transmissivity, S = storage coefficent

Groundwater Vistas was selected for this study due to its widespread use and its relative simplicity in application. However, it was recognised that it was not ideally suited to modelling a chalk aquifer (dominated by secondary {fissure} permeability), as MODLOW was designed for large scale, homogenous, alluvial aquifers. However, the assumption of the continuous porous medium analogy, in which the behaviour of a chalk aquifer is assumed to tend towards the behaviour of an intergranular (primary permeability) aquifer at large scales, justifies the selection of a MODFLOW-based model. A thorough discussion of the continuum approach (continuous porous medium analogy) is provided by Domenico & Schwartz (1990; p. 83-87), and this introduces the concept of the representative elemental volume, a theoretical volume of a fractured rock mass within which all potential heterogeneities are encountered, and which thus represents the minimum volume at which the continuum approach can be applied.

6.4.4 Applying groundwater modelling to the Lambourn catchment

The aim of the modelling work was to elucidate subsurface processes and parameter configurations that controlled the spatial pattern of flow accretion in the Lambourn, and to identify generic controls that could be applied to other catchments. This aim was formalised by recognising two objectives:

a) To confirm the accuracy of the catchment scale parameter set by simulating the surface water discharge from the catchment;
b) To then use the model as a tool to investigate local scale controls on flow accretion.

In order to meet these objectives, and produce a representative *Groundwater Vistas* simulation of the Lambourn catchment, a four-stage modelling process was undertaken:

1. Define a simplified conceptual model of the catchment;
2. Represent the elements of the conceptual model in the modelling framework;
3. Run the model in steady state and transient conditions, and calibrate to a measured record of catchment discharge, to produce a base case simulation;
4. Use the base case simulation to test conceptual scenarios and undertake sensitivity analyses on key parameters.

6.4.5 Building the numerical model from the conceptual model

The characteristics of the model simulation and the justification for their use are summarised in Table 6.3.

Characteristic	Value (s)	Justification
Grid cell size	50m x 50m	Maximum size that allowed manageable simulation run times
Grid dimensions	700 columns, 400 rows	Allowed whole of Lambourn catchment and its environs to be included
Grid orientation	Vertical axis of model rotated to an orientation of 37º east of grid north	Placed river valley axis parallel to the long axis of the simulation (see Figure 6.12)
Perimeter boundary conditions	No flow throughout	See description below
Internal boundary conditions	Drain cells for seasonal water courses, river cells for perennial water courses	Appropriate conceptualisation for base case scenario
Drain / river cell elevations	Based upon Ordnance Survey 1:25 000 scale contours (5m interval), supplemented by limited survey work in the field	Most appropriate dataset for base case simulation
Hydraulic conductivity	From 10 to 180m/d (X and Y orientations equal, Z at 10% of X)	Based upon the transmissivity distribution of Owen (1981) using a constant saturated thickness of 60m (Price *et al.*, 1993) [see Figure 6.13]
Storage coefficient, S	From 0.35% to 2.65%	Calculated from transmissivity (T) via the equation: $S = 10^{-4.4}\ T^{0.7}$ derived by MacDonald & Allen (2001) from test pumping of the chalk aquifer across the UK
Layer setting	Single layer, unconfined	Modelling of uppermost active zone of chalk in an unconfined area
Aquifer base	60m below average water table (surface produced from borehole water level data)	Normal maximum effective thickness of the chalk aquifer put forward by Price *et al.* (1993)
Recharge	Modified weekly MORECS EP[1]	See description below
Starting head levels	Average groundwater elevation surface based upon data from over 100 boreholes	Most appropriate water table scenario
Transient stress periods (time steps)	1 month (2 weeks)	Most appropriate timescale for multi-annual simulations
Calibration period	5 years (1978 – 1983)	Restricted by input / calibration datasets
Model solver package	PCG2[2]	Based upon experience with test models and discussion by Osiensky & Williams (1997); see below

Table 6.3 Features of the model simulation and their conceptual justification
[1]Effective Precipitation
[2]Pre-Conditioned Conjugate Gradient version 2

Figure 6.12 shows the outline of the simulated area and the active section of the model superimposed upon a colour flood representation of a digital elevation model (DEM). The DEM covered the whole of the active domain and was used to represent the top of the aquifer, and also the base of the aquifer in some sensitivity analyses, using a fixed thickness below ground level.

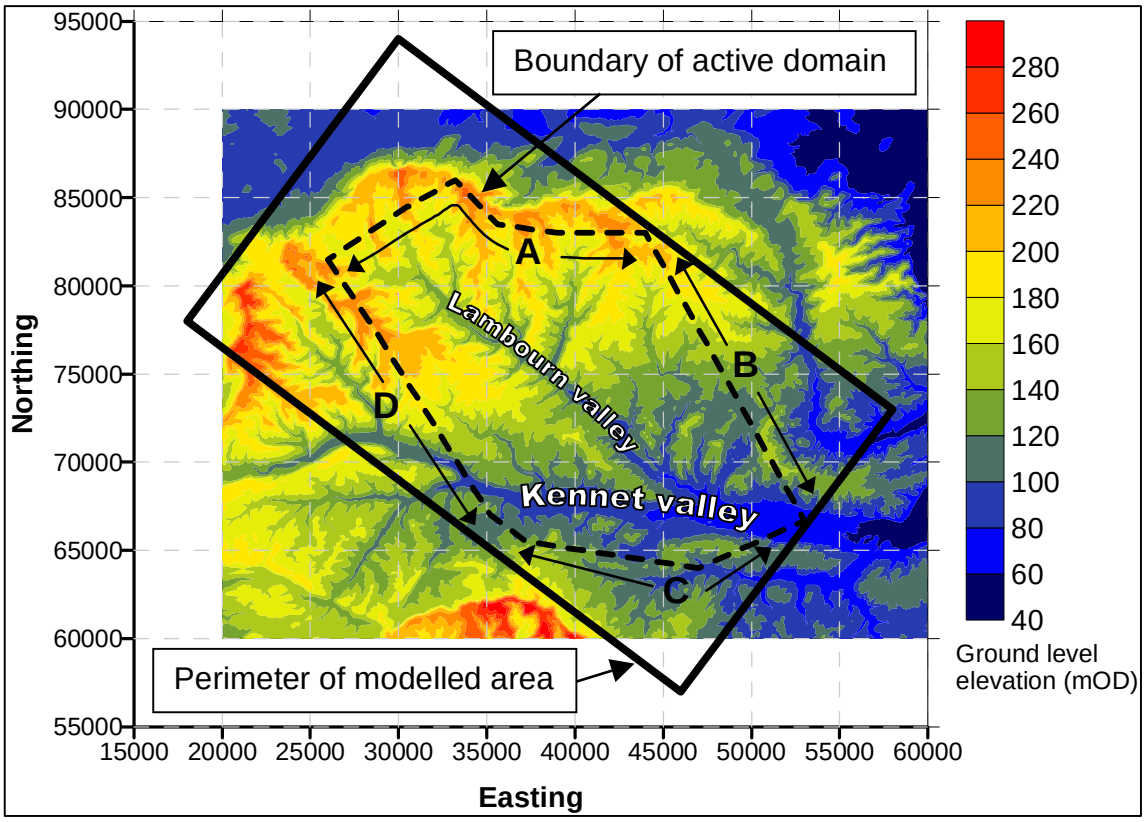


Figure 6.12 Location of modelled area and active model domain
[Topographic detail based on digital spatial data licensed from the Institute of Hydrology, ©IH. © Crown copyright (0186A). Axis scales are Ordnance Survey Landranger for square SU, in metres. **A** to **D** are boundary conditions described below.]

Perimeter boundary conditions

The perimeter of the active model domain was marked by no flow cells, with the result that there was no groundwater discharge across the model boundary, and hence discharge from the model only occurred via surface water outlets. This was a reasonable approximation of hydrological conditions, given the nature of the selected boundaries.

Boundary 'A' (Figure 6.12) represents the regional groundwater divide associated with the crest of the chalk escarpment, and as such, no groundwater flow would be expected to cross it. Whilst the position of the divide does vary between maximum and minimum groundwater levels, the change is too small to be significant.

Boundary 'B' represents a simplified groundwater flow line marking the divide between the Lambourn and the adjacent Pang catchment. This divide is temporally stable and there is no evidence for the regional movement of water from the Lambourn catchment towards the River Thames in the east. Boundary 'C' marks the edge of the confined zone of the chalk aquifer (based upon Owen, 1981), where it is overlain by Eocene deposits in the floor of the Kennet valley. Given the significant reduction in chalk permeability (for example, valley floor values reducing from an unconfined range of 1000 – 2500m^2/d to a confined range of 270 – 450m^2/d; Owen & Robinson, 1978), and the associated reduction in flow rates, the confined zone effectively represents a no flow boundary and most groundwater discharges to the River Kennet. Boundary 'D' represents an approximation of the groundwater divide between the Lambourn catchment and the Aldbourne catchment to the west. There is no evidence to suggest that significant flow occurs laterally between these catchments.

Representation of surface watercourses

Three packages within *Groundwater Vistas* can be used to represent surface watercourses: drain, river and stream. All three packages are categorised within the 'Boundary Conditions' module, which also includes no-flow cells and various types of constant head boundary. The three surface watercourse packages share some similar functionality in the way cells of particular types are installed, and how fluxes across the cells are calculated. These aspects are described in more detail below. In the following sections, where the term 'watercourse' is used, this is a generic term for any flowing surface water body, but where the terms 'drain', 'stream' or 'river' are used, these refer to the specific model package.

Allocating grid cells to the various packages can be undertaken on a cell-by-cell basis (the only input technique possible for stream cells), but this is laborious for a model with many watercourses and a fine mesh. Alternatively, input (for drain and river cells) can be undertaken via a 'polyline', a line digitised on the screen within the model using the cursor, enabling a watercourse shown in the underlying base map to be replicated within the model, and the appropriate parameters conferred. Values (such as bed elevation, width and bed conductance characteristics) are input for the start and end of the line and if different values are used the parameters are automatically varied incrementally over the length of the segment.

Although the polyline approach allows rapid initial installation, its functionality is compromised by the limited post-installation editing capability. For example, once a reach has been input the only editing facility (except to delete and re-enter the whole reach) involves changing each cell individually, or setting all cells in a reach to exactly the same set of values, which is unrealistic for terms such as bed elevation. Once a reach is present, it is not possible to simply edit the start or end cells so that the bed elevation gradient, width etc. can be recalculated for the reach. This 'non return' type of input facility can significantly lengthen the model set up process if parameters are amended and renders the calibration process more time consuming. For example, undertaking sensitivity analysis on watercourse bed elevation becomes very laborious, rather than being a straightforward process. This results in bed elevation and associated parameters being generally dealt with in a cursory way, if at all, in calibration and sensitivity analyses undertaken using this model. At least one other groundwater model (the US Department of Defence / Boss International-produced Groundwater Modelling System; GMS) allows greater flexibility in terms of both inputting and editing of stream parameters and this ease of use promotes inclusion of these parameters in sensitivity analyses.

Drains are unsuitable for modelling *interaction* between the aquifer and surface watercourse because they only allow flow out of the aquifer, not into it. They work on the basis of the difference between the aquifer head at the drain cell and the drain bed elevation. When the head is above the bed of the drain, discharge from the aquifer occurs at a rate controlled by the relative elevation difference between the aquifer head level and drain bed, and also by the conductance of the drain bed material, which is a function of its hydraulic conductivity and thickness. Once the head level falls below the bed of the drain, discharge to the drain cells ceases.

A potential problem when using drain cells relates to the surface water accounting system. As drain cells cannot allow infiltration, they are likely to overestimate potential flows in drains. This is a result of simply summing the fluxes from all the cells in a reach. In some cases, it is likely that a proportion of water would have returned to the aquifer where there are short lengths of streambed above the local water table. These potential losses are not accounted for, as they simply appear as zero fluxes. The magnitude of the potential error this causes depends upon the length of drain

reach used and the bed profile of the valley floor being modelled. The greater the length of drain, and the more stepped its long profile, the larger potential errors are likely to be. The inaccuracy of the drain package approach could be assessed by using stream cells instead, with their reportedly superior surface water accounting capability. In reality, the problems of using stream cells themselves are significant (explored below) and thus the relative accuracy of either approach would be difficult to assess.

Unlike drain cells, **river cells** allow both gain from, and loss to, the aquifer and thus allow river - aquifer **interaction** to be assessed. However, the efficacy of this package is limited by its lack of surface water accounting capability, it being unable to recognise transfers of surface water from cell to cell, which leads to unrealistic patterns of local gain and loss. In addition, the model violates the conservation of mass by gaining water in an unaccounted manner. Losses from river cells to the aquifer appear as a separate source of water to the model, in addition to the input from recharge, and this water then causes mass balance problems in the final model evaluation.

Stream cells are a specialised form of river cell with reportedly enhanced surface flow accounting capability, being able to identify transfers of surface water from one stream cell to the next. However, from experience with a number of different simulations this capability must be applied with extreme caution as accounting procedures are not robust. Localised patterns of unrepresentative behaviour are often displayed by stream cell reaches, with large inflows and outflows occurring in adjacent cells for no apparent reason. There also appear to be particular problems relating to the use of flux targets for model calibration. Targets are essentially a visual feature to allow the user to make a convenient assessment of the accuracy of a particular simulation. As such, the targets themselves should have no influence on the mechanics of a particular simulation, excluding their application in auto correlation processes. However, it was recognised during this study that changes in flux target values actually modified significantly the manner in which the flux accounting process operated, and thus changed the simulated results without any modification of the model parameters. This is undesirable as it produces non-unique solutions for a constant set of input parameters. In conclusion, despite the apparent suitability of stream cells for the type of simulation undertaken in this study, they were not used because of their unreliability and their restrictive installation capability.

Hydraulic conductivity

The spatial pattern of hydraulic conductivity was based upon a transmissivity map defined by Owen (1981), which was also used as the basis for the model by Rushton *et al.* (1989), with a more detailed illustration of the configuration presented by Allen *et al.* (1997; Figure 4.3.14). A constant saturated thickness of 60m was used to calculate hydraulic conductivity (K), and the resulting pattern for the base case simulation (with K being multiplied by a constant from the original pattern) is illustrated in Figure 6.13.

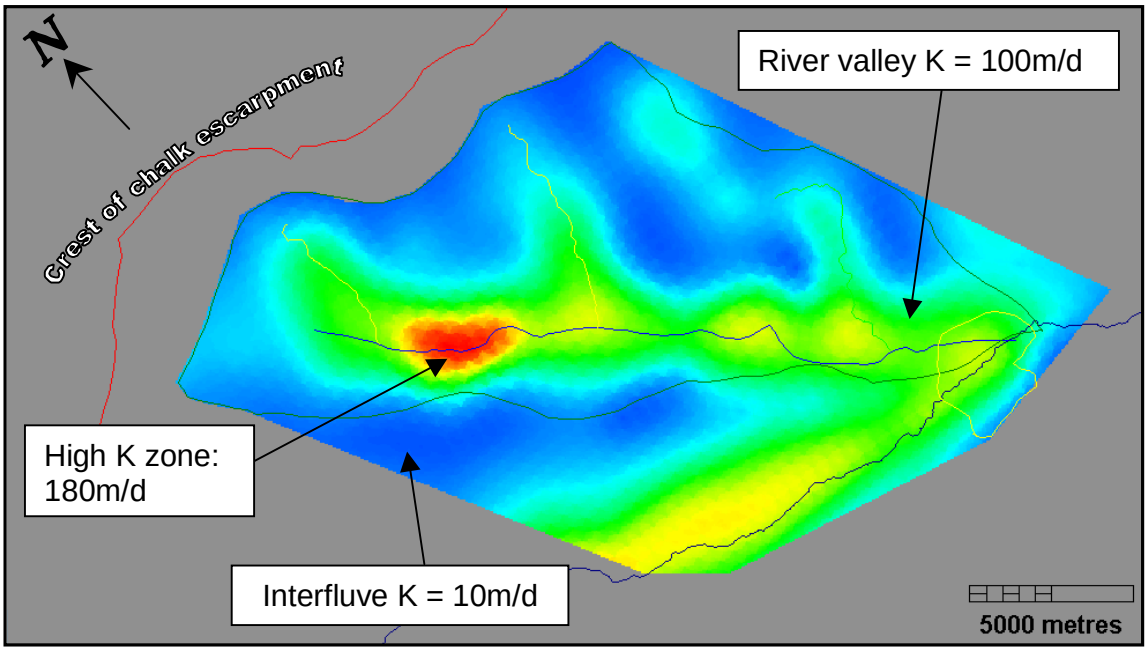


Figure 6.13 Distribution of hydraulic conductivity for the base case simulation (aFinal v2l)

The rectangle of Figure 6.13 denotes the perimeter of the modelled area (shown in Figure 6.12), with the grey area representing 'no flow' cells in the model. The central area of Figure 6.13, displaying the distribution of hydraulic conductivity (K), is the active model domain. The pattern of K is typical of a chalk aquifer, with elevated values in river valleys, decreasing by an order of magnitude to interfluve locations (Allen *et al.*, 1997).

Recharge

The recharge input was based upon weekly MORECS EP, but modified via a two-stage process. Initially a constant multiplier of 1.6 was applied to the base dataset

to rectify the long term underestimate of catchment discharge by EP (discussed in Chapter 4), and also to correct for an additional 10% of catchment discharge, estimated to be the unrecorded losses from the catchment (for example beneath the gauging weir at Shaw). Once the record of recharge magnitude had been produced, a temporal correction (delay) was then applied, as MODFLOW takes no account of unsaturated zone thickness, applying recharge instantaneously to the water table.

The recharge delay was calculated using the B_{av} value of one month (from Section 4.5.2), and the average thickness of the unsaturated zone across the catchment (contoured using Surfer), based upon borehole water levels and the DEM topographic surface. From the grid file of unsaturated zone thickness, the catchment average value at average water level was found to be 37m, which was assumed to correlate with the B_{av} of one month. The grid file of unsaturated zone thicknesses was then used to apply a weighted delay factor to each model cell, and the corrected weekly MORECS EP was then applied with an appropriate delay in order to calculate the actual recharge reaching the water table in any week.

Solver packages

There are four solver packages provided with version 2 of *Groundwater Vistas*, which undertake the process of calculating the output of the model. These are SIP (Strongly Implicit Procedure), SSOR (Slice Successive Over Relaxation), PCG2 (Pre-Conditioned Conjugate Gradient version 2) and PCG4. The PCG4 solver was never able to converge, even with very simplistic simulations, and so was not used in the modelling process.

As to the efficacy of the other three solvers, there is little information in the literature pertaining to their usage. The only study to compare them (Osiensky & Williams, 1997) found the PCG2 solver to be the most robust, as it produced a uniform result regardless of the solver parameters used. It was also found to be accurate relative to an analytical solution by the Theis method. Osiensky & Williams found that the SIP solver also produced robust results, but that the SSOR solver was unable to produce an accurate representation of the analytical solution, regardless of the solver parameters used, which led to the efficacy of this particular solver being questioned. Thus, the PCG2 solver was recommended as the best option, although admittedly based on the findings from only a single, relatively simplistic simulation.

However the findings of this study were themselves questioned in a discussion on the original paper (Lan, 1998) who suggested that the supposed inexperience of the original authors, and the particular model set up used to evaluate the solvers, was the reason for the failure of the SSOR technique. Lan went on to discuss the merits of all three solvers and stated that each might fail in a particular set of circumstances, and thus none should be seen as superior to the others. He showed that the SIP solver could also produce good results provided the optimal solver parameters were used. However, as the correct selection of these parameters demanded a significant amount of trial and error, or previous modelling experience, it was suggested that non-optimal selections might often be used, especially by inexperienced modellers.

Simulations undertaken during this study support the contention of Osiensky & Williams. When using a simplistic generic model to evaluate potential influences on dry valley / main valley intersections, it was found that the SIP and PCG2 solvers produced very similar results (within 1% relative to flux targets) provided the correct set of solver parameters were selected. However, the SSOR solver was unable to duplicate this solution, regardless of the solver parameters that were used. In later regional model simulations it was found that only the PCG2 solver would converge. A number of different combinations of SIP parameters were attempted (within established guidelines) but convergence would not take place. Thus, the PCG2 solver was used for all catchment scale simulations.

6.4.6 Calibration

Steady state calibration

The objective of the modelling work overall was to evaluate how the nature and distribution of channel and aquifer parameters influenced the flow accretion pattern, especially at the 1 to 3km scale in the upper half of the catchment. In order to provide a context for this more detailed level of study, it was first necessary to simulate the catchment discharge in both steady state and transient conditions.

The main parameter used to achieve steady state calibration was transmissivity (T), through modifying hydraulic conductivity. The original T distribution was based upon a pattern defined by Owen (1981) from extensive pumping tests undertaken during groundwater resource investigations, and later used by Rushton *et al*. (1989) in their model of the West Berkshire Downs. However, the simulations undertaken in this study

did not incorporate the variability in T with saturated thickness used by Rushton *et al.*, so to achieve a satisfactory representation of catchment discharge, the simulations required the original T distribution to be multiplied by a constant. A similar procedure was also found to be necessary by Bullock *et al.* (1995) during the calibration process for their single layer model of the Lambourn catchment.

Steady state calibration, using various multipliers, is shown in Figure 6.14, and the best result was achieved with simulation number **aFinal v2l (**using a multiplier of six), which reproduced average flows at East Shefford, Welford and Shaw gauging stations within +/- 6% of their recorded values. This simulation used a recharge input of 1mm/d, based on a long term catchment average discharge of 1.72 cumecs and a groundwater catchment of 168km^2, corrected with a 12% increase to account for potential groundwater underflow at the lowest gauging station and unrecorded groundwater flow losses directly to the River Kennet.

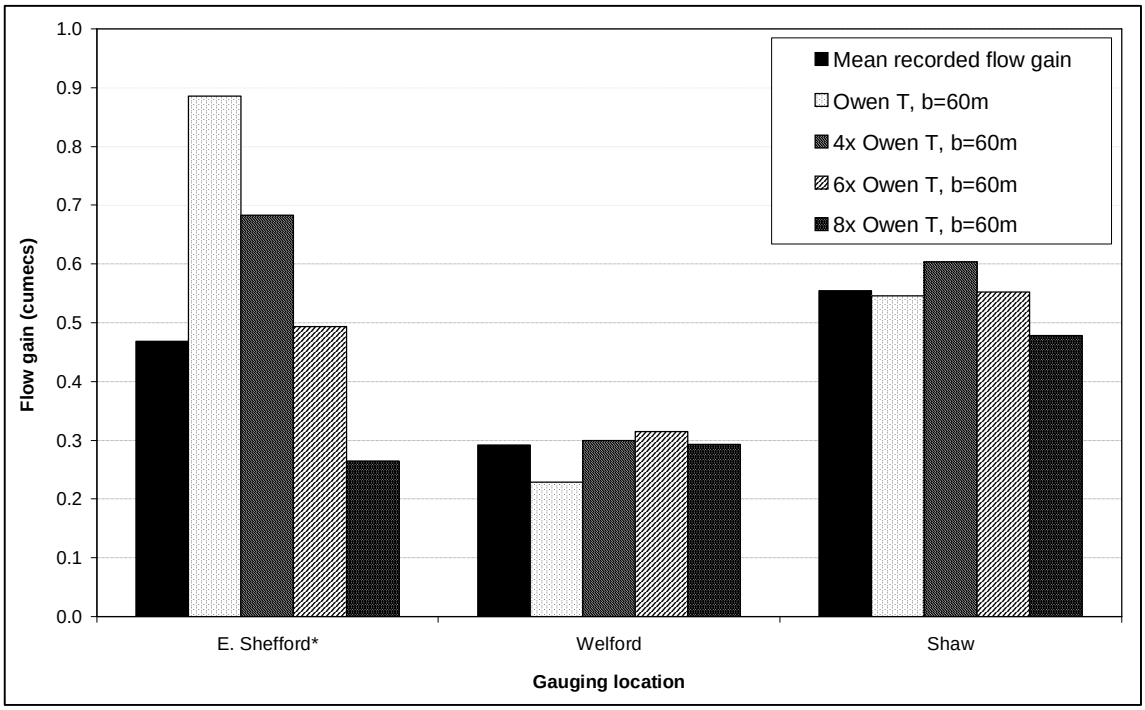


Figure 6.14 Steady state calibration based upon transmissivity
* Flow gain calculated from Lower Lambourn

Groundwater level was a secondary calibration target, and the residual surface of observed groundwater levels minus modelled levels for steady state simulation **aFinal v2l** is presented in Figure 6.15.

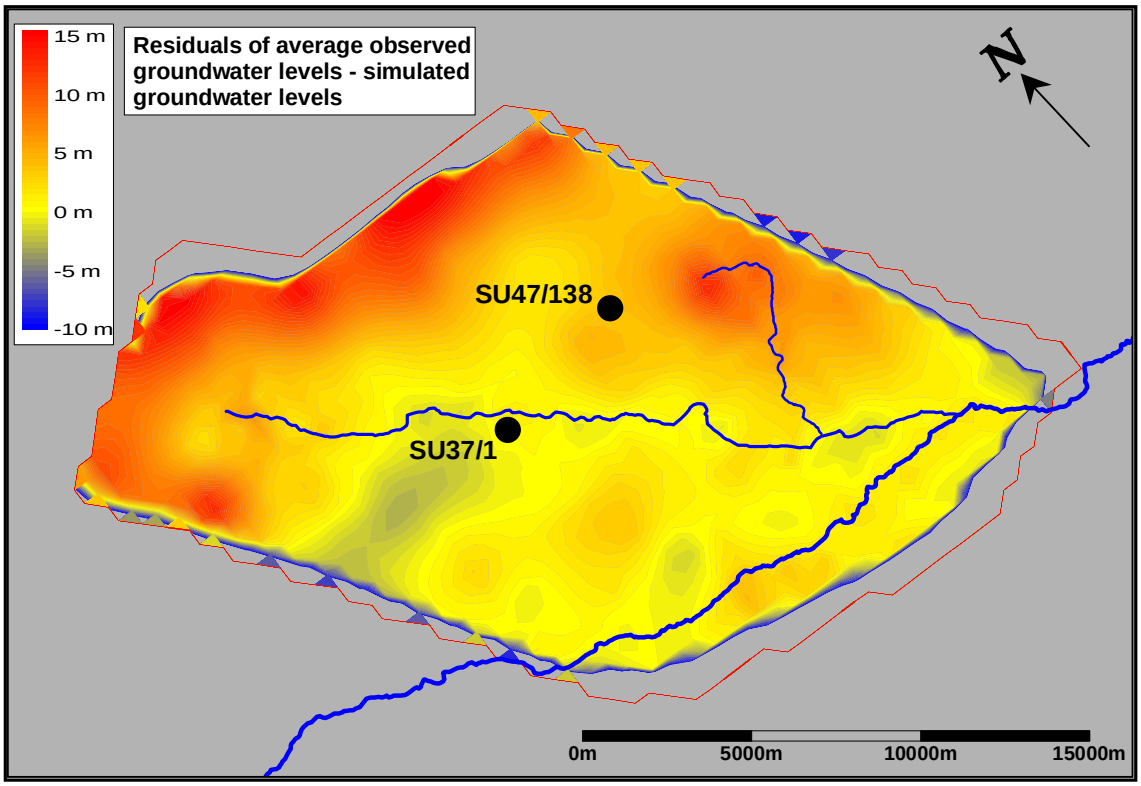


Figure 6.15 Groundwater level residual surface for simulation aFinal v2l

The pattern of residuals shown in Figure 6.15 illustrates the generally good representation achieved by simulation **aFinal v2l**. The bulk of the active model domain is within +/- 5m of observed levels, with only the northern boundary of the model along the regional catchment divide displaying larger errors, with the modelled levels being up to 15m too low. As the principal purpose of the model was the accurate simulation of river discharge, groundwater level errors at the margins of the catchment were not considered highly significant.

Following successful simulation of both discharge and groundwater levels under catchment average conditions, the simulation of catchment conditions in **aFinal v2l** was then extended by adding storage data and a transient recharge input in order to evaluate its performance under transient conditions.

Transient calibration

Data from the lowest gauging weir at Shaw were used to calibrate the initial transient simulations for the hydrological year 1978/79 based on catchment discharge. Figure 6.16 presents examples of calibration runs using variable multipliers for storage coefficient.

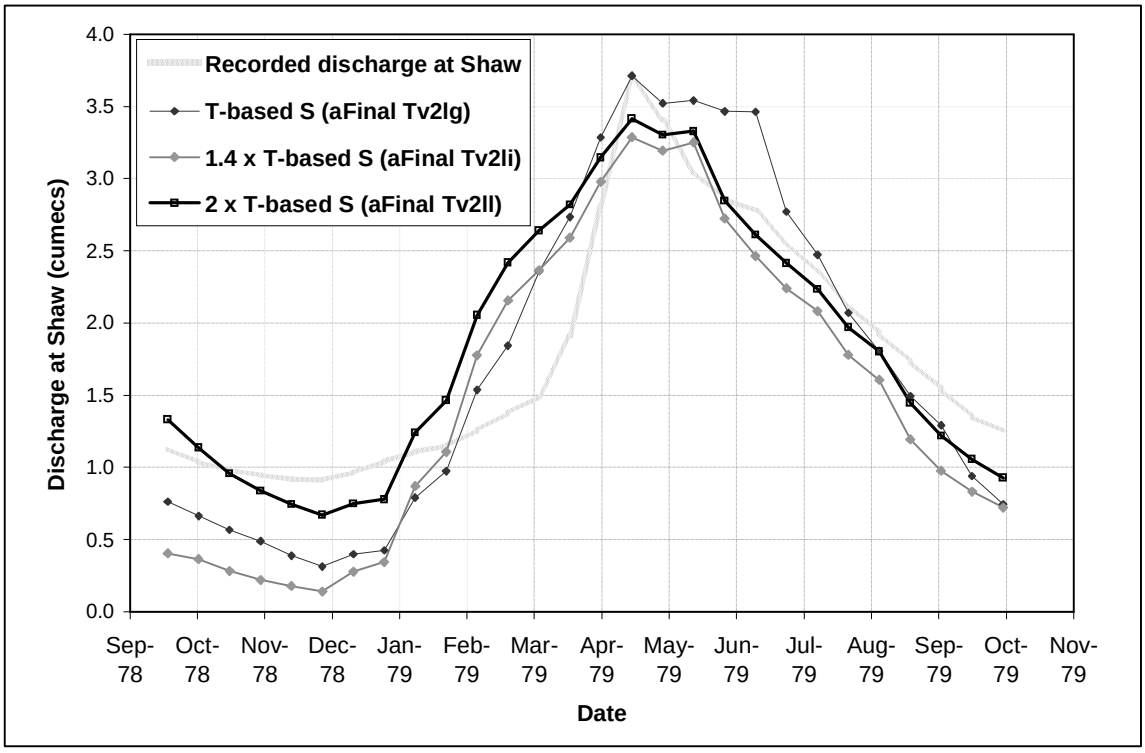


Figure 6.16 Transient calibration against discharge at Shaw using variable storage

The transient simulations presented in Figure 6.16 all reproduced the general pattern of discharge at Shaw, but all reacted too rapidly to the onset of recharge. However, the simulation using storage calculated as two times the transmissivity-based storage values was considered the best overall representation of Shaw discharge, being accurate in terms of timing and magnitude of peak discharge, and particularly in simulating the receding limb of the hydrograph. This simulation (**aFinal Tv2ll**) was then verified by modelling discharge at Shaw and at East Shefford over a longer time period. Discharge from East Shefford gauging weir was used to assess how accurately the seasonal section of the channel had been simulated, but the use of this record restricted the timescale over which verification could be undertaken. There is a continuous record of discharge at Shaw gauging station from 1962 to present, but the record from East Shefford ceased in 1983 (before being restored during the duration of this study). MORECS data, which provide the recharge input for the model simulations, are only available from 1978 onwards, and thus the verification period was restricted to a period of five hydrological years from 1978 - 1983. A comparison of the recorded discharge and simulated discharge (from **aFinal Tv2ll**) at Shaw and East Shefford for this period is given in Figure 6.17.

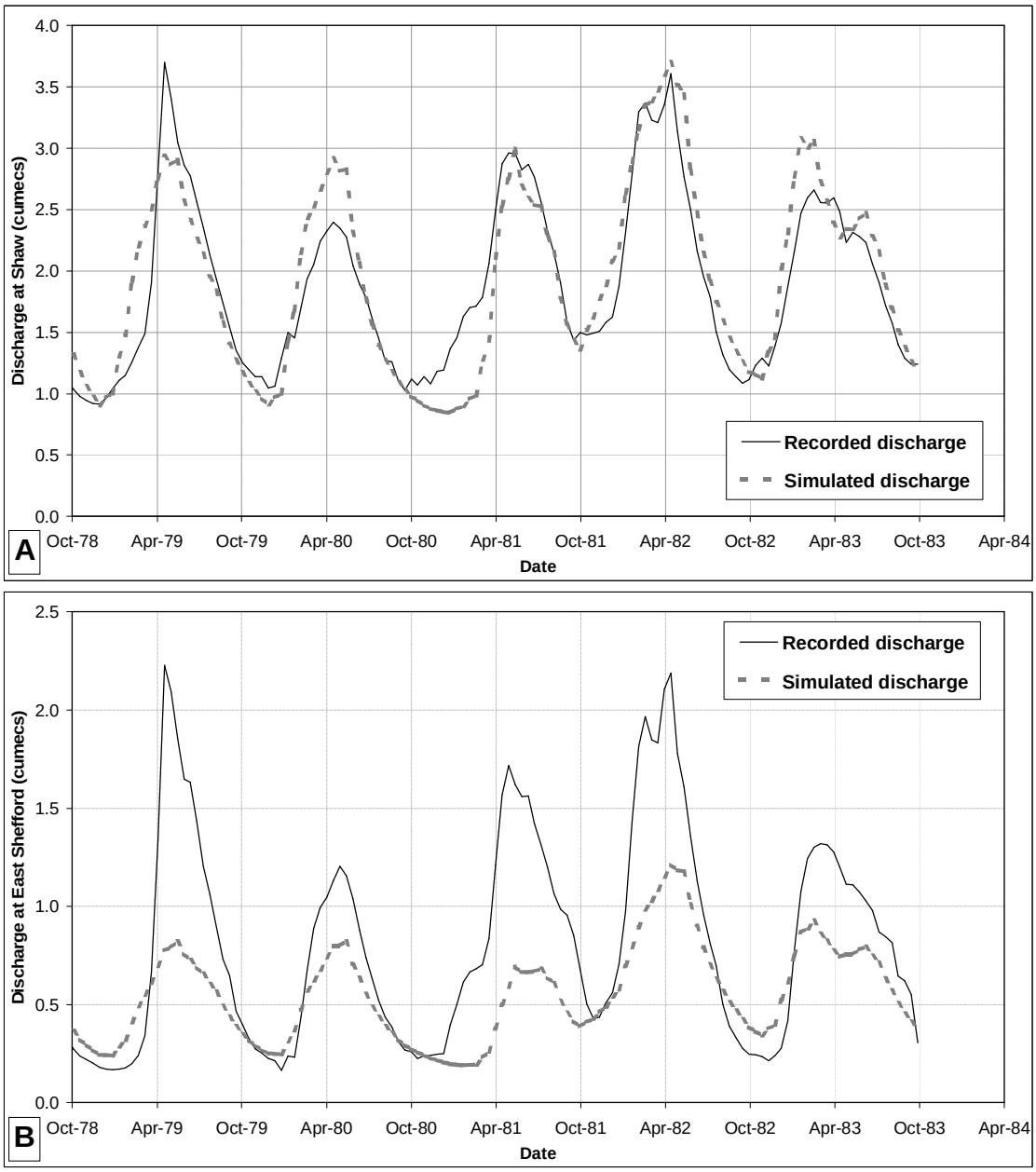


Figure 6.17 Recorded and simulated discharges at Shaw (**A**) and East Shefford (**B**) gauging stations for the period of verification

The recorded pattern of discharge at Shaw (Figure 6.17A) was generally well simulated by the model, in terms of both timing and magnitude of peaks and troughs. The simulation at East Shefford (Figure 6.17B) was less reliable, with consistent and significant under-estimation of peak discharges, although the timing of peaks was generally accurate. Low flows were more successfully simulated, but these were still less accurate than at Shaw. The result of this mismatch between the mid-catchment and

end of catchment sites indicated that less inflow was being simulated in the seasonal section of channel than was actually occurring.

A number of water table records from observation boreholes were also compared to the simulated pattern of groundwater levels, (examples being given in Figure 6.18), forming a secondary element of the verification.

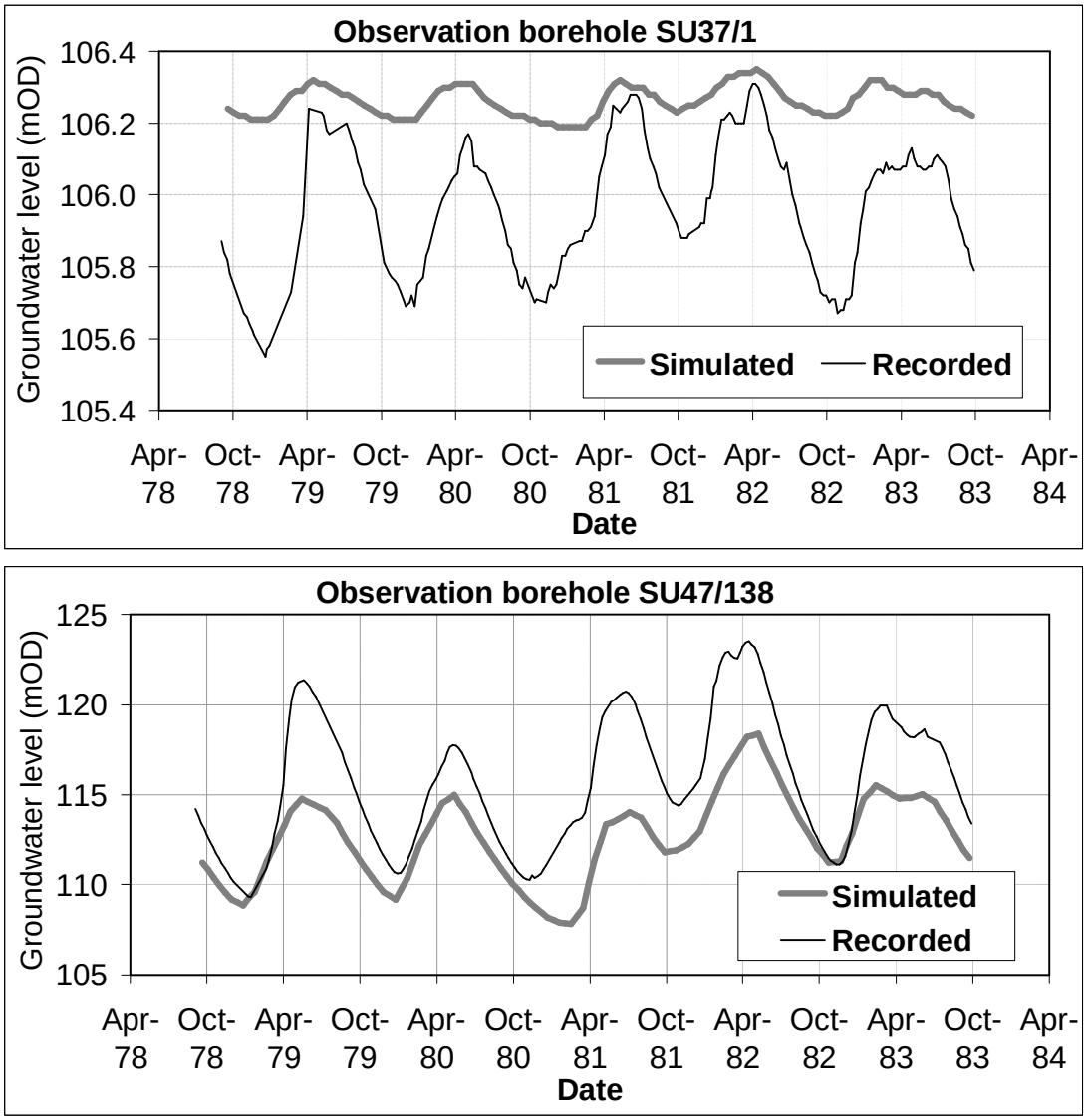


Figure 6.18 Comparison of simulated and recorded groundwater levels from the calibrated 5-year transient base case simulation
(see Figure 6.15 for borehole locations)

The two observation boreholes shown in Figure 6.18 have differing locations based upon a cross-section through the catchment. SU37/1 is at a channel proximal site close to the centre of the catchment at West Shefford (the 'deep observation borehole'

of Figure 6.9), whilst SU47/138 is also located centrally within the catchment, but at a distance of 4.5km north-east of the river channel. The pattern of simulated and actual water levels shows a mismatch between valley floor and interfluve locations, with modelled levels generally above recorded levels in valleys and *vice versa* at interfluve locations. The simulated valley floor levels, being higher than recorded levels throughout the length of the channel, should have resulted in higher than recorded inflows in the seasonal section. However, this was not the case, as illustrated in Figure 6.17B, which suggests that original bed conductance values in the seasonal section were too low, and this was one possibility explored through sensitivity analysis.

6.4.7 Sensitivity analysis

Sensitivity analysis of detailed flow accretion patterns was completed under steady state conditions, as the recorded verification data (based upon current meter readings) was only truly representative of average catchment conditions.

Flow accretion profiles have been used in a number of groundwater modelling studies as a means of presenting results from a calibrated simulation (for example: Oakes and Pontin, 1976; Connorton & Hanson, 1978; Wyness *et al.*, 1994; Wilson & Akande, 1995). However, specifically seeking to recreate flow accretion profiles, and test their sensitivity to various parameters, has not been a specified objective of any known groundwater modelling project. In this study, a modified form of flow accretion profile (the accretion rate profile), is used as the primary sensitivity analysis baseline. This is superior to the normal flow accretion profile, as it displays the accretion rate for each reach as an absolute value, rather than as a subtle variation in the slope of a cumulative profile, which can be difficult to distinguish and quantify.

Spatially variable versus constant K

To assess how significant the influence of the spatially variable pattern of K was on the accretion rate profile, simulations were undertaken using both constant and spatially variable K (each displaying the same average K value), with selected results being shown in Figure 6.19.

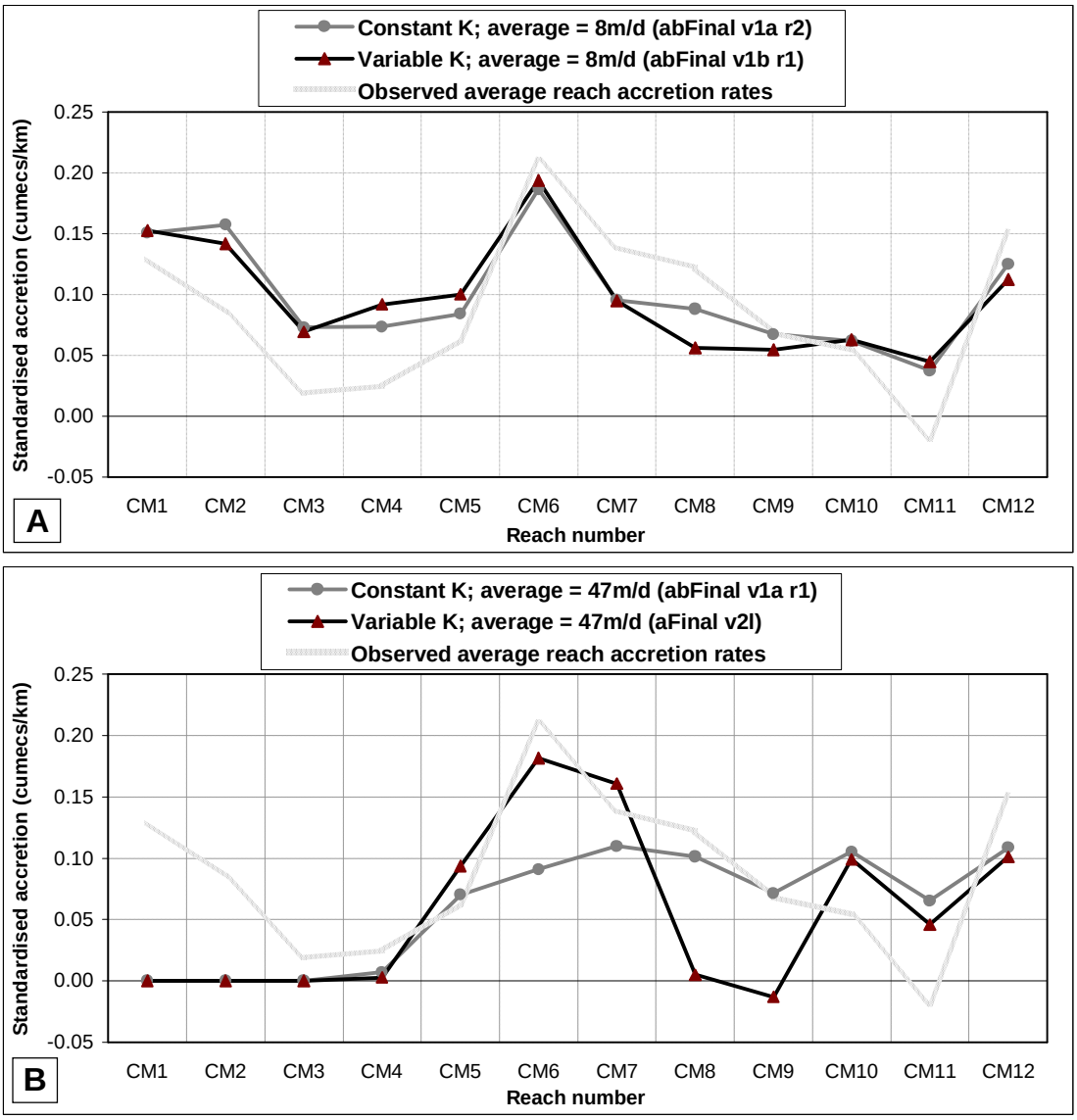


Figure 6.19 Influence on accretion rates of variable versus constant K
(see Figure 5.11 and Table 5.4 for details of current meter reaches)

From the accretion rate profiles shown in Figure 6.19 it is apparent that the spatially variable pattern of K has relatively little influence at low values of K (**A**), but is more significant at higher values of K (**B**). Generally, the low K scenarios are superior in their representation of the upper section of the river, whilst the spatially variable high K scenario effectively simulates the upstream and downstream ends of the perennial section (CM6 to CM12), although the mid section (CM8, 9) is erroneous. A wider range of K scenarios, in comparison with the observed average accretion rate profile, are presented in Figure 6.20.

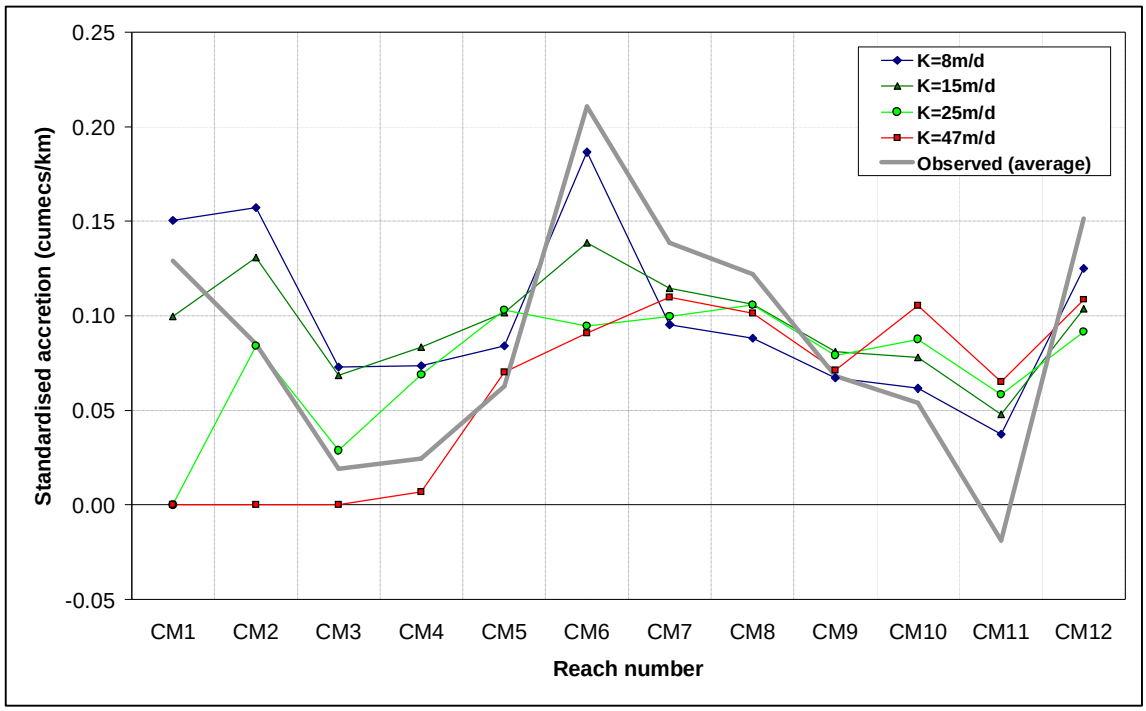


Figure 6.20 Sensitivity of accretion rate profile to spatially constant K value

The low K scenarios represent the general pattern of accretion rates adequately, with peaks occurring in reaches CM1, 6 and 12. They simulate accretion rates in the seasonal reaches (CM1 to CM5) most effectively, but the magnitudes are too high. The accretion rate in reach CM1 is shown to be highly sensitive to K in the range 15 and 25m/d. The higher K scenarios produce too flat an accretion rate profile throughout the length of the river.

Drain and river bed elevation

The principal control on river – aquifer exchange at any location is the differential hydraulic gradient between groundwater level and river stage. In the model simulations, seasonal sections of the river were represented by drain cells, and perennial sections by river cells, the latter group having a fixed stage (water depth) of 1m above the defined bed elevation. Discharge to drain cells occurs when the groundwater level is higher than the drain bed level, whilst discharge to river cells occurs when groundwater levels are higher than the river stage. In both cases, the bed elevation of the watercourse is an important control on river – aquifer exchange. The sensitivity of accretion rates to variations in bed elevations are shown in Figure 6.21, for various constant K scenarios.

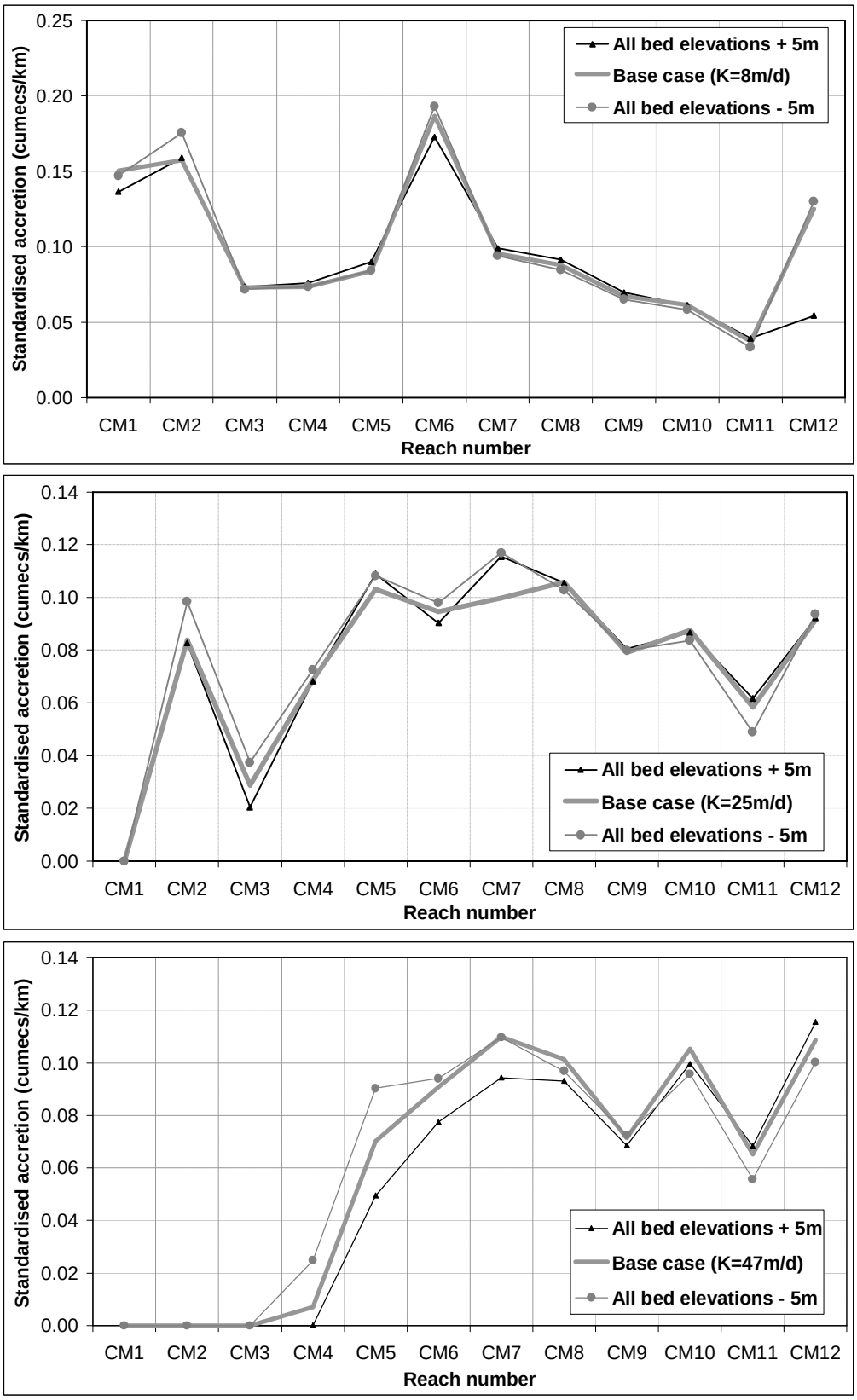


Figure 6.21 Accretion rate profiles showing sensitivity analyses based upon bed elevation for three spatially constant values of K

It appears from Figure 6.21 that simulated accretion rates are generally insensitive to bed elevation levels, although at higher K values the sensitivity is slightly enhanced. The longitudinal pattern of accretion rate variability for the higher K scenarios is not consistent, with higher bed elevations actually showing *increased* rates of accretion in the lowest reaches. This is due to lower discharges in the upstream reaches producing a greater subsurface flow volume to the lower reaches, thus causing increased rates of discharge in these downstream locations.

Bed conductance

Both drain and river cells in MODLOW calculate river – aquifer fluxes based upon differential gradient and a bed conductance term, which is calculated from:

(bed width x bed K) / bed thickness = conductance (units length/time)

In order to evaluate the sensitivity of accretion rates to the conductance term, the K value was varied over the range 0.1 to 100m/d, keeping bed width constant at 5m and bed thickness constant at 0.2m. This represented a three order of magnitude variation in conductance that covered all likely width/thickness/K scenarios. The results are presented in Figure 6.22, which shows that simulated accretion rates are generally insensitive to bed conductance, but there is some increased sensitivity when aquifer K is high. The elevated bed conductance scenarios generally display higher accretion rates than the minimum scenario, but the patterns are by no means uniform.

6.4.8 Modelling overview

The aim of the modelling work was to provide a means of elucidating sub-surface controls on patterns of flow accretion, which had been identified from current meter data. This aim was not fulfilled, owing to a combination of logistical and software constraints: essentially the modelling study provided more information on the process and practise of groundwater modelling than it did on the sub-surface parameter configurations and hydrological system of the Lambourn catchment. Even so, the modelling work did produce a number of valid findings, which are described below.

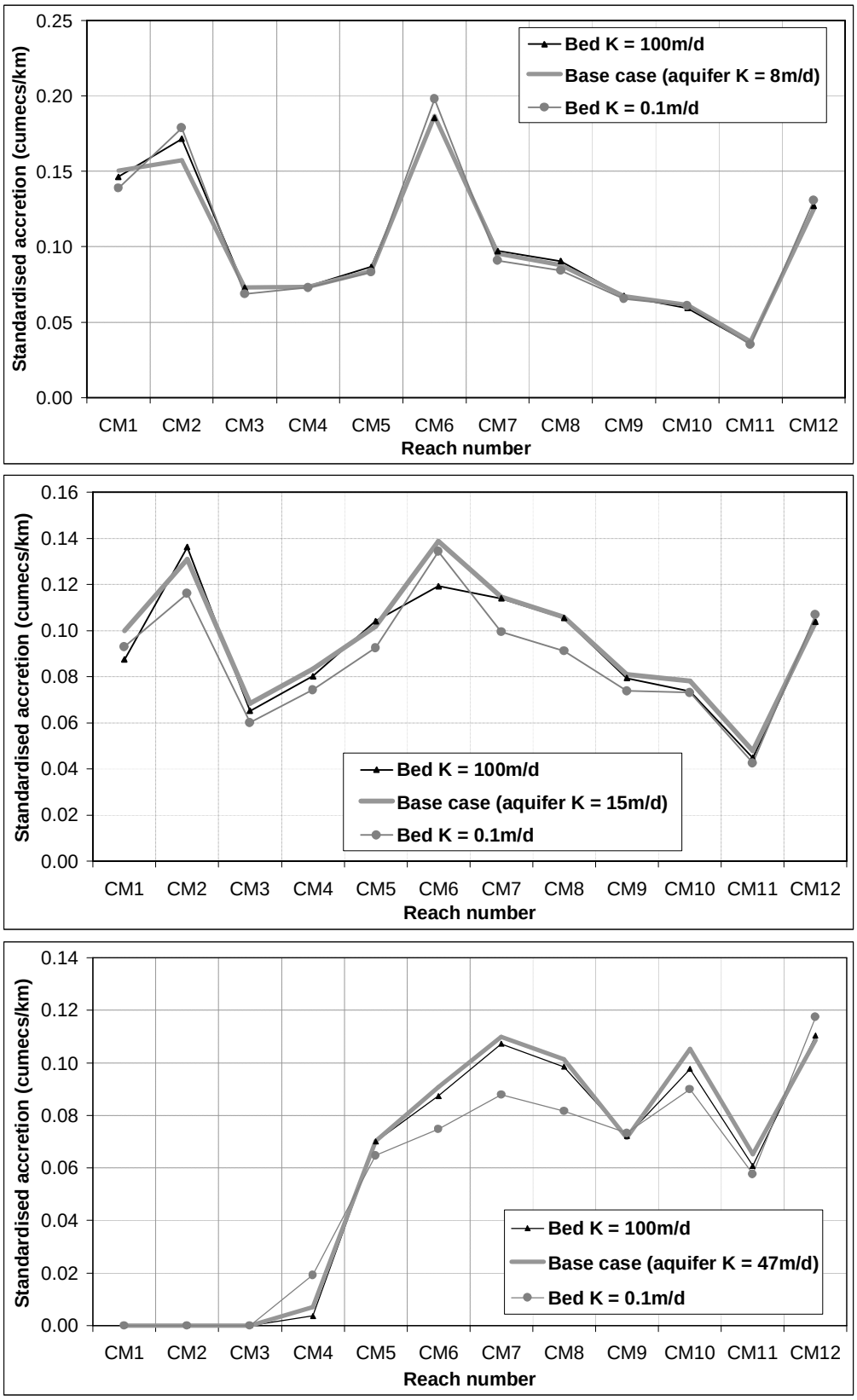


Figure 6.22 Accretion rate profiles showing sensitivity analyses based upon bed conductance for three spatially constant values of K
[Bed K = 10m/d for all base case scenarios]

The relatively simple simulation used in this study was able to reproduce catchment discharge adequately, in a transient state, over a period of 5 years. However, by comparing simulated river flux data, from a mid-catchment location, with recorded data from East Shefford gauging station, it was shown that accurate reproduction of catchment discharge gave no indication as to the accuracy with which the accretion rate profile was being simulated. The transient simulations that best replicated catchment discharge were found to poorly represent discharge at East Shefford, as accretion in the seasonal section of channel was significantly underestimated. This appeared to be a consequence of the overestimation of K in the lower (perennial) portion of the catchment. Overall, simulations using lower values of K, which approximated the pattern of transmissivity given by Owen (1981), produced a better representation of the mean reach accretion rate profile. The most accurate simulation of the profile in this study was based upon a mean K value of only 8m/d, with little difference in accuracy found between a spatially constant K value and a spatially variable one.

The simulations in this study generally used a traditional K distribution pattern, with an order of magnitude contrast between river valley and interfluve areas (100m/d versus 10m/d), although the interfluve value used here was higher than in some studies (e.g. c. 1m/d by Bullock *et al.*, 1995). This river valley – interfluve contrast in K is questioned elsewhere (Section 7.3.2), and this conceptual shortcoming may reflect the difficulty experienced both here and by Rushton *et al.* (1989), where it was found to be impossible to simulate accurately both stream flow and groundwater levels simultaneously, even given the more sophisticated variable transmissivity representation used by Rushton *et al.*

This study demonstrated that the accuracy of groundwater level elevations required for representative simulation of river – aquifer interaction makes them an unrealistic calibration target for replicating river flows. In most large scale groundwater modelling scenarios achieving head levels within +/- 1m of recorded levels would be considered successful, but in river – aquifer interaction terms this range can make the difference between large aquifer to river flows or *vice versa*. Hence, using flux (discharge) targets as the primary calibration tool was shown to be the more realistic approach. The reasonable accuracy of the simulated catchment discharge produced in

this study shows that such results can be achieved from a simplistic conceptual model, but at the expense of portraying groundwater levels accurately.

The apparent lack of sensitivity to significant modification of bed elevations shown in Figure 6.21 is likely to be a manifestation of the model configuration. Being surrounded by no flow cells, and with drain and river cells as the only discharge points, the absolute water level within the model could rise or fall relative to the change in bed elevation, if applied uniformly across the model, thus maintaining a consistent pattern of accretion rates. Discharges to the surface watercourses were not reduced due to lateral losses from the catchment, due to the presence of no flow cells along the lateral and regional catchment divides. Whilst the model configuration was adequate for simulation of water levels within the normal seasonal range expected, it was incapable of satisfactorily simulating extreme water level morphologies imposed by the sensitivity analyses.

The apparent insensitivity to bed conductance in Figure 6.22 is also likely to be due to the model configuration. The combination of the underlying pattern of longitudinal flow accretion, and the lateral restrictions on groundwater discharge, prevented a meaningful assessment of the sensitivity of the bed conductance parameter.

6.5 SUMMARY

This chapter sought to address potential controls on the spatial pattern of flow accretion, using a combination of statistical, analytical and numerical modelling approaches. The statistical results revealed that the variability in regional hydraulic gradients was not responsible for the spatially variable pattern of flow accretion rates, indicating a significant element of local control. One possible component of this local control on accretion rates may be valley floor permeability, which was examined at three sites using an analytical technique. This technique produced a range of values for valley floor permeability (very rarely calculated in the literature), which although representing a limited spatial sample, did show some correlation with calculated accretion rates. Numerical groundwater modelling was used in an attempt to extend our understanding of the sub-surface flow system, but although failing in this principal aim, the work did identify a number of pertinent factors relating to numerical simulation of river – aquifer interaction. The various findings from this chapter are explored as part of a general discussion in Chapter 7 on the results of the study as a whole.

Chapter 7 Discussion

7.1 INTRODUCTION

This study has established that the chalk stream – aquifer flow system of the Lambourn catchment is highly interactive, acting in a complex, non-linear, heterogeneous manner. The results demonstrate that the responses of such systems can be successfully characterised, but show that effective investigation of river – aquifer interaction must encompass the dynamics of water movement through the whole catchment. There are two principal facets to this approach: a temporal context, that correlates patterns of recharge, storage and discharge in order to quantify rates of water flow; and a spatial context, that investigates patterns of flow exchange along the river profile, allowing the dominant controls to be inferred. Together, these two elements enable patterns of flow exchange to be identified.

This chapter considers these distinct, but complementary, aspects of catchment hydrology in detail, but first places them in a palaeohydrological context, by examining the manner in which chalk catchments may be evolving.

7.2 PALAEOHYDROLOGICAL CONTEXT

The recognition of a state of disequilibrium is important in our understanding of the evolution of chalk catchments. The apparent imbalance between the surface and subsurface development of these catchments appears to result in their evolution towards a pseudo-karstic condition, in which no surface flow occurs under normal conditions. This evolutionary concept provides the context in which to place our contemporary understanding of river – aquifer interaction in chalk catchments.

There is extensive evidence (in the form of relic alluvial deposits) to show that active flow once took place over much wider areas of chalk catchments, indicating that the drainage network was of significantly greater extent. Whether this was under conditions of limited infiltration and increased overland flow under periglacial conditions (as suggested *inter alia* by Morgan, 1971; Williams, 1980), larger upstream catchment areas and higher groundwater levels prior to retreat of the escarpment to its current position (e.g. Fagg, 1923), or simply historic periods of higher rainfall, is

unclear. However, there appears little doubt that the drainage network is shrinking over time, whilst the chalk aquifer is simultaneously developing by constant dissolution.

Using contemporary records of discharge and water chemistry, the mass of calcium carbonate removed annually by the River Lambourn (M_c) can be calculated using:

$$M_c = (Q_a \times T_a \times C_c) / 1\times10^6 \qquad \text{Equation 7.1}$$

Where:

M_c = Mean annual mass of calcium carbonate removed (tonnes/year)

Q_a = Long term average instantaneous discharge (1.76 cumecs) [1962 –2003]

T_a = Time (seconds/year) [3.16×10^7]

C_c = Long term mean calcium carbonate concentration (236g/m^3)

[The mean calcium carbonate concentration is derived from 146 samples taken by the Environment Agency from the River Lambourn at Newbury over the period 1981 to 2000]

The calculated value of M_c indicates that around 13 000 tonnes of calcium carbonate is being removed from the catchment every year, which equates to around 78t/km^2 over the groundwater catchment of 168km^2. This is in the same order as an estimate of 55t/km^2 from an undisclosed chalk catchment presented by Wooldridge & Morgan (1937). The mass of calcium carbonate removed from the Lambourn catchment by dissolution equates to a volume of solid chalk of around 6 500m^3 (based on a dry density of 2Mg/m^3; Bowden *et al.*, 2002), and this can be considered predominantly as an increase in fissure volume, as dissolution within matrix material is likely to represent only a small component, given matric permeability and flow rates (Price, 1987). When this volume is compared to an estimate for the total effective storage volume of the Lambourn groundwater catchment (assuming an effective thickness of 50 metres and a specific yield of 0.01), it represents about 0.008%. This suggests that if we use contemporary records as an analogue for past conditions, disregarding the clear limitations of this approach, then the current effective storage has developed over a period of approximately 13 000 years. This value is in line with estimations made by Price (1987), who proposed that the current state of development of the UK chalk aquifer could have occurred over a period of c. 16 000 years.

Under historic conditions of active downcutting, zones of enhanced fissure development in the shallow subsurface, occurring mainly in valley floor locations, were lost, at least in part, due to erosion. However, chalk streams, such as the River Lambourn, are currently under aggrading conditions, and have been so for a period of some 10 000 years (Cheetham, 1980), such that any subsequent aquifer development has been cumulative. It is difficult to determine whether chalk is being primarily removed from the unsaturated zone in interfluve areas, during the descent of aggressive recharge waters (Price, 1987), or whether it is removed from already well-developed fissure systems, where groundwater flow is concentrated beneath valleys (Ineson, 1962). However, if only a proportion of the material is removed from fissures beneath valleys, then the active subsurface drainage network is constantly developing. It is likely that this development will be associated with a reduction in the drainage network extent over time, suggesting that chalk catchments may be evolving to an ultimate state where no surface water flow occurs, except under extreme conditions, much in the nature of a mature karstic landscape.

This disequilibrium between surface water aggradation and subsurface dissolution, and the consequent evolution of chalk catchments towards a mature state, provides the context for assessing current river – aquifer interactions in chalk catchments, and is an important consideration when comparing catchments from different chalk provinces, which might have very different geomorphological histories. Despite two centuries of active research in south-east England (much of which comprises Chalk outcrop), the nature of the geomorphological evolution of the area since the beginning of the Palaeogene is still open to considerable debate (Jones, 1999).

7.3 TEMPORAL DYNAMICS

The investigation of temporal patterns of behaviour in this study sought to address three research gaps identified from the literature, in particular:

1. to elucidate the timescale of catchment scale flow processes, including both unsaturated zone and saturated zone components;

2. to determine quantitatively the control of groundwater levels upon river discharge;

3. to verify estimates of recharge against long-term catchment discharge.

In point of fact, the work undertaken on the temporal dynamics of the recharge – storage – discharge sequence in the Lambourn catchment produced four main findings:

i. bulk rates of unsaturated zone vertical flow identified from this study were found to be much higher than most rates reported previously;

ii. calculated values for chalk interfluve permeability were found to be much higher than those reported previously;

iii. the MGS, representing catchment groundwater storage level, was quantitatively defined as the key parameter in a successful analytical model of catchment discharge;

iv. MORECS EP was shown to underestimate long-term catchment discharge by at least 30%.

These results contrast with the channel-focused emphasis normally assumed for studies of river –aquifer interaction. However, they are very strongly linked to the processes affecting river – aquifer interaction, and they represent the results of a bulk or 'diffuse' approach to investigating such interaction (being similar in nature to a method such as base flow recession analysis). This approach recognises the holistic nature of permeable catchment systems, where the recharge, storage and discharge elements function in an intimately interlinked manner, and it uses the nature of these inter-relationships to characterise the way in which water moves through the catchment, effectively utilising rainfall as a natural tracer.

7.3.1 Unsaturated zone flow rates

The recharge – storage time lag (equivalent to the unsaturated zone travel time) was represented in this study by a spatially variable parameter 'B' (see Figure 4.12). The catchment mean value for this parameter was estimated as 1 month, with an effective maximum value of 3 months (Section 4.5.2). Given the mean thickness of the unsaturated zone as 28m, and a maximum thickness of 80m, a consistent, vertical, unsaturated velocity of 0.9m/d was obtained (Section 4.5.3). This value contrasts with

velocities ranging from 0.8 to 1.8m/**annum** that have been reported in the literature from sites where it has been inferred that recharge has mainly occurred via matrix flow, with fissure flow occurring very occasionally, if at all (e.g. Smith *et al.*, 1970 reported in Price, 1987; Wellings & Cooper, 1983; Wellings, 1984; Gardner *et al.*, 1991; Mahmood-ul-Hassan & Gregory, 2002).

The restricted spatial and vertical extents of most chalk recharge studies make no attempt to address the recognised fracture heterogeneity present in unweathered chalk (Bloomfield, 1996; Younger & Eliot, 1995). In addition, their limited areal coverage, having been generally undertaken on the Upper or Middle Chalk of the Southern Chalk province, also inhibits their wider extrapolation (Jones & Cooper, 1998). Surprisingly, there appear to be no subsurface investigations (for example using geophysics) prior to the siting of recharge study plots, which means that no account is taken of the possible presence of cryoturbation structures (involutions) (e.g. Ballantyne & Harris, 1994; p.102) in the uppermost few metres of chalk, which could dramatically alter shallow vertical flow rates on a lateral scale of only a few metres.

In contrast to these recharge study-based velocities, significantly higher rates of unsaturated flow (of the same order of magnitude as those derived in this study) have been reported, and attributed to transport via fissure flow. These rates were derived using various criteria, for example: the presence of suspended solids and bacteria in boreholes soon after heavy rainfall (Downing *et al.*, 1978); extrapolation from rainfall and groundwater level data (presented by Wellings, 1984); and the occurrence of short-lived bacteria in boreholes penetrating a thick unsaturated zone (MacDonald *et al.*, 1998). Rainfall rates suggested for initiation of such flows are not exceptional: Downing *et al.* (1978) suggested a rate of 4mm/d sustained for several days, whilst Price (1987) estimated a range of 3 - 5mm/d. The intensity of precipitation necessary to initiate such fissure flows will be dependent to a degree upon antecedent conditions, but also upon the nature of any material overlying the chalk, as this can provide shallow storage capacity to buffer short-term, high intensity rainfall events and thus restrict the occurrence of fissure flow (Cooper *et al.*, 1990).

Evidently, **both** matric and fissure flow processes operate in the Chalk, but what is absent from our current understanding is any appreciation of their relative importance on the larger (catchment or regional) scale. The recharge – storage correlation-based

vertical velocity of around 1m/d calculated from this study suggests that fissure flow is the dominant means by which recharge is transferred through the unsaturated zone, at least on a volumetric basis, in the groundwater catchment of the River Lambourn. This may reflect the higher than normal frequency of vertical fracturing in the Chalk of the Lambourn catchment, which would provide an enhanced route for vertical movement of water, and significantly, the catchment is recognised as possessing unusually high permeability (Owen, 1981), some of which is likely be present as sub-vertically inclined discontinuities. However, it may be that the vertical flow rates identified here are actually far more widespread; for example, infiltration lags presented by Oakes (1981) and discussed by Calver (1997b) show that unsaturated velocities in the order of 0.6 to 1.4m/d were recorded at four sites near Cambridge. Comparable rates of vertical unsaturated flow may have been largely unobserved elsewhere; for example there has been no wide-scale verification of the much lower rates derived from recharge investigations. The lack of calibration, or sensitivity analysis, of the areal representativeness of vertical flow rates derived from such studies undermines their credibility, particularly for characterising processes occurring in the deeper unsaturated zone, located 10 to 50m below ground level. Overall, it appears likely that the infiltration lag times identified in this study provide a more realistic basis for estimating **bulk** unsaturated vertical flow rates than rates derived from shallow, soil process-focused, studies.

7.3.2 Chalk catchment interfluve permeability

The permeability of the chalk aquifer has been principally characterised by analysis of pumping test data from abstraction boreholes, which are predominantly situated in river valley and major dry valley locations, and thus our knowledge is subject to significant spatial bias (MacDonald & Allen, 2001). In contrast, chalk interfluve regions have been generally neglected as they are thought to have only limited potential for water supply, and have only been considered in the context of catchment scale groundwater modelling, where some quantification of their character is required. The general lack of meaningful data from such areas has inhibited their representation in catchment models (Allen *et al.*, 1997). An additional problem associated with chalk interfluve areas lies in their spatial definition, in contrast to impermeable catchments where a topographic basis can be used. Whilst the drainage

density of chalk catchments is very low, most are dissected by a widespread network of dry valleys. These extend from the main river valley, sometimes as far as the surface water divide, giving them a 'valley axis density' (*sensu* Cheetham, 1980) comparable to (or even greater than) an equivalent impermeable catchment, and this can lead to difficulty in identifying 'true' interfluve areas. In the context of this study, 'interfluve' is used to define any area of the catchment beyond the extent of the main river valley or a 'first order' dry valley.

Regardless of their exact spatial definition, chalk interfluve areas **are** significant as they represent the majority of a catchment area (perhaps as high as 90%), and obviously the bulk of recharge occurs in these regions. The manner in which recharge is transferred through the unsaturated zone, and thence via groundwater flow to the discharge point in the river valley, is of critical importance in understanding the timescales of catchment scale flow processes. Rates of unsaturated vertical flow have been discussed previously, and the accurate estimation of these rates is particularly important in interfluve areas, given the significant thickness of the unsaturated zone (over 80m in extreme cases). Also important is the saturated permeability of interfluve areas, as the majority of the groundwater flow path (from the water reaching the water table to it being discharged to a river) occurs beneath interfluve zones. However, as mentioned previously, our knowledge of interfluve permeability is very poor. Even in an intensively investigated area such as the West Berkshire Downs, only two interfluve pumping tests are recorded in the Aquifer Properties Manual (Allen *et al.*, 1997), and these give transmissivity (T) values of 1.0 and 0.5m^2/d (although no details are given on the duration of the test or the analytical method used for their derivation), whereas there are 53 valley-based locations recorded with T values ranging from 18 to 3200m^2/d, with an average of 1001m^2/d.

The timescale for bulk groundwater flow in the Lambourn catchment was represented by a spatially variable parameter 'C' (see Figure 4.12), and values calculated from recharge – storage – discharge time lags ranged from an average of 1.4 months (C_{av}) to an effective maximum of 9.1 months (C_{max}). The value for C_{max} was used, in conjunction with calculated values for regional hydraulic gradients, to derive the bulk interfluve permeability (hydraulic conductivity, K), which ranged from 57 to 227m/d (based upon Sy [Specific Yield] values of 0.5% and 2% respectively). These K

values are significantly higher than those derived from previous studies, for example 27m/d (from Brettell, 1971; T = 1590m^2/d, effective thickness = 60m, Sy = 1.56%) and 20m/d, based upon the average T value for the West Berkshire Downs of 1001m^2/d mentioned above and an effective thickness of 50m.

The implication of these findings is that recharge – discharge time lags are far shorter than would be envisaged by our current understanding of interfluve permeability, and the resulting values for the bulk permeability of interfluve areas appear to be higher than the elevated chalk permeabilities derived from valley locations. In order to reconcile the apparent discrepancy between these two sets of permeability values, a number of previously unrecognised processes may need to be invoked. These include significant lateral migration in the unsaturated zone and the presence of widely spaced, but highly transmissive, vertical fissures in interfluve areas.

The lateral movement of recharge during its vertical migration through the unsaturated zone is a little recognised process in chalk catchments, but given the paucity of appropriate investigation its incidence on a wide scale cannot be dismissed. One of a limited number of recorded occurrences, taking place at shallow depth at a site on chalk outcrop, is outlined by Barraclough *et al.* (1994), who describe the sideways movement of deuterium (used as a tracer) beyond the lateral boundaries of a plot to which it was applied. Another recorded occurrence is described by Gooddy *et al*. (2002) in relation to migration of slurry from unlined storage lagoons located on chalk outcrop in Southern England. A third occurrence, which emphasizes the role of small marl seams, is implied by Zaidman *et al*. (1999) in connection with geophysically-based characterisation of the unsaturated zone of the Chalk at a site in Yorkshire. The significance of marl seams for restricting vertical flow is also recognised by Duperret *et al*. (2002), who conceptualise the local chalk in northern France as a multi-layered aquifer, separated by marl bands, in investigations of coastal erosion on chalk cliffs. The occurrence of such behaviour is entirely in keeping with our knowledge of the lithological fabric of the Chalk, comprising numerous, sub-horizontal discontinuities, with the Upper Chalk having persistent flint bands, and the Middle Chalk numerous marl bands. Any sub-horizontal discontinuity could be capable of restricting vertical flow, and thus forcing descending recharge to move laterally in the direction of the local dip of the strata. This behaviour has been recognised from the Middle Chalk in Kent, where the significant permeability

developed above marl bands gives rise to distinct spring lines (Cross *et al.*, 1995). Given that water in the unsaturated zone, which has been recently derived from precipitation, is chemically aggressive and capable of dissolving chalk, it would not be surprising if preferential flow paths were established above lithological discontinuities. Over time these features may have developed sufficiently through dissolution to allow the rapid lateral movement of water, perhaps at velocities in the range 10 to 100m/d (roughly equivalent to 0.1 to 1mm/second). Given the travel times through the unsaturated zone of 1 to 3 months found from this study, the estimated maximum lateral rate could translate into sub-horizontal displacement on a scale of 3 to 9km. However, in the case of the Lambourn catchment this would not necessarily promote rapid flow to the river, as the dip direction of the Chalk is to the south-east, paralleling the orientation of the river valley. In order to move water from the unsaturated zone towards the river, and thus reduce the need for highly elevated interfluve permeability, an additional component of the flow system is required, and this could take the form of structurally controlled, sub-vertical fractures, oriented perpendicular to the river and the dip of the strata.

The occurrence of sub-vertical structures in the Chalk has long been recognised, for example in relation to the need for horizontal headings (adits) to be driven to maximise the yield from early water supply wells, by intersecting highly permeable sub-vertical features (e.g. Wooldridge & Morgan, 1937). The yield from such features can be impressive, as illustrated by Downing *et al.* (1993; Figure 1.5, p.11). However, advances in drilling and pumping technology led to the use of smaller diameter boreholes with no horizontal adits (Downing *et al.*, 1993) and it is data from the test pumping of such boreholes that underpins our current knowledge of the permeability distribution of the chalk aquifer. Not only does this reliance introduce the spatial bias that has been mentioned previously, but it also introduces a degree of orientational bias by concentrating physical characterisation on the basis of sub-horizontal structures, to the exclusion of sub-vertical features. The potential occurrence of this orientational bias can be illustrated by examining the results from an intensive programme of drilling in the West Berkshire Downs (for Stage 1 of the Thames Groundwater Scheme): of the 93 boreholes drilled (the majority of which were geophysically logged), only two boreholes (at Compton and Banterwick Barn) intersected significant vertical fissures,

and these were later confirmed by CCTV logging (Robinson, 1975). However, this result gives little information concerning the relative importance of sub-vertical features to the functioning of the aquifer system.

Given the relative surface footprints of a borehole and a vertical structure, the 'strike rate' described above is not surprising, however, the fact that sub-vertical features (SVF) have been observed only occasionally in boreholes does not justify our disregarding their possible influence on water flow through the chalk aquifer. This is particularly pertinent when determining the contribution of SVFs to bulk chalk permeability, upon which they may exert a significant control. This is illustrated by work undertaken on the chalk aquifer of northern France by Bracq & Delay (1997), who found a strong correlation between morphological indicators of vertical fissuring and transmissivity derived from test pumping. Furthermore, Zaidman *et al.* (1999) showed that vertical joint sets in the unsaturated zone can rapidly convey recharge to significant depths, and these structures may also transfer water laterally. In the Lambourn catchment this transfer is likely to be towards the river, thus decreasing the flow path length that takes place in the saturated zone beneath interfluve areas. Moreover, the presence of widely spaced (for example on a scale of hundreds of metres), highly permeable, SVFs in interfluve areas, connected only to permeable horizons in the unsaturated zone, could account for the very low interfluve permeability values calculated from the occasional pumping tests undertaken in such areas – unless an interfluve borehole actually intersected one of these structures then its permeability would not be recognised. A schematic representation of this conceptual model is given in Figure 7.1.

Given the likely spacing of the SVFs and the paucity of drilling in interfluve areas, it is not surprising that such structures have never been recognised in a borehole, but their presence may well dominate the passage of water through interfluve areas. However, some question as to the effectiveness of such structures in moving water vertically remains, given that observations in chalk quarries indicate that vertical structures rarely connect more than two or three horizontal bands (P. Younger, pers. comm.). If such areas are to be better represented in groundwater models, for the improvement of catchment scale simulations as a whole, then the presence, significance and distribution of SVFs need to be better understood.

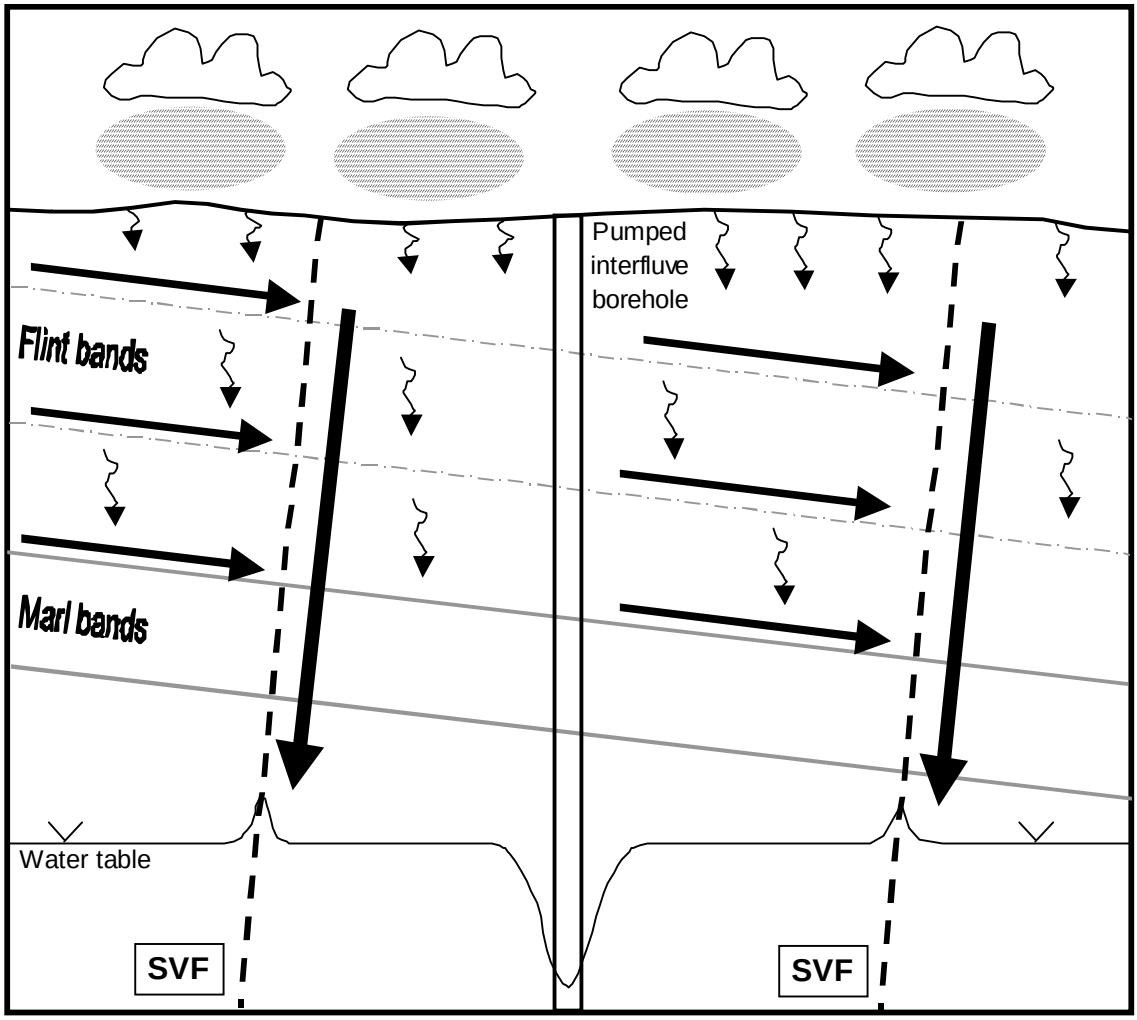


Figure 7.1 The possible influence of sub horizontal discontinuities and sub vertical features (SVFs) on unsaturated zone flow and interfluve permeability

In summary, it is difficult to derive representative catchment mean values for chalk permeability. Most pumping tests have been undertaken in valley locations where permeability is known to be enhanced, and thus results from these sites may not represent the catchment as a whole. Alternatively, permeability may be calculated using a base flow recession-type approach (e.g. Rorabaugh, 1964), but this method has a limited ability to represent the variability in catchment morphology, as the distance from the groundwater divide to the river is represented by a single value. Bulk parameter values derived in this study, from recharge – storage – discharge correlation, provide an alternative to, or a comparison with, bulk values estimated from base flow recession analysis, and may assist in defining aquifer parameters for interfluve locations, especially when undertaking groundwater modelling. The elevated bulk

permeability values for interfluve areas may be indicative of the greater occurrence of widely spaced, but highly transmissive, vertical fissures than is currently recognised.

7.3.3 The influence of catchment storage level on river flows

A permeable catchment acts to a certain degree in the manner of a linear reservoir, with the groundwater level (storage level) playing a key role in controlling catchment scale river discharge. This relationship has been consistently recognised in chalk catchments on a qualitative basis (described *inter alia* by Macdonald & Kenyon, 1961; Bradford, 2002), but formal analysis of the relationship has not been widely described, partly due to the difficulty of producing a representative measure of catchment storage level, and this has limited its application for flow prediction purposes. Work presented in this study revisited the concept of the Mean Groundwater Stage (Brettell, 1971), and used monthly groundwater level records from 22 observation boreholes, weighted using Thiessen polygons, to produce a 20-year time series for a representative catchment storage level, which provided the basis for comparison with river discharge at both the catchment and reach scale.

MGS and catchment discharge

Using multiple linear regression, the MGS was found to be by far the most important control on catchment discharge, representing more than 70% of the total correlation, which was based upon MGS and three other parameters (four month moving average EP, previous month's EP and rate of change of MGS). The correlation equation derived by multiple linear regression was used to create a synthetic time series of catchment discharge, which was found to be an accurate representation of the true discharge record. The effectiveness of this approach supports its wider use as an alternative technique, compared to hydrological or groundwater modelling, for producing a discharge record for a chalk catchment with little or no gauging data, but which does have a groundwater level record. This may be particularly pertinent for establishing a baseline ('natural') flow regime in a catchment where the available record of discharge has been significantly modified by groundwater abstraction.

MGS and reach discharge

Results presented in Table 6.1, correlating MGS with individual reach accretion rates, showed that six of the twelve reaches displayed a positive correlation with an R^2 value of 50% or greater. Two other reaches displayed smaller, but still significant R^2 values (0.40 and 0.36), whereas the remaining four reaches showed no correlation. This latter group included the Weston and Welford reaches, whose anomalous behaviour has been examined previously, and also reaches 10 and 11 at Hunts Green and Woodspeen, the latter being the only reach to display a mean accretion rate of below zero. From this overview we can see that eight out of nine reaches with 'normal' patterns of accretion exhibit significant positive correlation between MGS and reach accretion rate, which shows the strong control of catchment storage level on the **absolute magnitude** of individual reach accretion rates over time. However, examination of regional hydraulic gradients in Chapter 6 showed no effective correlation with reach accretion rates and thus the manifestation of catchment storage appears to provide no control on the **relative magnitude** of reach accretion rates, i.e. their spatial variability.

Overview

Using the MGS to represent catchment storage level has been shown to be effective in the analytical modelling of discharge from the Lambourn catchment. However, the application of this type of approach may be restricted in other catchments where there are only limited numbers of observation boreholes, especially where these are significantly influenced by groundwater abstraction. Identification of the optimum number and location of observation boreholes that allow a representative MGS to be calculated would be useful further research.

7.3.4 MORECS EP versus long term catchment discharge

Using monthly-based figures, MORECS EP represented only 69% of catchment discharge over a 22-year period. However, there were significant annual variations, with MORECS EP ranging from 47% to 96% of catchment discharge. The mean value of 69% is likely to underestimate the true value, as the recorded river discharge may neglect unrecorded losses from the catchment, for example underflow at the lowest gauging station and any groundwater outflows from the catchment. A truer mean value for MORECS EP may be only 60 to 65% of actual recharge, which is comparable to an

estimate made by Jones & Cooper (1998) that was based upon an independent verification of MORECS EP using a large lysimeter. The magnitude of this error brings into question the use of the national coverage (40 x 40km square) MORECS database as the basis for calculations of catchment water resources, for example by the Environment Agency, with its attendant resource management implications, which are considered in Chapter 8. However, it is recognised that site specific MORECS data, particularly in areas with a dense raingauge network and well defined soil properties, is likely to be considerably more accurate than the generalised data used in this study.

7.4 SPATIAL DYNAMICS

Investigation of the spatial dynamics of the Lambourn catchment in this study sought to address two research gaps drawn from the literature reviewed in Chapter 2: firstly, the need to assess spatial variability in chalk stream – aquifer interactions; secondly, the requirement to identify the underlying controls on a spatially variable pattern of accretion. These research needs were addressed by first identifying the spatial pattern of accretion on the River Lambourn, based upon current meter readings, and then correlating geological, hydrological and topographic catchment characteristics with the accretion pattern to identify potential controls. The number and spacing of the current meter stations allowed a representative and detailed chalk stream accretion profile to be defined. The results were presented as both traditional accretion profiles and as plots of standardised accretion rate versus location, which clearly showed the spatial variability in accretion rates. This detail allowed controls on the accretion pattern to be inferred, supported by lithological and geophysical datasets.

7.4.1 The defined spatial pattern of accretion

In Chapter 5 the pattern of flow accretion along the River Lambourn was shown to be spatially variable, with recognisable point source inputs, in contrast to the uniform pattern that has been implicitly assumed in previous research on chalk streams. However, the most significant element identified from the accretion pattern of the River Lambourn was the gradational transition between reaches with high and low accretion rates, which occurred in a cyclical pattern along the river profile. This provided evidence for the possible control of catchment scale features on a c. 12km longitudinal cycle, overprinted at a smaller (reach) scale by local features.

The heterogeneous pattern of flow accretion, based upon current meter data at a spacing of 1 to 3km, was in contrast with the near-homogenous pattern derived from continuous discharge data at a scale of around 10km, indicating that the pattern of flow accretion is scale dependent. The spatial precision with which the accretion pattern could be identified was controlled by the spacing of the current meter stations, which was itself constrained by the accuracy of the current meter readings: if the stations were too close together the volume of accretion might be less than the error margin of the gaugings, and consequently the accretion rate would be poorly defined. It has been recognised from ecological investigations undertaken at the sub-reach scale (e.g. White, 1990), that both influent and effluent flows occur across a pool-riffle boundary, with downward flow at the riffle head, and upward flow at the riffle tail. Obviously the recognition of such a phenomenon requires not only measurement at an appropriate scale but also at the correct location. For example, if a measurement were undertaken in a reach ending at a riffle crest, then the reach would appear to be losing water, in the absence of any other influences. Meanwhile, if the reach being studied included the whole of the riffle then the gains and losses would cancel one another out and no exchange would be recognised. This illustrates the key importance of the investigative scale with regard to the interpretation of accretion results.

7.4.2 Controls on the spatial pattern of accretion

The detailed pattern of accretion appears to be controlled by interplay between regional and local scale features. Local controls predominate at a longitudinal scale of some tens to hundreds of metres, and manifest themselves in the nature and location of ‘point source’ discharges. For example, groundwater discharges at West Shefford (see Figures 5.11 and 6.9) and at Weston (see Figure 5.11) do not occur directly into the channel, but occur as floodplain springs, which establish minor channels parallel to the main river, before joining it further downstream. At these locations, the character of the groundwater discharge is apparently controlled by the interplay between channel bed permeability and the combined nature and distribution of the valley floor alluvial deposits. As discharge occurs preferentially to the floodplain surface, which is at a higher elevation than the channel bed, then the floodplain alluvial deposits must represent a significantly more permeable pathway than the channel bed material, based upon the gradient-pathway product (GPP) approach. However, there appears to be an

underlying regional control, operating on a quasi-sinusoidal cycle of 12km lengths of channel, which has a significant influence on the overall pattern of flow accretion. There appear to be two possible explanations for this recurring, catchment scale pattern of accretion: firstly, relating to vertical cycles of litho-structural controls; secondly, relating to a topographic control, which may also be linked with a litho-structural origin.

Catchment scale controls

Lithological and structural features are recognised as significant controls on the geometry of permeability in the chalk aquifer (Allen *et al.*, 1997). The 'wavelength' of the recurring spatial pattern of accretion rates identified in this study may be controlled by the distribution of sub-horizontal (bedding plane parallel) features, with a true vertical spacing of around 80m, based on a regional dip of 0.5°. However, this spacing does not equate to any recognised lithological pattern in either the 'traditional' chalk stratigraphy (shown in Figure 7.3) or the 'new' stratigraphy (Bristow *et al.*, 1997), with which the catchment has been recently remapped by the British Geological Survey (Aldiss & Royse, 2002).

Similarly, the 80m spacing does not correlate consistently with the pattern of any recognised electrical marker bands shown in an idealised 16" normal resistivity log for the local Chalk succession presented by Robinson (1975). If, indeed, the large-scale control on the spatial pattern of flow accretion is principally due to lithological features then they are too subtle to be recognised by mapping or geophysical techniques that have been used in the past. This suggests that the cyclical pattern may be coincidental, with different elements controlling the upper and lower cycles along the length of the river. However, there does appear to be a consistent correlation between topography and accretion.

The basis for linking accretion with topography is founded upon the spatial correlation of reaches displaying above average accretion with junctions between the main river valley and perpendicular (generally dry) valleys. All the high accretion reaches are adjacent to (or immediately upstream of) the intersection of major perpendicular valleys with the Lambourn valley, for example at Lambourn village, Great Shefford and the confluence of the Winterbourne with the Lambourn. In fact there are no major dry valleys joining the river valley that are not represented by a high

accretion reach, which suggests that such valleys may be a significant control on flow accretion.

Dry valleys are considered to possess enhanced permeability relative to interfluve locations (e.g. Allen *et al.*, 1997), but this factor alone does not appear sufficient to explain the enhanced accretion rates at their junctions with a river valley. A conceptual model of these intersections could envisage that elevated permeability beneath a dry valley leads to a highly focused, near-perpendicular input of groundwater to the flow system beneath the river valley, which in turn could lead to local 'inundation' of this down-valley flow system, causing the excess water to be discharged to the river, producing high accretion rates. However, this explanation neglects the palaeohydrological development of the aquifer, which should lead to preferential development of the main valley transmissivity at these intersection sites, due to enhanced flow rates and dissolution, allowing the groundwater flow system beneath the main valley axis to have developed sufficiently to enable it to transmit this additional flow volume without overflow to the river.

The ability of dry valleys to function as captors of regional scale groundwater flow is clearly illustrated in the anomalous behaviour of the reach downstream of East Shefford (in the Weston / Welford area), where the accretion rate is shown to have an inverse relationship with catchment discharge, which is contrary to all other reaches. This pattern can be explained if the Great Shefford dry valley acts to capture regional scale flow as groundwater levels increase, causing the reach downstream of East Shefford to fall increasingly into a 'shadow zone' as its groundwater catchment area is significantly reduced. This effect is shown schematically in Figure 7.2, and leads to accretion rates in the Weston and Welford reaches remaining approximately constant as groundwater levels and catchment discharge increase.

Whilst the temporal variability in accretion rates downstream of a dry valley junction can be adequately explained by the interception effect of the dry valley, the background control on high accretion reaches adjacent to dry valley junctions is far more difficult to elucidate. A tentative explanation may be that the dry valley input **is** the cause of the increase in accretion, but that its influence is magnified due to a mismatch in development rates between the dry valley and main valley flow systems.

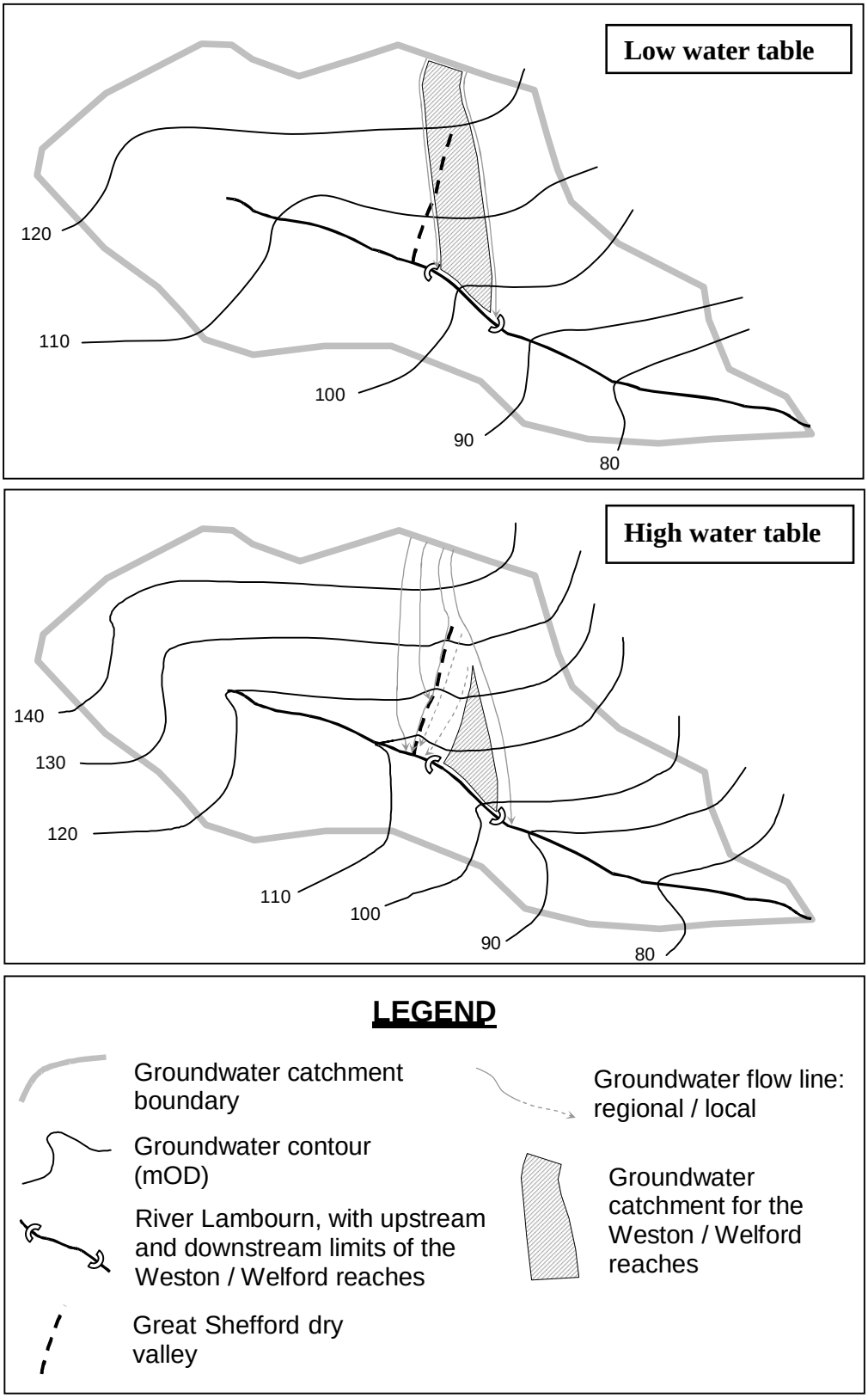


Figure 7.2 Schematic representation of the proposed influence of the Great Shefford dry valley under conditions of low and high water table

How such a pattern of disparity in development could have arisen, and been perpetuated as the groundwater and surface-water flow systems have evolved, is difficult to conceptualise. However, a possible insight into the occurrence of scale-related, differential permeability development in the Chalk is provided by Younger (1989), who proposed that periglacial processes were responsible for producing transmissivity variations between wide and narrow sections of the Middle Thames valley. It may be possible that a similar evolutionary control is responsible for initially promoting local dry valley permeability development over river valley development, and this disparity was subsequently maintained by local hydraulic morphology, causing the apparent 'overflow' effects and high accretion rates observed at dry valley / main valley intersections.

Local scale controls

Local scale controls considered in this study included the lithology of the Chalk, valley floor alluvial gravel architecture, valley floor / bed sediment permeability and bed level topography, of which the most important appears to be Chalk lithology. It is evident from geophysical logging undertaken in the Lambourn catchment that the Chalk Rock exerts a significant control over the effective aquifer thickness in the seasonal section of the channel, and this in turn is likely to exert a degree of control over patterns of flow accretion in this area.

Investigation in an observation borehole at West Shefford (reference number SU37/1, which was also instrumented during this study) showed that the Chalk Rock marked the base of the active flow system at c. 30mbgl, on the basis of flow logging and measurements of electrical conductivity. This suggests that the Chalk Rock possesses negligible vertical permeability at this location, thus restricting the active groundwater flow zone to the uppermost 30m of the aquifer.

Meanwhile, the outcrop of the Chalk Rock on the Lambourn valley floor occurs between Bockhampton and Eastbury, which coincides with the occurrence of two reaches (3 and 4) with the lowest mean accretion rates of any on the river (with the exclusion of the negative reach 11). These circumstances can be explained if the Chalk Rock at outcrop (and shallow depth) is also considered to possess negligible vertical permeability, as in this state it would effectively isolate the river from any regional-scale sources of accretion, with the bulk of groundwater flow being 'confined' beneath

it. However, at some point between the outcrop of the Chalk Rock and the site at West Shefford, there must be a significant transformation of the groundwater flow system, as the upper, active section of the aquifer migrates from beneath the Chalk Rock to above it. This conceptual model is illustrated schematically in Figure 7.3 as a longitudinal section, with average reach accretion rates for comparison. The gradational transition of groundwater flow from beneath to above the Chalk Rock could account for the continuous increase in the accretion rate observed between Eastbury and East Shefford, but does not explain the similar pattern observed in the perennial section of channel downstream, as no equivalent hard ground is present here, and thus the wider control on this section of the river remains enigmatic.

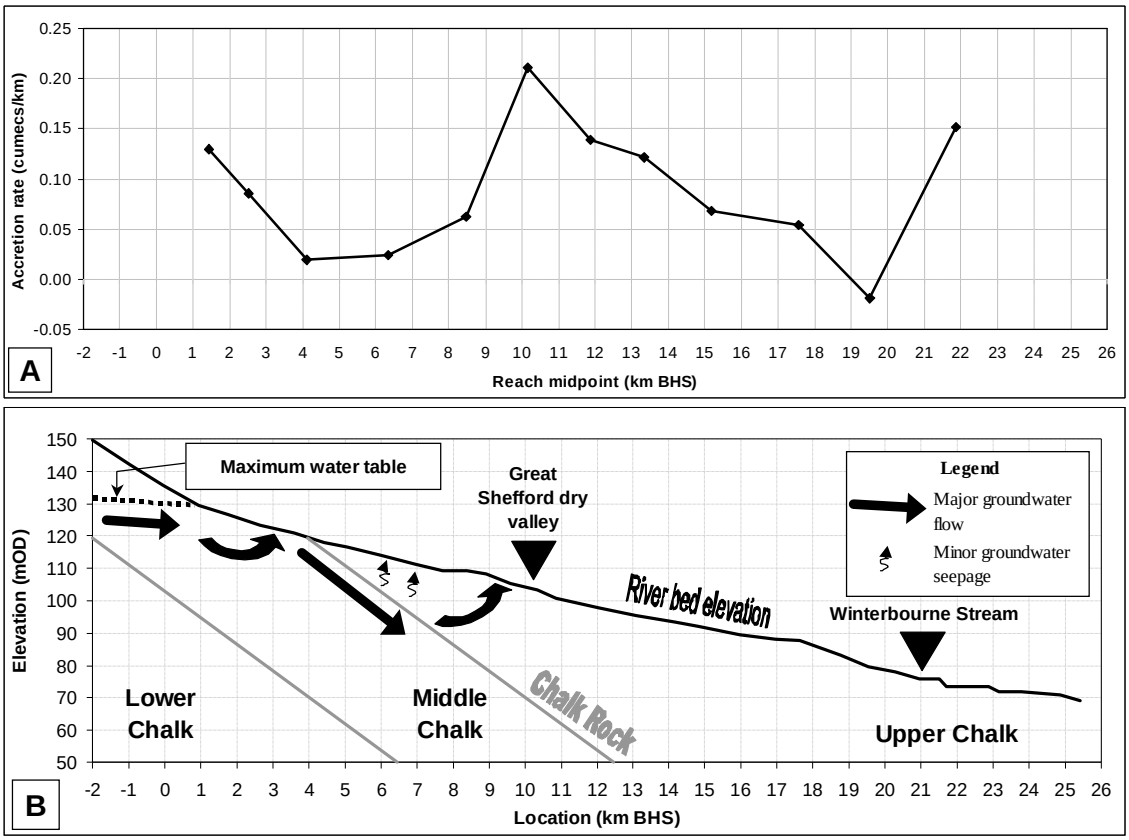


Figure 7.3 Comparison of average reach accretion rates (A) with a longitudinal section of the River Lambourn (B), showing geological information and schematic groundwater flows paths in the seasonal section of channel

Information on the influence of valley floor alluvial deposits upon patterns of flow accretion on the River Lambourn is limited. Only a small number of boreholes have been drilled on the main valley floor itself, and details of the alluvial material

intersected during drilling are poor. One site where valley floor information is available is located between West Shefford and East Shefford, and this reach exhibits both the highest standardised mean accretion rate and highest maximum rate recorded on the river. At the upstream end of the reach, the drillers log from observation borehole SU37/1 at West Shefford records 5m of gravel overlying the Chalk bedrock. However, at East Shefford, chalk is visible in the banks of a pool constructed on the southern side of the floodplain adjacent to the gauging weir, indicating that the thickness of any gravel present must be less than 0.5m. This observation is reinforced by the presence of chalk at the base of a small spring located c. 50m north of the gauging weir, giving a maximum gravel thickness on this side of the river of less than 1m. This indicates that between West Shefford and East Shefford there is a significant reduction in the thickness of alluvial gravel present, and this must inevitably lead to the discharge of water from the gravels to the river, perhaps via intermediate floodplain springs.

An estimate for the potential impact of this scenario upon the reach accretion rate was made using the known floodplain morphology and a range of gravel permeability values (26m/d to 2600m/d: Domenico & Schwartz, 1990; Table 3.2, p. 65). Assuming all water flowing through the gravel at West Shefford was discharged to the river upstream of East Shefford, the estimated flow gain ranged from 0.0004 to 0.040 cumecs, representing 0.2 to 19% of the unstandardised mean reach accretion rate of 0.317 cumecs. From this estimate it is apparent that the influence of alluvial gravel on river discharge is not the dominant control on accretion on this reach, but that if the alluvial gravels have high permeability, such an effect may be far more significant in a reach with a lower background rate of accretion. Overall, the degree to which longitudinal variability in the thickness of alluvial gravels along the River Lambourn affects reach accretion rates is difficult to calculate, given our current, sparse knowledge on the presence, thickness and nature of the gravel deposits. However, such variability must impose a degree of control on the observed pattern of accretion, given the likely permeability contrast between the gravels and the underlying chalk aquifer. With more detailed characterisation of the alluvial gravels, the significance of their control on flow accretion can be better understood, allowing the influence of other controls to be identified more clearly.

In contrast to the assessment of the specific influence of alluvial **gravels** discussed above, there was also a more general consideration of the permeability of channel-proximal alluvial deposits, including river bed sediments, as it was recognised that, where present, these could influence the occurrence and rate of river – aquifer transfers. To place this element in context, a representation of valley floor / bed sediment permeability has been used in numerous groundwater models of chalk catchments (e.g. the 'River Coefficient' of Rushton *et al.*, 1989), but the field-based definition of this parameter has been poorly documented, with only a limited number of model-derived values, and apparently no representative, field-based calculations, being reported (Calver, 1997a). Younger *et al.* (1993) present field-derived data for the River Thames at Gatehampton, but here the bed sediment consists dominantly of low permeability organic material, which is unrepresentative of the mainly gravel substrate of a chalk stream such as the River Lambourn. Field-derived bed permeability values from this study (presented in Section 6.3) are compared with model-derived values presented in the literature in Table 7.1 below.

Location	**Derivation method**	**Bed sediment permeability value**	**Source**
River Lambourn, Berkshire	Comparison of accretion rates and channel proximal hydraulic gradients	15 - 390m/d	This study (Section 6.3)
River Kennet catchment, Berkshire	Not reported [*values used within a regional groundwater model*]	450m/d [*calculated here from reported typical river coefficient of 4500m^2/d/km for the Winterbourne Stream*]	Rushton *et al.*, 1989
Rivers Little Ouse, Thet and Wissey, Norfolk	Calibration within numerical groundwater model	0.05 - 1.7m/d [*calculated here from reported model 'head constant' values*]	C.M. Wilson & S. Kjaran, reported in Calver, 1997a

Table 7.1 Reported values of chalk stream bed sediment permeability

Whereas the values calculated from this study extend over a considerable range, they still fall within the limits reported by previous studies, albeit from a very restricted sample. Assessing the significance of valley floor / bed sediment permeability as a control on accretion rates is complicated by the limited dataset and the number of other potential controls. However, the occurrence of discharges to floodplain springs (for example at West Shefford and Weston), in preference to direct discharge to the channel, suggests that local permeability contrasts do exert some control on flow paths, although

these may not significantly alter reach accretion rates unless the indirect discharge from a floodplain spring is recorded as a contribution to a reach downstream. The permeability values calculated in this study were 33m/d at Bockhampton (reach number 3, mean accretion 0.020 cumecs/km), 15 and 25m/d at East Garston (reach number 4, mean accretion rate 0.024 cumecs/km) and 52, 140 and 390m/d at West Shefford (reach 5, mean accretion rate 0.063 cumecs/km). There is some weak correlation between calculated permeability and mean accretion rate, with the highest permeability values at West Shefford being linked with the highest accretion rate. However, what is more interesting is the variability displayed by the three values derived from the West Shefford site, which indicate the potential variability over small spatial scales. The lowest value (52m/d) was derived from a shallow piezometer close to the river, and is the most representative for comparison with the other sites, which now exhibit a more limited range from 15 to 52m/d. The value of 140m/d was based upon data from observation borehole SU37/1, drilled close to the river to a depth of over 100m into the Chalk. As such, the groundwater level used to calculate the permeability was influenced by both river stage and its function as a depth-averaged chalk aquifer water level. Thus the volume of material 'sampled' to derive the permeability value potentially incorporated a section of highly transmissive chalk; hence the significant increase relative to the shallow piezometer value. A further increase in potential sample volume was incorporated by the third value of 390m/d, derived from a shallow piezometer located at the edge of the floodplain, some 90m from the river. In this instance the sample volume was laterally increased to include around half the total width of the floodplain. By the significant increase in calculated permeability, it is apparent that this included some high permeability material, which can be conceptualised as a mixture of alluvial gravel and highly fissured chalk. Overall, the potential influence of valley floor / bed sediment permeability upon accretion rates remains unclear. However, given the significant variability displayed by a single site, values for such a parameter must be accepted with a degree of caution as to their representativeness. This variability also indicates the level of investigative detail required to adequately define the influence of this element.

The possible control of river bed elevation on accretion rates formed only a minor element of this study, and was restricted to a comparison of mean accretion rates

with a longitudinal bed profile derived from the digital elevation model (DEM) mentioned in Section 6.4. The accuracy of the DEM was tested by comparison with sites surveyed from OS benchmarks and was found to be inaccurate on a scale of 0.5 to 3m. Considering this limitation, it was found that there was no unique correlation between bed gradient and accretion rate, although reaches with similar rates displayed a consistent gradient (for example reaches 3 and 4), and significant changes in accretion rate were often accompanied by changes in gradient, for example around Great Shefford (reach 6). However, overall the lack of a consistent correlation between gradient and accretion rate suggested that it was a control of, at most, only secondary importance.

Summary

From the various parameters explored above, it is apparent that no single process can definitively be proposed to account for the observed pattern of accretion. It is likely that some, or all, of the postulated processes function together to create the observed pattern, and better recognition of the significance of individual contributions should form the key objective of future research in this area.

This study provides an overview of relevant investigative techniques, but also presents baseline values for a number of key hydrological parameters. This baseline enables comparison with results derived from other chalk catchments, so that the effects of broader spatial influences, such as tectonic history, geomorphological evolution and palaeohydrology, can be assessed. The conclusions arising from this study, together with their implications for water resource management in chalk catchments, are presented in the final chapter, together with a vision for future research requirements.

Chapter 8 Conclusions and implications

8.1 CONCLUSIONS

This study has identified a number of key hydrological attributes that characterise the flow system of the Lambourn catchment, and which relate to the six objectives outlined in Section 1.4. Of these objectives, significant progress was made towards meeting numbers 1 to 4, but only limited progress towards objectives 5 and 6.

Many of the attributes detailed below have not been previously defined in other chalk catchments, and thus there is no database available against which to compare them in order to assess how representative the Lambourn catchment is of chalk catchments in general. However, the values defined in this study provide a preliminary characterisation of the Lambourn catchment's interlinked river – aquifer system, and provide a basis for future comparison with other chalk catchments. The details of the key attributes are presented below, with the numbering relating to the aforementioned objectives:

1 (a) The transfer of water through the unsaturated zone has a mean duration of 1 month and an effective maximum duration of 3 months, giving a mean vertical unsaturated flow velocity of 0.9m/d.

1 (b) Bulk groundwater flow through the catchment has a mean duration of 1.4 months and an effective maximum duration of 9.1 months, the latter value giving a bulk hydraulic conductivity value for the catchment of 114m/d (based upon a mean specific yield of 1%), which may be indicative of the greater occurrence of widely spaced, but highly transmissive, vertical fissures, particularly in interfluve areas, than is currently recognised.

2 The catchment average groundwater level (represented by the Mean Groundwater Stage, MGS) is the dominant control on the magnitude of catchment discharge, accounting for around 70% of its variability using multiple linear regression. A synthetic record of catchment discharge, based upon a four parameter linear regression equation, including the MGS value, accurately

simulated recorded patterns of monthly discharge over a 16 year period from 1978 to 1994.

3 (a) The catchment average accretion rate ranges from 0.029 to 0.286 cumecs/km, with a mean of 0.088 cumecs/km, based upon an 18 year record of data from 1983 to 2001. Mean, reach-scale accretion rates range from –0.019 to 0.211 cumecs/km and display a quasi – sinusoidal spatial pattern with a wavelength of c. 12km.

3 (b) Point-source inflows, which form the seasonal head of the River Lambourn at Lynch Wood springs (near Lambourn village), effectively control the discharge in the bulk of the non - perennial channel downstream. Junctions between major dry valleys and the Lambourn valley are associated with reaches displaying elevated rates of accretion. The presence of the Chalk Rock at outcrop, and at shallow depth, in the base of the Lambourn valley is associated with reaches exhibiting low rates of flow accretion

4 Six values for the effective permeability of the floor of the Lambourn valley (comprising elements of the shallow chalk aquifer, alluvial deposits and bed sediment) were defined using Darcy's Law and field data at three sites, giving a range from 15 to 390m/d, with a mean of 109m/d.

Through objective 5, we sought to use numerical groundwater modelling to examine the influence of bulk aquifer properties on spatial patterns of flow accretion. Whilst a calibrated model of the Lambourn catchment was completed, and shown to adequately simulate catchment discharge over a 5-year period, the model was unable to effectively investigate spatial patterns of accretion in sufficient detail to identify bulk aquifer controls on accretion. However, it was able to illustrate that accurate simulation of catchment discharge is no guarantee of similar accuracy in reproducing the spatial pattern of flow accretion.

Objective 6 sought to improve the understanding of flow dynamics in chalk catchments by presenting an enhanced conceptual model of flow paths from recharge to discharge. Some progress was made towards this objective, by identifying controls on discharge locations to the river and by recognising the importance of processes

operating in the unsaturated zone, but this fell short of a new, holistic understanding of catchment scale flow paths.

The results from this study supplement the existing body of knowledge regarding the characterisation and functioning of the chalk aquifer. MacDonald & Allen (2001) provided a benchmark characterisation of UK chalk aquifer properties by summarising the results of hundreds of pumping tests. However, it was acknowledged that even this extensive dataset was heavily biased towards characterising the chalk in valley locations, whereas the features of chalk interfluve areas (over which the majority of recharge occurs) are poorly constrained. The present study went some way to addressing this shortcoming and found that interfluvial permeabilities may be higher than previously realised, suggesting that interfluve areas warrant more detailed investigation.

Traditional groundwater tracer testing undertaken in the chalk aquifer (e.g. Price *et al.*, 1992; Banks *et al.*, 1995) has been successful in assessing specific flowpaths, but this approach has provided little information on the contribution of the defined flowpaths to the bulk movement of water through the aquifer. The temporal aspect of this study used a statistical approach to correlate elements of the recharge – storage – discharge sequence, and essentially used rainfall as a **bulk** tracer to assess bulk groundwater flowpaths.

Considering the spatial aspect of this study, there was a focus upon flow accretion profiles, not as calibration tools for a groundwater modelling approach, but as a basis for investigating controls on the natural spatial pattern of groundwater – river interaction. The resulting detailed accretion pattern provided an insight into the complexity of chalk stream - aquifer systems, and the lithological and topographic controls identified here extended the conceptualisation of Bradford (2002) to provide an outline of possible controls operating in other chalk catchments.

This study also provided some insight into the potential problems of using catchment scale models in the representation of local scale patterns of accretion, and showed the difficulty of achieving simulations that were well calibrated for both river discharge and groundwater levels. Both the quantitative and qualitative aspects of these findings have implications for the management of water resources in chalk catchments, and these are considered in the section below.

8.2 WATER RESOURCE MANAGEMENT IMPLICATIONS

Optimal management of chalk catchments (and other permeable catchments) involves balancing the abstraction of groundwater with the needs of the surface water system. These needs are not purely ecological, but may incorporate aspects of navigation, amenity and dilution of wastewater effluent. The key requirement of effective management in these systems is to understand the timing, location and magnitude of impacts on the surface water system due to groundwater abstraction. These impacts can be considered by three assessment methodologies: resource assessment, direct impact assessment and indirect impact assessment.

Resource assessment is essentially a water balance approach, normally undertaken on an annual timescale. This type of assessment takes no account of timing or location of any impact, and makes no distinction between a seasonal and continuous abstraction. Notwithstanding possible concerns over the accuracy of the recharge input (highlighted with regard to MORECS EP data in this study), this type of assessment is technically straightforward and robust, and has been the foundation for water resource management for decades.

Direct impact assessment involves defining the timing, location and magnitude of the impact associated with groundwater abstraction in situations when the cone of depression (caused by pumping) intersects the river channel, which then functions as a recharge boundary, preventing any additional expansion of the cone in that direction, unless flow in the channel ceases. This type of assessment is normally restricted to abstraction sites located within 500m of a watercourse. Provided representative parameters are available for the area, this type of impact can be assessed using an analytical method, for example Jenkins (1970) (although this explicitly excludes the influence of recharge), or a more advanced technique such as IGARF II (Impact of Groundwater Abstraction on River Flows II; Parkin *et al.*, 2002) which combines analytical and numerical methodologies via an artificial neural network, using a database of generic scenarios to select an appropriate simulation of the input parameters.

This study has highlighted a potential flaw in direct impact assessment methods by recognising the significance of point source inflows to a watercourse, such as the seasonal source of the River Lambourn at Lynch Wood springs. Unless the spatial

pattern of accretion in the watercourse has been well defined, there will be little or no recognition of the potential for the impact of the groundwater abstraction to extend up to 10km downstream (the length of the seasonal channel) where flows may be principally supported by the headwater springs. Even small changes in groundwater levels at such headwater locations could reduce groundwater discharges sufficiently to increase significantly the period each year when flows are absent from the seasonal channel, and in a worst case could cause complete cessation of flow in the seasonal section of channel. Such changes in flow regime would have a profound impact on the ecology of the seasonal channel.

Indirect impact assessment is relevant for situations where the abstraction is located a significant distance from the watercourse and the cone of depression does not expand to intersect the river channel. Defining the impact in terms of timing, location and magnitude in this scenario is problematic, particularly for seasonal abstractions. Essentially the impact is related to a capture of river baseflow, with the timing of the impact upon river flow being related to the bulk groundwater flow velocity in the aquifer (the rate of baseflow migration).

Having investigated time lags in the recharge - storage - discharge sequence, this study provides an alternative means of characterising the bulk flow velocity and can thus assist in defining the timing of diffuse impacts. For example, in the Lambourn catchment, given the calculated bulk hydraulic conductivity of 114m/d, a bulk storage value of 1% and a representative mean catchment scale hydraulic gradient of 0.0036 (calculated from Table 4.7), the bulk flow velocity is in the order of 41m/d (c. 24 days per km). Considering a theoretical summer abstraction (April to September) located in the Lambourn catchment 3km upgradient from the river channel, the timing of the impact will be lagged by c. 2.5 months, such that its first manifestation will occur in mid June and will extend through to mid December. This impacted period includes the months of August / September / October, which are the most vulnerable months of the year from a low flow perspective, and as such this abstraction is likely to be detrimental to the low flow situation. Alternatively, this method could be used to define a minimum separation from channel (measured along regional flow lines) for the location of summer abstractions such that their impacts would not occur during the most vulnerable period of the river hydrograph. With the parameters given above, this separation would

be around 9km, such that impact from the start of abstraction in April would not be manifested until the beginning of November, at which point the river flow would be rising due to the onset of recharge.

The location of impact will be dependent upon the morphology of the aquifer permeability, but can be approximated by considering catchment scale groundwater flow paths. Unlike direct impacts, indirect impacts are unlikely to occur on the section of channel closest to the point of abstraction, as the impacted groundwater flow path will intersect the channel some distance downstream.

In conclusion, this study has described an alternative means of assessing indirect impacts of groundwater abstraction upon river flows, and in particular has highlighted the need to consider the flow accretion profile when assessing direct impacts, as these may extend far beyond the immediate zone of impact upon the channel. These insights may assist in the management of water resources in permeable catchments, but this study has identified a number of areas where additional research is required, and these are described below.

8.3 FUTURE RESEARCH

Future research needs identified in this study are described below in three categories; river – aquifer exchange processes, permeable catchment resource management and chalk aquifer permeability conceptualisation.

1 **River – aquifer exchange processes - research needs:**

- To develop robust methodologies for identifying locations of major point discharges, as these have important roles as key suppliers of stream discharge, perhaps over considerable lengths of river, and also potential major locations of point source contaminant inputs to streams.

- To undertake detailed field studies to identify the dominant controls on accretion, including packer testing of shallow chalk permeability, geophysical / physical characterisation of floodplain materials, vertical and lateral head gradient definition on valley floor and valley slopes and assessment of bed sediment permeability.

2 Permeable catchment resource management – research needs:

- To produce a generic description for the optimum number and location of groundwater level points that allow a representative catchment MGS to be calculated, accounting for catchment morphology and spatial permeability distribution. This would then allow simple estimation of baseline (natural) flow regimes for catchments with no unimpacted gauging data. Due to its simplicity, this technique could then be applied as a scoping tool to a large number of catchments to allow a ranking of impact severity to be drawn up, as a basis for identifying catchments for more detailed investigation and remediation.

- To produce a definitive recharge calculation methodology for use across England and Wales to standardise catchment water resource assessment. This methodology should be exposed to vigorous retrospective verification using independent discharge data from a number of representative catchments having long duration, reliable records and providing national coverage.

3 Chalk aquifer permeability conceptualisation - research needs:

- To develop methods of tracing recharge from infiltration at the ground surface through to discharge into the river, involving movements on a spatial scale of 1 to 10km and a temporal scale of 3 to 12 months, to allow quantitative characterisation of bulk flow processes.

- To undertake detailed geophysical and CCTV surveys of the shallow chalk in valley floor locations, which may require the use of innovative screen material or drilling techniques to prevent collapse. Such investigations are rarely undertaken due to the installation of solid casing at shallow depths for borehole stability, but in so doing the most active and transmissive section of the aquifer is concealed from investigation.

- To better understand the presence and distribution of sub-vertical features and their significance in controlling interfluve permeability and lateral migration in the unsaturated zone, which has significance for recharge estimation, determination of unsaturated zone storage and contaminant migration.

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APPENDIX 1

Glossary of technical terms

Aquifer	A saturated permeable geologic unit that can transmit significant quantities of water under ordinary hydraulic gradients (Freeze & Cherry, 1979: p. 47)
Benthic	Describes bottom dwelling fauna and flora (Whittow, 1984)
Confined aquifer	An aquifer that is confined between two low permeability formations, above and below (Freeze & Cherry, 1979: p. 48)
Cretaceous	A geological time period extending from about 135 million to 65 million years before present (Whittow, 1984)
Darcy's Law	The fundamental groundwater flow law described by Henri Darcy in 1856. [For full explanation see Equation 6.1 p. 164]
Dupuit – Forchheimer	A theoretical approach to characterise groundwater flow in an unconfined system bounded by a free surface. It is based on two assumptions: (1) flowlines are assumed to be horizontal and equipotentials vertical; (2) the hydraulic gradient is assumed to be equal to the slope of the free surface and to be invariant with depth. It is, in effect, an empirical approximation to the actual flow field that neglects the vertical flow components. (Freeze & Cherry, 1979: p. 188)
Effective precipitation	In hydrology, that part of the precipitation that enters a stream channel (Whittow, 1984)
Electrical conductivity	The ability of a substance to conduct an electrical current. For groundwater samples it can be used to estimate total dissolved solids (TDS) in mg/l using: TDS = *A* C where 'C' is electrical conductivity in microsiemens and '*A*' is between 0.55 and 0.75. (Freeze & Cherry, 1979: p. 139,140)
Groundwater	Subsurface water that occurs beneath the water table in soils and geological formations that are fully saturated (Freeze & Cherry, 1979: p. 2)
Holocene	The most recent period of geological time, extending from around 10 000 years to the present (Whittow, 1984)
Hydraulic conductivity	The constant of proportionality (K) in *Darcy's Law,* with units length/time, which is a function of both the porous medium and the fluid. It represents the flow velocity under unitary hydraulic gradient.

Hydraulic gradient (i)	Change in hydraulic head (fluid level) per unit change in distance in the direction of fluid movement (dimensionless) (Freeze & Cherry, 1979: p. 16)
Macroinvertebrate	A member of the group of animals without a backbone composed of vertebrae, which can be distinguished without the aid of a microscope (Whittow, 1984)
Lateglacial	An alternative name for the final phases of the last glacial stage in Britain and NW Europe lasting from about 14 000 to 10 300 years before present (Whittow, 1984)
Lotic (environment)	Referring to the ecology of running waters (Whittow, 1984)
Permeability	Used informally in this study as analogous to *Hydraulic conductivity*, as the fluid present is always groundwater at normal temperatures and salinities, with negligible variability in viscosity. Formally, intrinsic or specific permeability (k) is a function only of the porous medium and is used when fluids exhibiting widely varying viscosities are present (e.g. in oil fields) and thus a parameter to describe the medium, irrespective of the fluid, is attractive. (Freeze & Cherry, 1979: p. 27, 28)
Piezometric surface	Analogous to potentiometric surface: the level to which water in a well will rise in a *confined aquifer*; located above the top of the aquifer formation. (Freeze & Cherry, 1979: p. 48, 49)
Pleistocene	The first epoch of the *Quaternary*, extending from 1.8 million to 10 000 years before present (Whittow, 1984)
Quaternary	A period of geological time extending from around 1.8 million years ago to the present, comprising two epochs; the *Pleistocene* and the *Holocene* (Whittow, 1984)
Specific yield (Sy)	In an *unconfined aquifer*, the volume of water released from storage per unit surface area of aquifer per unit decline in water table. The value represents the actual dewatering of pores in the porous medium and is much higher than the equivalent *storativity* or storage coefficient from a *confined aquifer*. (Freeze & Cherry, 1979: p. 61)
Storativity (S)	Analogous to storage coefficient: the volume of water released from a *confined aquifer* per unit decline in potentiometric (*piezometric*) surface. Values are much lower than the equivalent *specific yield* from an *unconfined aquifer* as no dewatering occurs; water is released from saturated storage via two mechanisms: (1) compaction of the aquifer material; (2) expansion of the stored water. (Freeze & Cherry, 1979: p. 59, 60)

Taxon (pl. taxa)	A named group or systematic unit of organisms of unspecified rank (Whittow, 1984)
Transmissivity (T)	For an unconfined aquifer of saturated thickness 'b'; transmissivity T = Kb in units of length^2/time, where K = *Hydraulic conductivity* (Freeze & Cherry, 1979: p. 61)
Unconfined aquifer	An aquifer in which the water table forms the upper boundary (Freeze & Cherry, 1979: p. 48)

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APPENDIX 2

National River Flow Archive summary sheets for gauging stations in the Lambourn catchment:

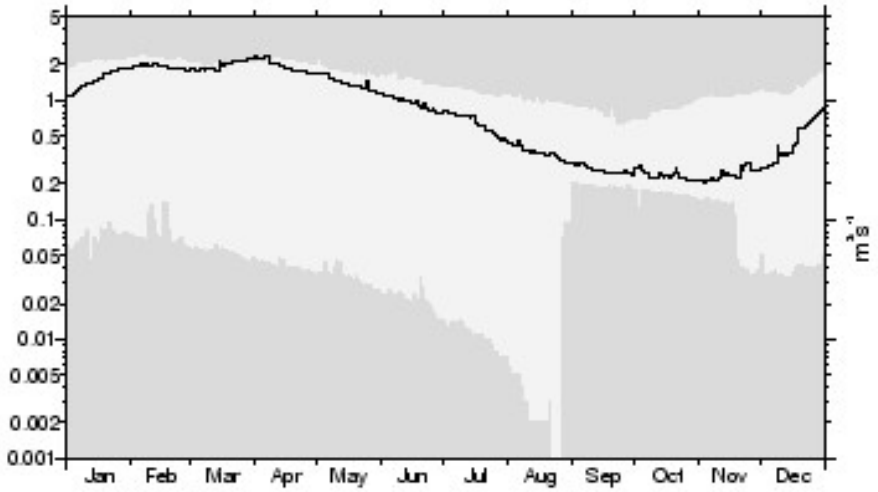
- Lambourn at East Shefford
- Lambourn at Welford
- Lambourn at Shaw
- Winterbourne Stream at Bagnor

39032 - Lambourn at East Shefford

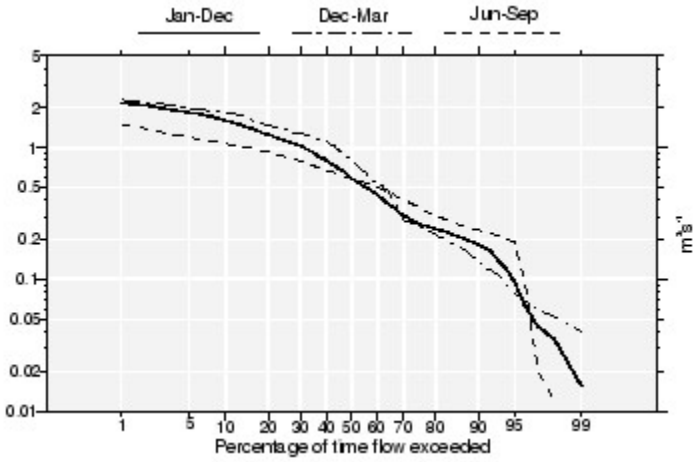
Grid Reference:	41 (SU) 390 745
Operator:	EA
Local number:	2253
Catchment Area:	154.0 km^2
Level of Station:	101.9 mOD
Max. Altitude:	261.0 mOD
Mean flow:	0.76 m^3s^{-1}
95% exceedance (Q95):	0.113 m^3s^{-1}
10% exceedance (Q10):	1.57 m^3s^{-1}
61-90 Av. Ann. Rainfall:	746 mm

SAMPLE HYDROGRAPH OF GAUGED DAILY FLOWS

Max. and min. daily mean flows from 1966 to 1983 excluding those for the featured year (1982; mean flow: 0.99 m^3s^{-1})



FLOW DURATION CURVE FOR GAUGED DAILY FLOWS

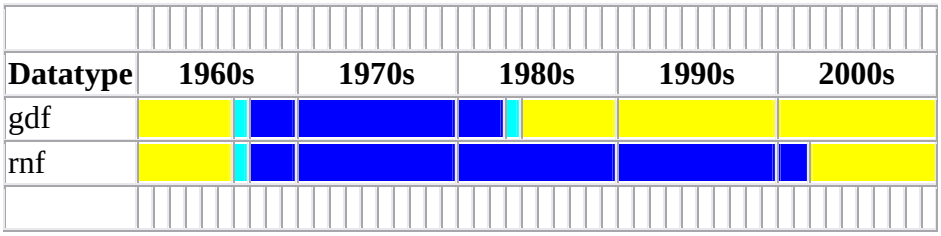


FACTORS AFFECTING RUNOFF

- Runoff influenced by groundwater abstraction/recharge.

RIVER FLOW AND CATCHMENT RAINFALL ON THE NATIONAL RIVER FLOW ARCHIVE

Gauged Daily Flows (gdf): 1966 to 1983
Monthly Catchment Rainfall (rnf): 1966 to 2001



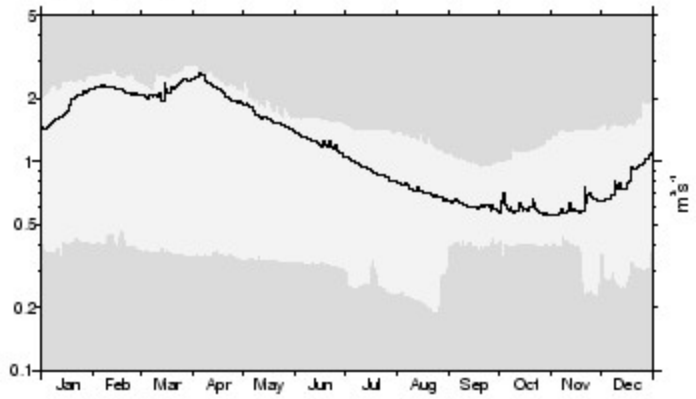
For many stations monthly peak flows are also archived. When daily flow data are not available monthly mean flows may be held on the National River Flow Archive.

39031 - Lambourn at Welford

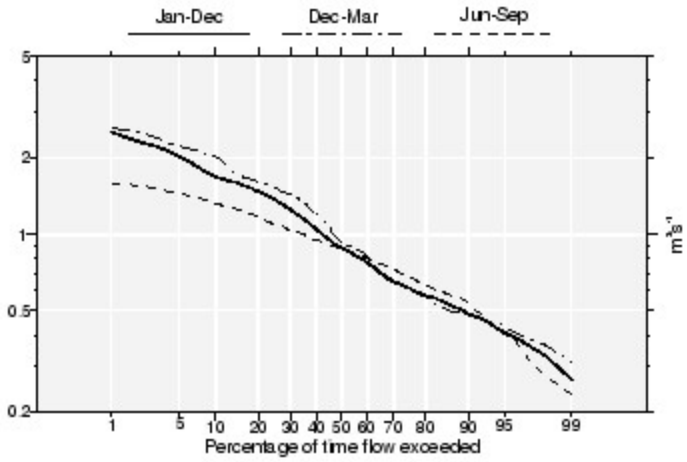
Grid Reference:	41 (SU) 411 731
Operator:	EA
Local number:	2255
Catchment Area:	176.0 km^2
Level of Station:	95.7 mOD
Max. Altitude:	261.0 mOD
Mean flow:	1.02 m^3s^{-1}
95% exceedance (Q95):	0.414 m^3s^{-1}
10% exceedance (Q10):	1.67 m^3s^{-1}
61-90 Av. Ann. Rainfall:	745 mm

SAMPLE HYDROGRAPH OF GAUGED DAILY FLOWS

Max. and min. daily mean flows from 1962 to 1983 excluding those for the featured year (1982; mean flow: 1.29 m^3s^{-1})



FLOW DURATION CURVE FOR GAUGED DAILY FLOWS

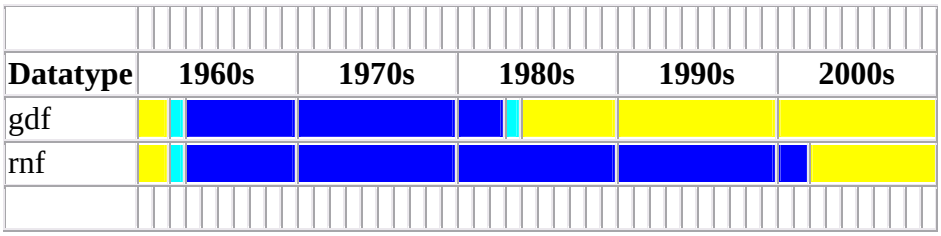


FACTORS AFFECTING RUNOFF

- Runoff influenced by groundwater abstraction/recharge.

RIVER FLOW AND CATCHMENT RAINFALL ON THE NATIONAL RIVER FLOW ARCHIVE

Gauged Daily Flows (gdf): 1962 to 1983
Monthly Catchment Rainfall (rnf): 1962 to 2001



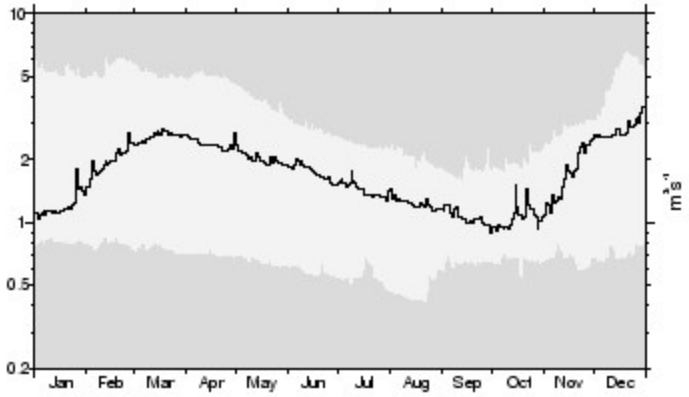
For many stations monthly peak flows are also archived. When daily flow data are not available monthly mean flows may be held on the National River Flow Archive.

39019 - Lambourn at Shaw

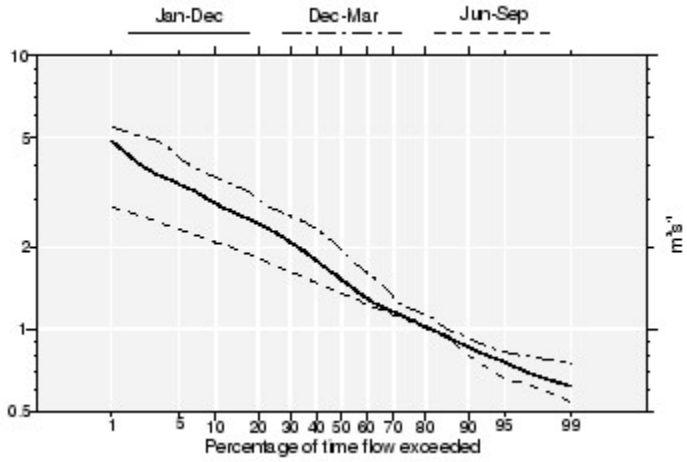
Grid Reference:	41 (SU) 470 682
Operator:	EA
Local number:	2269
Catchment Area:	234.1 km^2
Level of Station:	75.6 mOD
Max. Altitude:	261.0 mOD
Mean flow:	1.76 m^3s^{-1}
95% exceedance (Q95):	0.762 m^3s^{-1}
10% exceedance (Q10):	2.92 m^3s^{-1}
61-90 Av. Ann. Rainfall:	736 mm

SAMPLE HYDROGRAPH OF GAUGED DAILY FLOWS

Max. and min. daily mean flows from 1962 to 2003 excluding those for the featured year (2002; mean flow: 1.77 m^3s^{-1})



FLOW DURATION CURVE FOR GAUGED DAILY FLOWS



STATION DESCRIPTION

Crump weir (10.67m broad) with auxiliary d/s recorder. Possibility of a small overspill in high floods when storage may be provided by Donnington Lake. PWS abstraction in headwaters and d/s sluices (occasionally) influence flows, but net artificial disturbance to the regime is limited (apart from periods during which the West Berks Groundwater Scheme is operating - providing low flow support). Flow pattern is baseflow dominated.

CATCHMENT DESCRIPTION

Local suburban growth near station but primarily a rural catchment developed on the Berkshire Downs (Chalk).

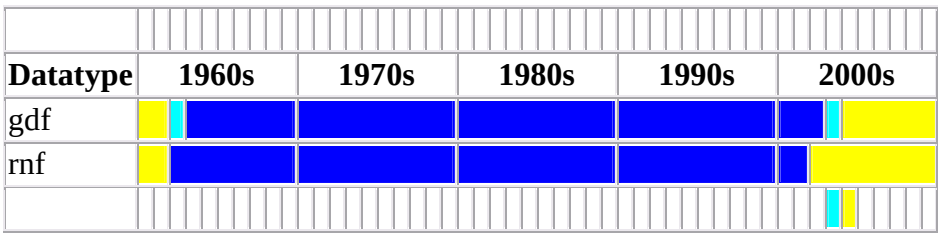
FACTORS AFFECTING RUNOFF

- Regulation from surface water and/or ground water.
- Runoff influenced by groundwater abstraction/recharge.

RIVER FLOW AND CATCHMENT RAINFALL ON THE NATIONAL RIVER FLOW ARCHIVE

Gauged Daily Flows (gdf): 1962 to 2003

Monthly Catchment Rainfall (rnf): 1962 to 2001



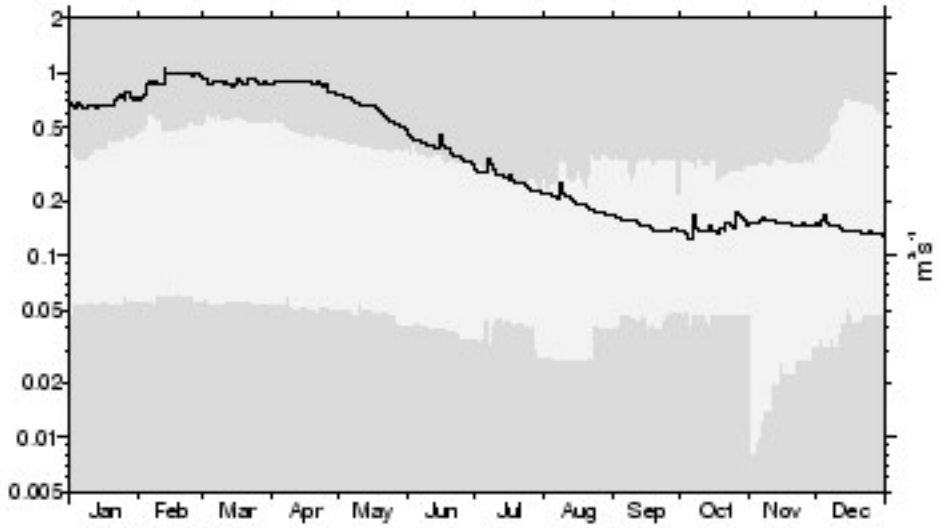
For many stations monthly peak flows are also archived. When daily flow data are not available monthly mean flows may be held on the National River Flow Archive.

39033 - Winterbourne St at Bagnor

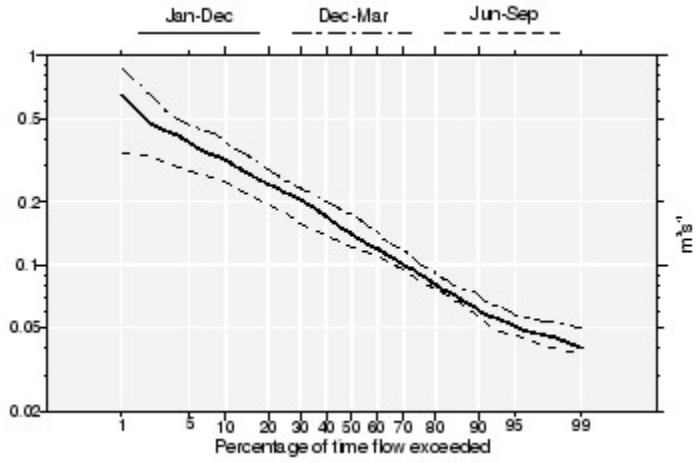
Grid Reference:	41 (SU) 453 694
Operator:	EA
Local number:	2264
Catchment Area:	49.2 km^2
Level of Station:	80.5 mOD
Max. Altitude:	230.0 mOD
Mean flow:	0.17 m^3s^{-1}
95% exceedance (Q95):	0.051 m^3s^{-1}
10% exceedance (Q10):	0.317 m^3s^{-1}
61-90 Av. Ann. Rainfall:	716 mm

SAMPLE HYDROGRAPH OF GAUGED DAILY FLOWS

Max. and min. daily mean flows from 1962 to 2001 excluding those for the featured year (2001; mean flow: 0.45 m^3s^{-1})



FLOW DURATION CURVE FOR GAUGED DAILY FLOWS



STATION DESCRIPTION

Crump weir, 3m broad - originally 5.5m but reduced to improve sensitivity (in 1968). Full range. Runoff reduced by gw abstractions; for limited periods flows also substantially influenced by pumping and flow augmentation, associated with the West Berks Groundwater Scheme (e.g. winter 1969/70, 1976, 1989 and 1998).

CATCHMENT DESCRIPTION

A Chalk catchment; very rural character.

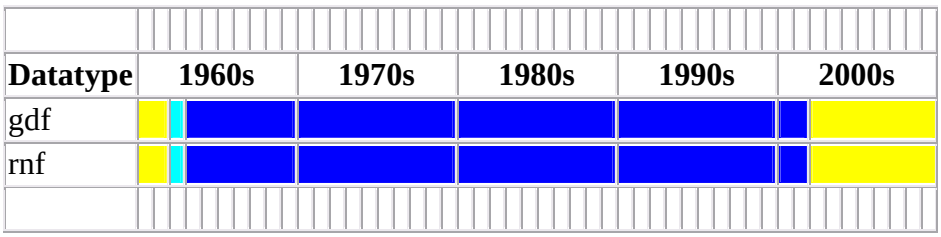
FACTORS AFFECTING RUNOFF

- Regulation from surface water and/or ground water.
- Runoff influenced by groundwater abstraction/recharge.

RIVER FLOW AND CATCHMENT RAINFALL ON THE NATIONAL RIVER FLOW ARCHIVE

Gauged Daily Flows (gdf): 1962 to 2001

Monthly Catchment Rainfall (rnf): 1962 to 2001



For many stations monthly peak flows are also archived. When daily flow data are not available monthly mean flows may be held on the National River Flow Archive.

APPENDIX 3

A review of historic groundwater investigations in the Lambourn catchment

The foundation for investigation of the Lambourn catchment was laid in 1956 when Thames Conservancy (now the Environment Agency, Thames Region) and the Metropolitan Water Board (now part of Thames Water Utilities Limited) jointly commissioned a study to "*investigate the feasibility of utilising groundwater resources for stream flow augmentation, and the extent to which resources in the Catchment of the River Kennet might be developed for this purpose*" (Brettell, 1971).

Following favourable conclusions from this preliminary study, a second study was commissioned to assess the potential groundwater resources of the Chalk and Limestone aquifers throughout the Thames basin (Brettell, 1971). This study aimed to investigate the use of groundwater pumped from under-exploited aquifers to supply London during drought. The plans anticipated that the Thames and its tributaries could be used as natural 'pipelines' to convey the water to the city. Following publication of the second study in 1964, Thames Conservancy devised plans "*to develop groundwater resources in the Oolitic Limestone of the Northern Cotswolds, and in the Chalk of the Wiltshire and Berkshire Downs and the Western Chilterns*". However, given the magnitude and experimental character of the proposed scheme, it was decided to first undertake a pilot study (subsequently known as the Lambourn Valley Pilot Scheme: LVPS) to assess its feasibility (Brettell, 1971).

In 1961, Thames Conservancy started a programme of installing surface-water gauging stations in the catchment (Hardcastle, 1978). Stations were completed at Shaw, Welford and Bagnor on the Lambourn in late-1962 and an additional station at East Shefford was completed in mid-1966 (Figure 1).

Work on the LVPS commenced in February 1967 with the drilling of nine abstraction boreholes and ten adjacent observation boreholes. Each abstraction borehole was individually test pumped with the work completed by February 1968. Further test pumping of the boreholes was undertaken later in 1968 and in 1969, at which time current meter flow measurements were taken at fixed locations along the river (Figure 1). These measurements, together with the records of discharge from the gauging

station, enabled the net gain (i.e. the net augmentation flow) to be calculated under different conditions.

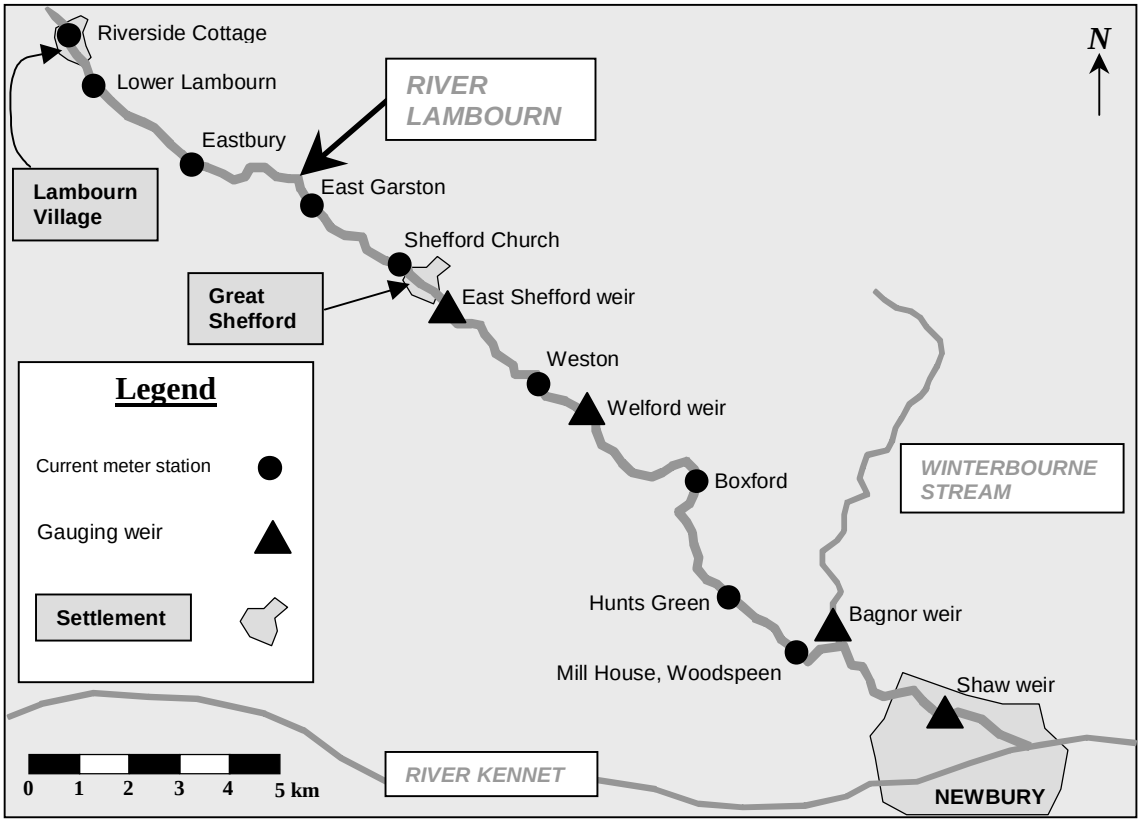


Figure 1 Locations of selected current meter stations and gauging stations used during the Lambourn Valley Pilot Scheme

On conclusion of the pilot scheme, work then began to implement the Thames Groundwater Scheme. The Scheme was approved at a public enquiry in 1972, and was authorised in March 1973. This immediately led, later in 1973 and 1974, to the drilling of 34 abstraction boreholes, 15 of which were in the Lambourn catchment (Hardcastle, 1978). Test pumping of boreholes, both individually and in groups, was completed in 1975 and early 1976.

In August 1976, the scheme was brought into emergency operation to provide river augmentation due to the exceptionally low recharge of the preceding winter. It was pumped for three months and provided nearly 7 x 10^6 m^3 of water for flow augmentation (Hardcastle, 1978), at an average rate of 0.85 cumecs, representing around 50% of the average discharge in the River Lambourn.

APPENDIX 4

Details of sewage treatment works discharges in the Lambourn catchment

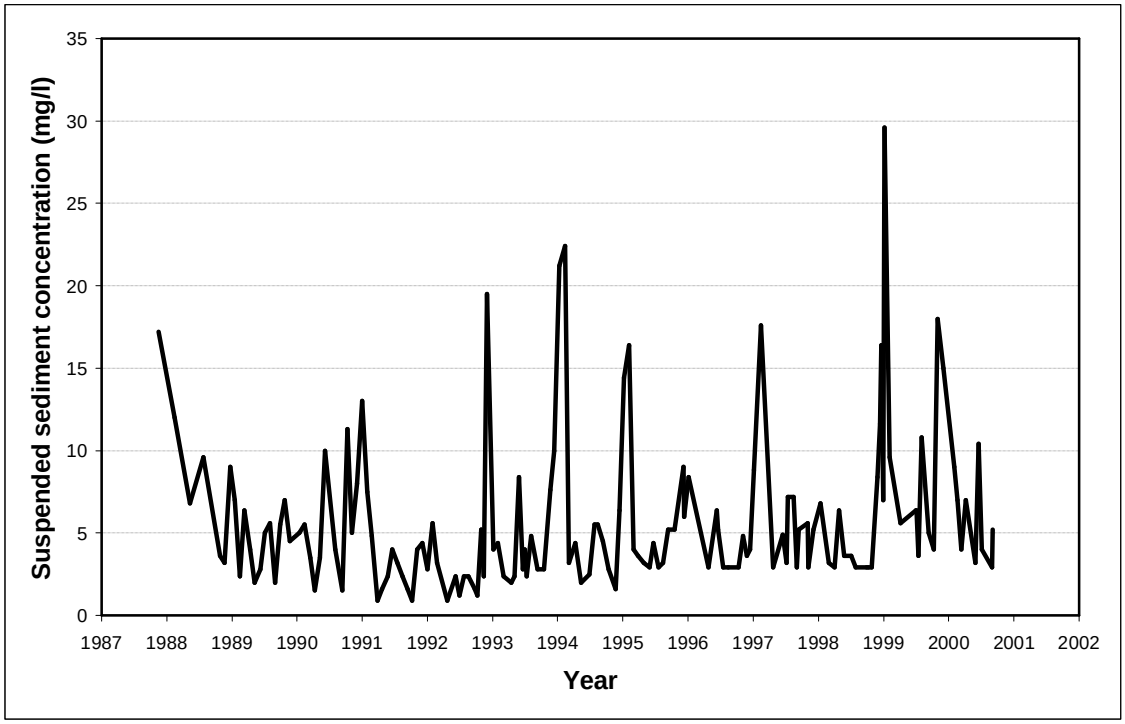
Name of STW	**Location (NGR) SU…**	**Receiving watercourse**	**Mean STW discharge 1998 (cumecs)**	**Mean STW discharge as percentage of mean receiving water discharge**
East Shefford	3935 7450	River Lambourn	0.0151*	0.89%
Boxford	4298 7195	River Lambourn	0.0008	0.05%
Winterbourne	4550 7210	Winterbourne Stream	0.0005	0.33%
Chieveley	4683 7390	Winterbourne Stream	0.0097	6.06%
Combined	N/a	River Lambourn	0.0261	1.54%

*Figure for 1997

The average combined STW discharge represents less than 2% of the mean flow of the River Lambourn. However, because of the river's status as a Site of Special Scientific Interest (SSSI), effluent discharges have been recognised as a potential water quality threat. A target level for phosphorus of 2mg/l has been set and compliance will be achieved by 31 March 2004 at the latest (House of Commons Environmental Audit – Seventh Report – Annex 2, 2000).

APPENDIX 5

Details of suspended sediment levels in the Lambourn catchment



Suspended sediment concentrations at East Shefford; based upon monthly sampling undertaken by the Environment Agency over the period November 1987 to September 2000.

APPENDIX 6

Tracer testing details

Comprising:

- Proforma notification to the EA (16 September 2000)
- Location maps accompanying Proforma
- Proforma Supplementary Information
- Additional information provided to the EA (27 October 2000), including gradient analysis figure
- Additional information provided to the EA (10 November 2000)
- Brief report on the results of the test, submitted to the EA on 14 March 2002

APPENDIX 6 (cont.)

PROFORMA FOR NOTIFYING THE ENVIRONMENT AGENCY OF INTENT TO UNDERTAKE A GROUNDWATER TRACER TEST

To: **TIM JOHNS, SCIENTIFIC SUPPORT TEAM LEADER, EA WALLINGFORD**
Date: 16 September 2000
Re: Tracer test at Great Shefford, Berkshire
[NB locality numbers in the text refer to the map on page 4]

1. I, the undersigned, propose to undertake a tracer test for the purpose of verifying the occurrence and location of discharges from the Chalk aquifer into the River Lambourn during the period of October and November 2000 (exact dates to be verified). I am fully aware of the recommendations contained in the EA R&D Technical Report W160 – *Groundwater Tracer Tests: a review and guidelines for their use in British aquifers* (Ward et al., 1998). I will maintain a complete record of testing and provide a summary report to the Environment agency within three months of completion of testing.

2. The testing will begin on or around the 25th October 2000 and finish on or around the 25th November 2000 (exact dates will be verified in writing at least two weeks prior to commencement).

3. The tracer to be used is Photine CU (an optical brightener). The mass of tracer to be used is 2kg, in the form of 10 litres of 20% solution, as supplied by the manufacturer.

4. The test will involve injection of tracer at EA observation borehole SU 37/63 (SU 3920 7658) [locality (1)] and monitoring via passive detectors at the following points:

   - At least 3 locations along the ephemeral stream flowing from its source near SU 3875 7553 [locality (2)] to its confluence with the River Lambourn at SU 3848 7513 [locality (3)];

   - At least 8 locations on the River Lambourn between SU 3811 7548 [locality (4)] and SU 3890 7473 [locality (5)].

5. The nearest public water supply wells (in the River Lambourn groundwater catchment) are at Fognam Down (SU 296 802) and Ashdown Park (SU 288 811) [see page 3] which are located 10.2km and 11.3km respectively from the injection point. The nearest groundwater discharge points are likely to be the ephemeral stream and/or the section of the River Lambourn detailed in Section 4 above. The purpose of the test is to identify where the discharges to the river occur.

Using the equation suggested by Ward et al. (1998) (Chapter 5 and Appendix A), based on Fickian one-dimensional dispersion, the tracer injection will result in the estimated maximum tracer concentrations, shown below, at each of the identified discharge points.

APPENDIX 6 (cont.)

Tracer	Discharge Point	Distance from injection point (m)	Maximum concentration (µg/l)	Duration (days) [x]
Photine CU	Ephemeral stream at around SU 3875 7553 [locality (2)]	1130	390*	2.9
Photine CU	River Lambourn at around SU 3845 7528 [locality (6)]	1480	150**	0.8

* assuming the entire flow of the stream of 20l/s consists solely of discharged groundwater containing tracer

** assuming the discharge to the river of groundwater containing tracer is 100l/s (0.1 cumecs) and that the receiving flow of the river is also 100l/s (i.e. there is 50% dilution on discharge to the river)

[x] these values are mutually exclusive, both assuming that the total mass of tracer is discharged via this route

6. The maximum concentrations, specified above will not have a significant environmental impact at the identified discharge points of the aquifer. Should the maximum concentrations be significantly higher than anticipated any impacts will be small and very localised, as the diluting influence of the river will rapidly reduce concentrations. Also the high photochemical instability of the tracer will cause it to be rapidly broken down once it is discharged from the subsurface and exposed to light.

7. The nominated responsible person is:

TIM GRAPES
CENTRE FOR ENVIRONMENTAL RESEARCH AND TRAINING
SCHOOL OF GEOGRAPHY AND ENVIRONMENTAL SCIENCES
UNIVERSITY OF BIRMINGHAM
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TEL: 0121 693 2888
FAX: 0121 693 2889

E-MAIL: T.R.GRAPES@BHAM.AC.UK

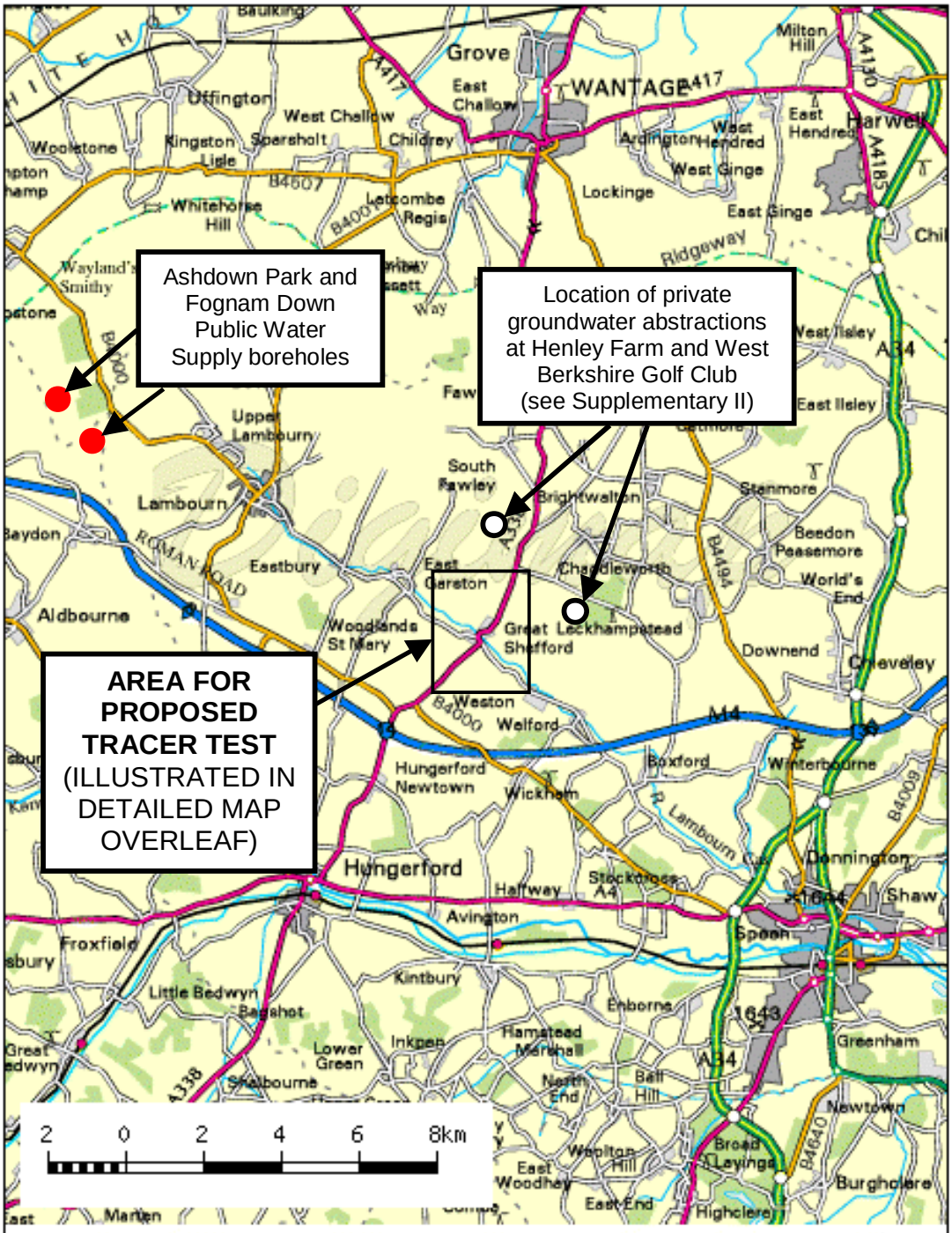
Yours sincerely

T R Grapes BSc (Hons) MSc FGS

(School of Geography and Environmental Sciences, University of Birmingham)

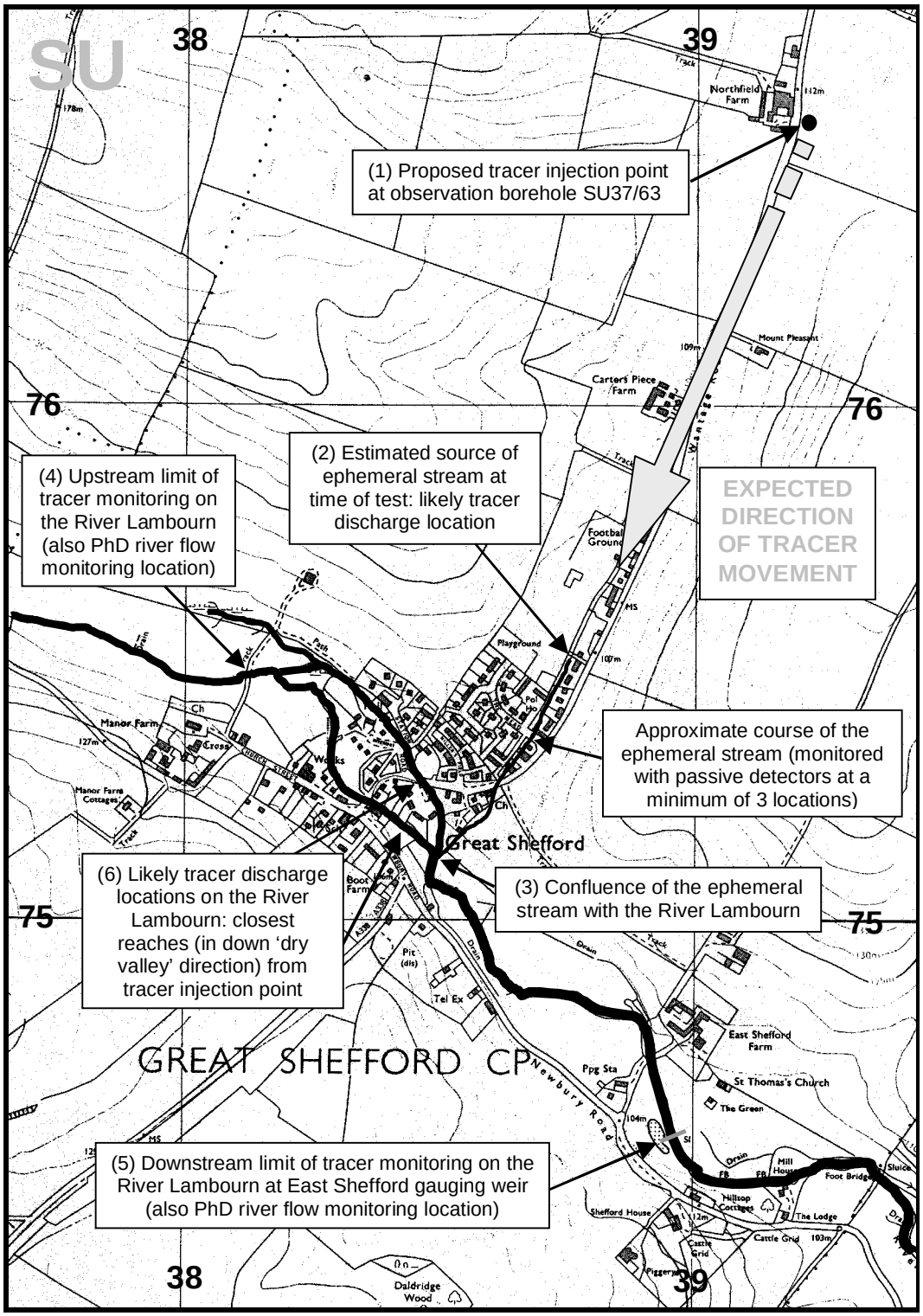
APPENDIX 6 (cont.)

REGIONAL LOCATION OF PROPOSED TRACER TEST



APPENDIX 6 (cont.)

A DETAILED MAP OF THE PROPOSED TRACER TEST AREA TO ILLUSTRATE LOCALITIES MENTIONED IN THE TEXT



Grid axes are in 1km increments based upon OS Landranger co-ordinates for square SU

APPENDIX 6 (cont.)

PROFORMA SUPPLEMENTARY INFORMATION

BACKGROUND

This tracer test forms part of a PhD being undertaken to study river–aquifer interaction in the catchment of the River Lambourn. The test will supplement records of river flow and water chemistry that have been continuously recorded at a site near Shefford church (SU 3811 7548) [locality(4)] and at East Shefford gauging weir (SU 3897 7458) [locality(5)] since June 1999.

JUSTIFICATION FOR USING THE PROPOSED MASS OF TRACER

The most difficult aspect of planning a tracer test is estimating the amount of tracer to use. If too little tracer is injected then its presence will never be recorded and the test will be a failure, as a null return cannot be considered firm evidence of there being no connection. Therefore, in order for the test to be successful, the tracer must be detected during monitoring. However, there are obvious water quality considerations that must limit the mass of tracer used, most important being the toxicological effects on aquatic organisms and humans.

In the following sections the rationale for the proposed mass of tracer is described and then the possible impacts are investigated. The proposed mass is then compared to other similar tests that have been undertaken to provide a context for comparison.

MINIMUM REQUIREMENTS FOR TRACER DETECTION

As stated above sufficient tracer must be injected such that it can be detected at the discharge locations. This is based upon firstly detecting the tracer and secondly differentiating the tracer from naturally occurring material which might mask it. Theoretically, Photine can be detected at levels as low as 0.36µg/l (Smart and Laidlaw, 1977; Table 3) but this is dependent upon levels of naturally occurring fluorescence due to dissolved and colloidal organic material. As the River Lambourn drains an agricultural catchment and has abundant riparian vegetation it may contain a significant portion of dissolved organic material. The possible fluorescence of this material is equivalent to an average Photine concentration of 36µg/l, estimated from a low flow situation in a Cotswolds stream draining an agricultural catchment (Smart and Laidlaw, 1977; Table 6). In order for the injected tracer to be detected its concentration in the river should be at least double the background fluorescence, i.e. at least 72µg/l.

APPENDIX 6 (cont.)

A worst-case scenario for success of the tracer test would combine a small groundwater discharge to the river with a greater than predicted river flow resulting in very low tracer concentrations that could not be detected. An estimate for this scenario would be a groundwater discharge of 50l/s into a receiving river flow of 150l/s (i.e. the tracer being diluted to 25% of groundwater concentration once discharged). In order for the river concentration to be at least 72µg/l the discharging groundwater must have a concentration of at least 288µg/l. Using the equation for Fickian one-dimensional dispersion (Ward et al.,1998) and an injection mass of 2kg, a groundwater discharge concentration into the river of 300µg/l is calculated. This matches the required discharge concentration above of 288µg/l and so 2kg of tracer appears to be suitable, providing that the average background fluorescence is no higher than 36µg/l.

EFFECTS OF PHOTOCHEMICAL DECAY

Photine CU has low photochemical stability and decays rapidly when exposed to light. Indeed '*the very fast decay of photine CU under all light conditions precludes its use a quantitative water tracer*' (Smart and Laidlaw, 1977). However, for the **qualitative** purpose of the proposed tracer test the photochemical stability of Photine CU is an advantage as once it is discharged from the subsurface into the river it will rapidly decay and become completely harmless, thus minimising any environmental impact.

The rate of photochemical decay can be approximated using the following equation:

$$F = F_I \, e^{-kt}$$ (Smart and Laidlaw, 1977)

Where: F = fluorescence (concentration) at time *t*

F_I = initial fluorescence (concentration)

k = decay coefficient

For Photine CU the decay coefficient is > 0.64/day assuming 'environmental' conditions (i.e. 12 hours of light / 12 hours of darkness).

Using this coefficient in the equation above the decay of the tracer in the ephemeral stream and the river can be calculated. The ephemeral stream at this time of year has a length from source to confluence with the River Lambourn of about 500m. Assuming the average flow velocity is 0.1m/s the average resident time of the tracer in the stream will be 1.4 hours before it is discharged into the main river at which point significant dilution will take place. In this scenario

photochemical decay has little influence. However, for any tracer in the ephemeral stream that is retained in dead flow zones photochemical decay may be significant. Decay will be rapid with the original peak concentration of 390µg/l falling to below estimated background levels of fluorescence after 4 days. In the main river decay will cause the peak concentration to fall below estimated background levels within 3 days. This illustrates the short-lived influence that the tracer has once it has been discharged into surface waters.

TOXICOLOGICAL IMPACTS: HUMAN

Based on a long-term dietary study dose, with significant factors of safety, Aldous et al. (1987) suggest a maximum peak concentration of 30µg/l for Photine in drinking water. The estimated maximum concentrations for the proposed test exceed this figure but neither the ephemeral stream nor the River Lambourn are used directly for Public Water Supply (PWS). The nearest PWS boreholes (described in Section 5) are more than 10km away. There are two local private groundwater abstractions: Henley Farm, SU 396 780, Licence No. 28/39/22/0105; and West Berkshire Golf Club, SU 410 760, Licence No. 28/39/22/0539 (see page 3). The first abstraction is for agricultural purposes and is located 1.2km upgradient from the injection point whilst the second is for non-agricultural spray irrigation and is located 1.8km down the regional hydraulic gradient (but perpendicular to the local gradient). It is possible that a small amount of tracer may reach the golf club borehole but considering their usage of the water this should cause no problems. Overall it is highly unlikely that the test will have any impact upon human health.

TOXICOLOGICAL IMPACTS: FISH

In the U.S.A. Sturm and Williams (1975) investigated the effects of acute toxicity and accumulation of fluorescent whitening agents on two species of freshwater fish; bluegill (*Leoponis macrochirus*) and channel catfish (*Ictalarus punctatus*). Fluorescent whitening agents (FWAs) are an alternative name for optical brighteners and two of the FWAs studied (FWA-3-A and FWA-4-A) are very similar to Photine CU in chemical structure. It was found that the acute toxicity for both FWA-3-A and –4-A was in the range 21–43 mg/l (21000–43000 µg/l). In separate research it was found that goldfish (*Carassius auratus*) suffered no ill effects from exposure to optical brighteners at concentrations up to 20mg/l (Akamatsu and Matsuo, 1973; quoted in Smart and Laidlaw, 1977). These concentrations are around two orders of magnitude (100 x) greater than the maximum concentration estimated for the proposed test.

APPENDIX 6 (cont.)

Sturm and Williams (1975) also investigated the potential accumulative effects of FWAs. It was found that bluegills and catfish exposed to FWA-3-A and –4-A at concentrations of 50µg/l did not accumulate to levels > 10µg/kg (the detection limit). Bluegills and catfish exposed to other FWAs at a concentration of 50µg/l did accumulate, to an average level of 2000µg/kg. However, once returned to water with only background levels of FWA the fish's body levels returned to background concentrations within 14 days and they displayed no long-term effects on their health.

From this evidence it appears that the proposed mass of tracer is unlikely to cause detrimental impacts upon fish populations.

COMPARISON WITH TRACER QUANTITIES USED IN OTHER TESTS

Three tracer tests have particular relevance to the proposed test, two because they used the same tracer in the same aquifer (Chalk) and the other because it was undertaken close to the proposed test site.

1. M1/M25 motorway junction TL 11 03 (Ward et al., 1998; site no. 5, Appendix D) (Price et al., 1992)

In this test on the Chalk in Hertfordshire 90kg (90 litres) of 20% solution Photine CU was introduced into a motorway soakaway. Monitoring was via passive detectors and water sampling at seven pumped boreholes and one observation borehole. The tracer was only detected at low concentrations in the unpumped observation borehole, which was located 3km from the injection point and the recorded travel times indicated a range of velocities from 0.1 to 1km/day. This test was similar in character to the proposed test in that the injection point was located in a Chalk dry valley (Price et al., 1992; paragraph 28) and the principal flow direction was towards a nearby river. The River Ver / River Colne confluence is located 3.2km from the injection point and lies close to the 'successful' observation borehole (Price et al., 1992; Fig. 1).

2. Kilham, Yorkshire TA 0664 (Ward et al., 1998; site no. 6, Appendix D)

This test involved injection of 25 litres of 20% solution Photine CU into a borehole in a dry valley in the Flamborough Chalk to investigate flow to a pumping station at the downgradient end of the valley. Monitoring was carried out in boreholes located 40m, 1.5km and 2.875km from the injection point but the tracer was only detected in the closest borehole. The arrival time

of 18 hours indicated a minimum velocity of 50m/d. The character of this test was also similar to the proposed test in that it involved tracing down a dry valley in a chalk aquifer, although the nature of the Chalk in the Northern Province is somewhat different from that in the Berkshire Downs.

3. Stanford Dingley, Berkshire SU5871 (Ward et al., 1998; site no. 3, Appendix D) (Banks et al., 1995)

This test was carried out less than 20km from the proposed test site, in the adjacent catchment of the River Pang. The purpose of this test was to verify connection between swallow holes and a major spring, Blue Pool. Four litres of concentrated Fluorescein solution (a fluorescent dye) were injected and it was detected at Blue Pool 16.5 hours later, indicating a maximum velocity of 6840m/d. This test was carried out in very similar aquifer material to the proposed test but was rather different in character as it involved tracing along a main (river) valley rather than down a dry valley. A different tracer was used than that for the proposed test and it is possible that the proposed tracer (Photine CU) will be more effective as it has a much lower tendency to sorb to chalk surfaces. However, it is less easy to detect than Fluorescein (detection limits of 0.36ppb and 0.002ppb respectively) (Ward et al., 1998; Appendix E p 4,6) and so overall their performance may be relatively similar. Considering that 4 litres of concentrated Fluorescein solution were used it is estimated that this might equate to ~ 8 litres of more dilute Photine solution.

SUMMARY:

Test site	**Distance**	**Gradient**	**Arrival time**	**Quantity of Photine (or equivalent)**
M1/M25, Hertfordshire	3km	0.0017	3 days – 4 weeks	90 litres
Kilham, Yorkshire	0.04km	?	18 hours	25 litres
Blue Pool, Berkshire	4.7km	0.0036	16.5 hours	~ 8 litres
Proposed test	*1.5km*	*0.002*	*2 days (estimated)*	*10 litres (proposed)*

APPENDIX 6 (cont.)

CONCLUSION

Having considered the hydrogeological and toxicological data it appears that an injection volume of 10 litres of 20% solution (2kg mass of tracer) is a reasonable compromise between assuring success of the tracer test and minimising any environmental impact.

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APPENDIX 6 (cont.)

School of Geography and Environmental Sciences
University of Birmingham

MEMORANDUM

From:	Tim Grapes
To:	Phil Humble, Environment Agency, Wallingford
Subject:	Groundwater tracer test at Great Shefford
Date:	07 March 2004

Phil

Further to your concerns raised during our telephone conversation of 17 October 2000, please find below additional information that I hope will satisfy your requirements. If you need any further details please do not hesitate to contact me.

ADDITIONAL INFORMATION

Evidence for a shallow, high permeability flow zone

Extensive drilling, geophysical logging and test pumping has been carried out in the Lambourn catchment in connection with the Lambourn Valley Pilot Scheme[1,2] and the subsequent Thames Groundwater Scheme[3,4]. Most boreholes were drilled on the floor of the Lambourn valley, Winterbourne valley or one of the numerous dry valleys in the catchment. The results from them were thus biased to characterise the chalk aquifer in valley floor locations. In the vast majority of boreholes that have been investigated three common aspects are identifiable:

1 The length of casing required was in the range 10 to 20m;
2 The principal inflows occurred at the base of the casing;
3 Pumped yields reduced significantly with relatively small drawdowns (5 to 10m) below normal rest water level.

The length of casing required is an indicator of the depth of an unstable section of chalk just below ground surface. I assume this instability is due to a high degree of solution weathering that will result in a shallow zone of very high permeability. This assumption is supported by points 2 and 3 which both suggest that there is very high permeability at a shallow depth within the chalk aquifer in valley floor locations. It is very likely that this zone exists in the dry valley where the planned tracer test will take place.

APPENDIX 6 (cont.)

Estimated direction of tracer movement

It is planned that the tracer will be injected at the base of the highly permeable zone in the injection borehole. At the injection location the regional gradient (at minimum water levels) is estimated to be 0.0022 (2.2m/km)[5] to the SSE while the local gradient towards the river is estimated as 0.0013 (1.3m/Km) to the SSW, based upon a water level of 107mAOD in the injection borehole and a river level elevation of 105mAOD. However, due to the permeability contrast with the deeper, more regional flow zone, the bulk of the tracer is likely to migrate down the dry valley towards the river. Only a small amount (perhaps 10%) is likely to follow the regional hydraulic gradient towards the SSE.

Possible contamination of West Berkshire Golf Course borehole
(Abstraction licence 28/39/22/539)

This borehole lies about 940m ESE of the injection point. Considering the regional gradient discussed above is to the SSE it is highly unlikely that any tracer will move towards this borehole. Additionally, comparing the water level in Lower Barn OBH (located less than 300m from the golf course borehole at a lower elevation) with the likely level in the injection borehole indicates a gradient *towards* the injection point. Even accounting for a small drawdown at this time of year in the golf course borehole the prevailing gradient is still towards the injection point. This relationship is illustrated on the attached sheet (page 4). Thus it seems highly unlikely that any tracer will appear at the golf course borehole.

Potential risk to private water supplies in Great Shefford village

Concerning the risk to private water supplies in the Great Shefford area, I have been in contact with Claire Monger in the Public Protection section of Environmental Health at West Berkshire Council. She has informed me that they have no record of any private water supplies in the vicinity of Great Shefford. However, as their records are incomplete, she suggests carrying out a leaflet drop of the area to warn anybody who might be affected. I believe that leafleting the whole village would be excessive. I have contacted the Chairman of the Parish Council and he is willing to raise the matter at the next meeting of the council. In addition to this I intend to put up notices at the village post office and village hall. These will ask anyone in the village who uses a private water supply to contact me. I also undertake to contact directly those people who are known to have boreholes or wells on their properties so that I can discover what their current

APPENDIX 6 (cont.)

usage is. With regard to this aspect could you supply me with precise location details for the 4 boreholes we discussed in our telephone conversation: SU 37/028, 029, 030, 052.

I trust you will find these actions to be sufficient to minimise any small, potential risk.

I look forward to hearing from you.

Yours sincerely

Tim Grapes

REFERENCES

1 Brettell, E.J., 1971. Report on the Lambourn Valley Pilot Scheme 1967 - 1969. Thames Conservancy, Reading.

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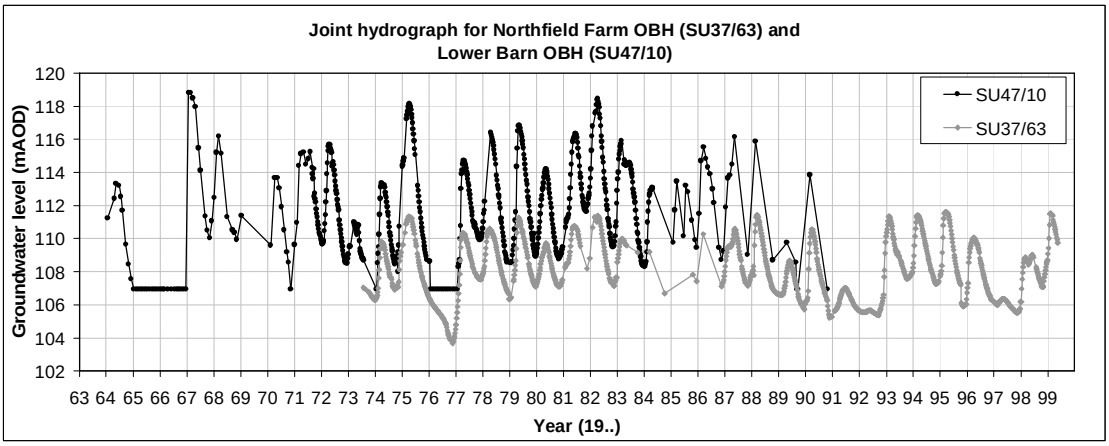
3 Robinson, V.K., 1975. Thames Groundwater Scheme: Report on borehole geophysical logging carried out during Stage 1. Internal Report, Thames Water Authority, Reading.

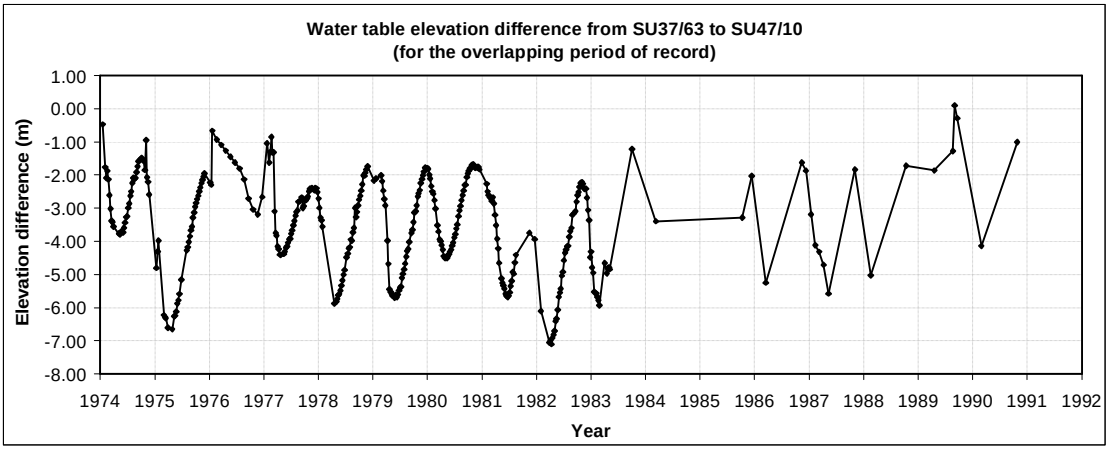
4 Owen, M., Bennett, S., Connorton, B.J. and Robinson, V.K., 1976. Thames Groundwater Scheme: Upper Lambourn Group pumping test 1975, Hydrogeological Analysis. Thames Water Authority, Thames Conservancy Division.

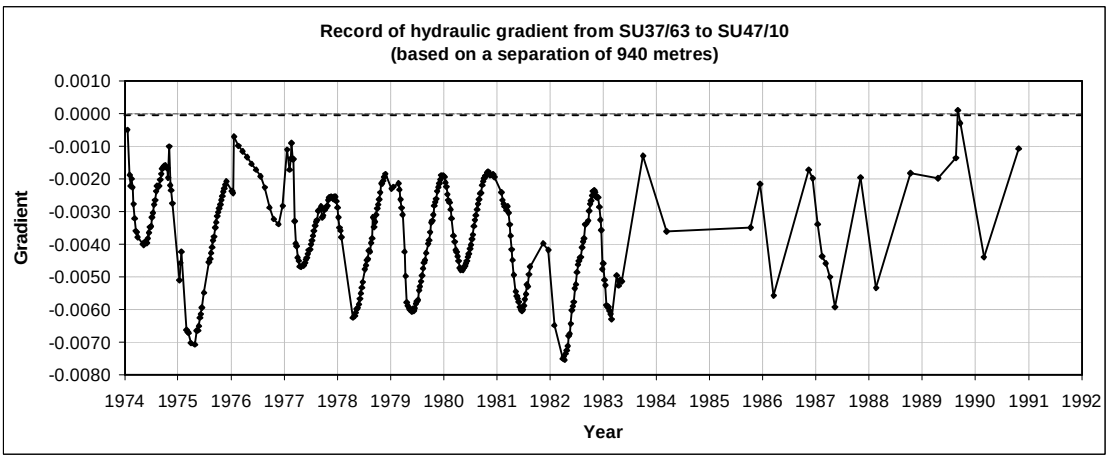
5 I.G.S./T.W.A., 1978. Hydrogeological map of the south west Chilterns and the Berkshire and Marlborough Downs. Institute of Geological Sciences / Thames Conservancy Division, Thames Water Authority.

APPENDIX 6 (cont.)

Gradient analysis regarding West Berkshire Golf Course Borehole







APPENDIX 6 (cont.)

School of Geography and Environmental Sciences
University of Birmingham

FAX DOCUMENT

From:	Tim Grapes
To:	Phil Humble, EA, Wallingford
Fax No:	01491 828 473
Subject:	Proposed tracer test at Great Shefford

Dear Phil

Further to our conversation this morning, please find below specific detail relating to the aims and objectives of the research, which I hope will be of assistance.

BACKGROUND

The proposed tracer test forms part of a PhD being undertaken at the School of Geography and Environmental Sciences, University of Birmingham. The research is funded by NERC, with the Centre for Ecology and Hydrology at Wallingford acting as a CASE (Co-operative Award in Sciences of the Environment) partner.

AIMS AND OBJECTIVES

The aim of the PhD is to improve understanding of the interaction between the River Lambourn and the underlying chalk aquifer. The broad objectives are to ascertain the location and magnitude of the interaction as accurately as possible, including its variation over different timescales, and to identify the dominant controls on the interaction.

From field monitoring it is evident that the River Lambourn gains significant flow in the vicinity of Great Shefford. This contrasts with the pattern seen upstream where there are no significant flow gains downstream from the seasonal source at Lambourn village. Thus the inflows from the chalk aquifer in the Great Shefford area are an important source of flow to the river as a whole. The aim of the tracer test is to help identify the local source of these inflows.

The objectives of the test are to:

1. ascertain whether the inflows are derived from the discharge of subsurface flow from the major dry valley to the north of the village;

2. identify as accurately as possible where these flows actually enter the river channel.

APPENDIX 6 (cont.)

If the test is successful the results will allow the source of an important component of river flow to be identified and will provide useful evidence to characterise the nature of the shallow chalk aquifer. It will also provide valuable information with regard to tracer test best practice, as tracing from a borehole to a chalk stream has not been undertaken in the past.

I trust these details are satisfactory and I look forward to discussing progress with you on Thursday or Friday of next week (16 / 17 November).

Yours sincerely

Tim Grapes
Research Student

Tel: 0121 693 2888
Fax: 0121 693 2889
E-mail: t.r.grapes@bham.ac.uk

APPENDIX 6 (cont.)

School of Geography and Environmental Sciences, University of Birmingham

REPORT ON GROUNDWATER TRACING TO THE RIVER LAMBOURN IN THE VICINITY OF GREAT SHEFFORD, BERKSHIRE.

By Tim Grapes, 14 March 2002

BACKGROUND

The tracer test formed part of a PhD research project studying groundwater – river interaction on the River Lambourn, which is being undertaken in the School of Geography and Environmental Sciences, University of Birmingham. The intention of the test was to identify a connection between a hypothetical dry valley subsurface flow system and the River Lambourn, in order to assess local flow directions and rates of movement.

PRIOR TO THE TEST

Before the test itself was carried out, background monitoring of the River Lambourn was carried out to assess the presence of existing fluorescent material in the water, as this could have masked the fluorescent signature from the tracer. Naturally occurring organic materials can cause fluorescence, as can effluent inputs. Monitoring of a number of sites over several months did not identify the presence of any background fluorescent material.

INJECTION

Injection of the tracer took place at 12.45pm on 3rd October 2001, when 10 litres of 20% solution Photine CU optical brightener (brand name Chromablanc HSB) were introduced into the Environment Agency's Northfield Farm observation borehole (number SU 37/63) located at National Grid Reference SU 3920 7658, adjacent to the A338 road 1.5km north of Great Shefford.

MONITORING REGIME

Monitoring took place at 16 locations along the River Lambourn between West Shefford (SU 3812 7547) and Westbrook (SU 4268 7225). A borehole at West Berkshire Golf Club (SU 410 760) was also monitored. The monitoring apparatus consisted of medical grade cotton wool in perforated, inert plastic canisters, with a small weight affixed to hold them in place. Each site consisted of two canisters, to allow both weekly and monthly accumulation to be assessed. The cotton wool of the samplers was changed weekly for the first 4 weeks following injection and then again after an additional month had passed, with monitoring concluding on 5th December 2001.

RESULTS

No tracer was identified from any of the monitoring sites. On the last day of monitoring (5th December 2001) a sampler was lowered into the injection borehole and allowed to remain for 5 minutes. This sample gave a positive result, indicating that some of the tracer was still present in the borehole, over 2 months after it had been first injected.

APPENDIX 6 (cont.)

CONCLUSIONS

Owing to the nature of tracer testing, the lack of a positive result cannot prove that there is no connection between the injection point and the River Lambourn, only that the tracer was not detected.

There are a number of possible reasons for this failure:

- Insufficient tracer was injected, thus dilution was so great that the final concentration in the river was below detection limits.
- The rate of tracer movement was much slower than anticipated and little or no tracer had reached the river during the period of monitoring.
- The tracer entered a flow path that was not directly connected to the river and it left the catchment without entering the river.
- The tracer followed the regional gradient in the chalk aquifer to the southeast, rather than the local gradient to the south-southwest, and entered the river downstream of the stretch that was being monitored.

It is likely that one of these scenarios, or several in combination, were responsible for the failure of the test to provide a positive result.

No real information concerning the hydraulics of the local river - aquifer system could be gained from the test results.

Prepared by:

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APPENDIX 7

Data acquired from external sources

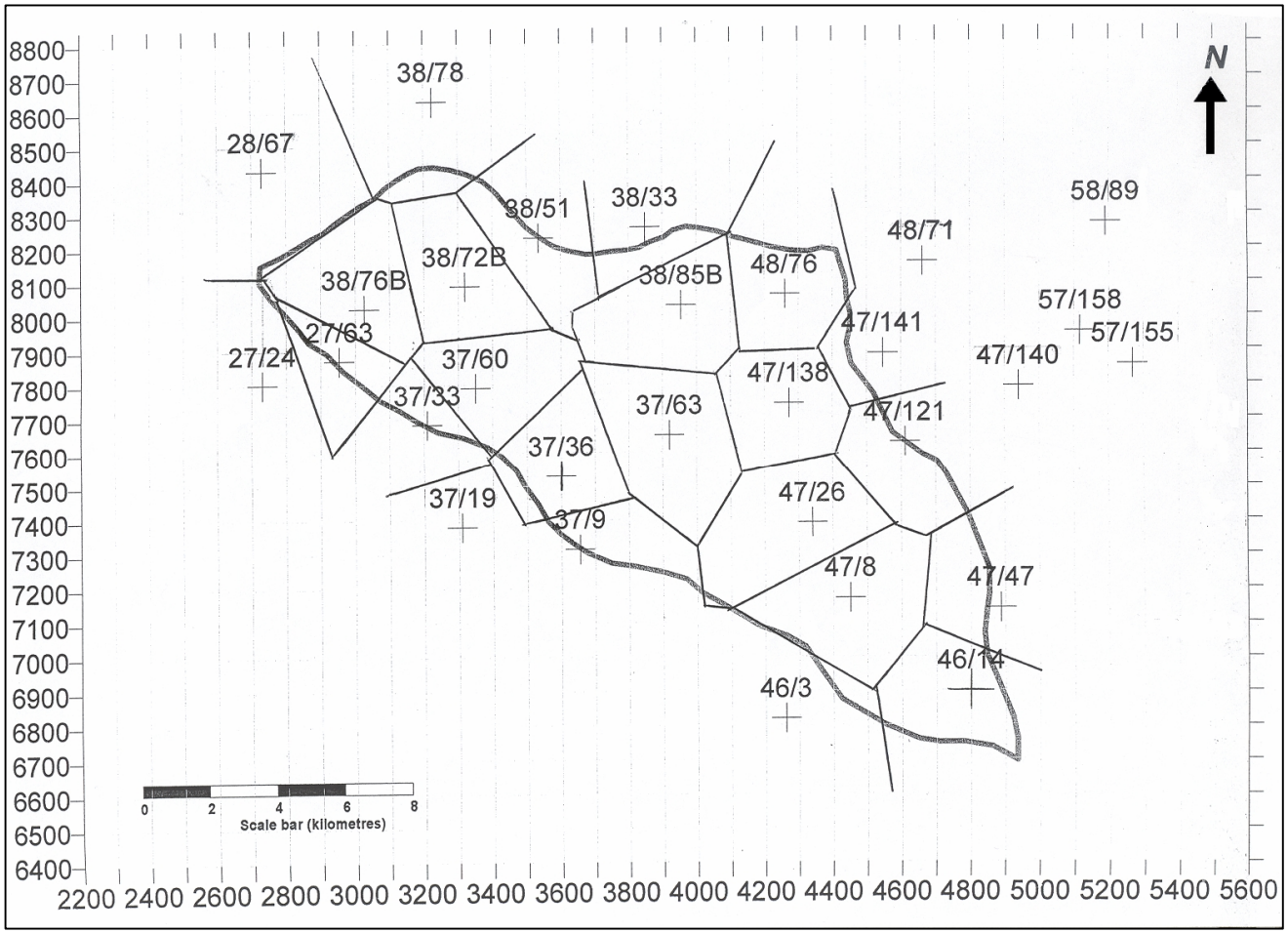
Source organisation	Types of data	Details
Environment Agency, Wallingford (West Area Office, Thames Region)	Groundwater levels	From ~ 50 boreholes monitored at frequencies varying from weekly to 6-monthly intervals
	Daily river flows	From 5 gauging weirs in the catchment; 2 with records of nearly 40 years and still being currently monitored
	Water quality measurements	Routine, background monitoring for 20 years, generally at a single location, but for a varying list of determinants
	Current meter flow gauging	A database of over 2200 gauged flows in the Lambourn catchment
Environment Agency, Reading (Regional Headquarters, Thames Region	Borehole lithological and geophysical data	Borehole and geophysical logs from over 30 boreholes recorded as part of the Lambourn Valley Pilot Scheme and Thames (West Berkshire) Groundwater Scheme
Thames Water Utilities Ltd. (TWUL)	Public Water Supply abstraction data and Sewage Treatment Works (STW) effluent returns	Annual abstractions for the period 1967 to 1998 from the 2 TWUL sources in the catchment Monthly average return flows for the period 1995 to 1998 from the 4 STWs in the catchment
Centre for Ecology and Hydrology, Wallingford	Digital Terrain Model (DTM)	Hydrologically-focused DTM of the Lambourn catchment and environs at 50m scale
West Berkshire District Council	Survey benchmarks	Location and elevation of local Ordnance Survey benchmarks to provide datum elevations for PhD monitoring points
The Met. Office	Weekly MORECS data	Weekly MORECS EP for Grid Square 159 from 1978 to 2001
British Atmospheric Data Centre (BADC)	Daily rainfall Daily air temperature	Rainfall data from various stations in the Lambourn catchment. Air temperature data from the closest station: RAF Lyneham in Wiltshire, some 25km to the west.

APPENDIX 8

LOCATIONS OF BOREHOLE RECORDS USED IN THE CALCULATION OF THE MONTHLY MGS RECORD

LEGEND

+	Borehole location
37/19	Borehole reference no.
	Mean groundwater catchment outline
	Thiessen polygon used in calculation of MGS value



Axis major intervals are 1km, values are eight figure OS Landranger co-ordinates for square SU

APPENDIX 9

Results of multiple linear regression between monthly EP and MGS

[Output from SPSS for Windows 11.0]

Variables Entered/Removed[b]

Model	Variables Entered	Variables Removed	Method
1	EP_M_12, EP_M_9, EP_M_1, EP_M_4, EP_M_6, EP_M_3, EP_M_8, EP_M, EP_M_5, EP_M_11, EP_M_2, EP_M_7, EP_M_10[a]	.	Enter

a. All requested variables entered.

b. Dependent Variable: D_MGS

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.871[a]	.758	.739	.63865

a. Predictors: (Constant), EP_M_12, EP_M_9, EP_M_1, EP_M_4, EP_M_6, EP_M_3, EP_M_8, EP_M, EP_M_5, EP_M_11, EP_M_2, EP_M_7, EP_M_10

GLOSSARY

R: The correlation coefficient between the observed and predicted values of the dependent variable. It ranges in value from 0 to 1. A small value indicates that there is little or no linear relationship between the dependent variable and the independent variables.

R Square: Goodness-of-fit measure of a linear model, sometimes called the coefficient of determination. It is the proportion of variation in the dependent variable explained by the regression model. It ranges in value from 0 to 1. Small values indicate that the model does not fit the data well.

Adjusted R Square: The sample R squared tends to optimistically estimate how well the models fits the population. The model usually does not fit the population as well as it fits the sample from which it is derived. Adjusted R squared attempts to correct R squared to more closely reflect the goodness of fit of the model in the population (SPSS Inc., 2001).

APPENDIX 9 (cont.)

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Correlations		
		B	Std. Error	Beta			Zero-order	Partial	Part
1	(Constant)	-.133	.156		-.850	.396			
	EP_M	7.895E-03	.002	.161	3.470	.001	.520	.262	.134
	EP_M_1	3.171E-02	.002	.643	13.672	.000	.787	.731	.526
	EP_M_2	4.856E-03	.002	.098	2.078	.039	.352	.161	.080
	EP_M_3	-1.02E-02	.002	-.206	-4.322	.000	-.051	-.321	-.166
	EP_M_4	-6.91E-03	.002	-.140	-2.920	.004	-.267	-.223	-.112
	EP_M_5	-3.82E-03	.002	-.077	-1.645	.102	-.370	-.128	-.063
	EP_M_6	-3.75E-03	.002	-.076	-1.618	.108	-.382	-.126	-.062
	EP_M_7	-2.48E-03	.002	-.050	-1.041	.300	-.349	-.081	-.040
	EP_M_8	-2.65E-03	.002	-.055	-1.133	.259	-.273	-.088	-.044
	EP_M_9	-2.90E-03	.002	-.060	-1.228	.221	-.132	-.096	-.047
	EP_M_10	-2.63E-04	.002	-.005	-.111	.912	.070	-.009	-.004
	EP_M_11	-3.45E-03	.002	-.071	-1.462	.146	.197	-.114	-.056
	EP_M_12	3.653E-04	.002	.007	.156	.876	.301	.012	.006

a. Dependent Variable: D_MGS

APPENDIX 9 (cont.)

GLOSSARY

Unstandardized Coefficients: Displays the regression coefficients with their standard errors.

B: Regression coefficients used to compute the regression equation.

Std. Error: A measure of how much the value of a test statistic varies from sample to sample. It is the standard deviation of the sampling distribution for a statistic. For example, the standard error of the mean is the standard deviation of the sample means.

Standardized Coefficients (Beta): sometimes called standardized regression coefficients, are the regression coefficients when all variables are expressed in standardized (z-score) form. Transforming the independent variables to standardized form makes the coefficients more comparable since they are all in the same units of measure.

t: Statistic used to test the null hypothesis that there is no linear relationship between a dependent variable and an independent variable or, in other words, that a regression coefficient is equal to 0. When the significance level is small (less than 0.10) the coefficient is considered significant.

Sig.: The conditional probability that a relationship as strong as the one observed in the data would be present, if the null hypothesis were true. It is often called the p-value. Typically, a value of less than 0.05 is considered significant.

Correlations: Displays the correlation matrix of regression coefficients.

Zero-order: The ordinary correlation coefficients, with no control variables. Values of the correlation coefficient range from -1 to 1. The sign of the coefficient indicates the direction of the relationship, and its absolute value indicates the strength, with larger absolute values indicating stronger relationships.

Partial: The correlation that remains between two variables after removing the correlation that is due to their mutual association with the other variables. The correlation between the dependent variable and an independent variable when the linear effects of the other independent variables in the model have been removed from both.

Part: The correlation between the dependent variable and an independent variable when the linear effects of the other independent variables in the model have been removed from the independent variable. It is related to the change in R squared when a variable is added to an equation.

APPENDIX 9 (cont.)

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	208.767	13	16.059	39.372	.000[a]
	Residual	66.484	163	.408		
	Total	275.251	176			

a. Predictors: (Constant), EP_M_12, EP_M_9, EP_M_1, EP_M_4, EP_M_6, EP_M_3, EP_M_8, EP_M, EP_M_5, EP_M_11, EP_M_2, EP_M_7, EP_M_10

b. Dependent Variable: D_MGS

GLOSSARY

Sum of Squares: The sum of the squared deviations about some quantity.

df: Value associated with a test statistic that is used in determining the observed significance level.

Mean Square: The sum of squares divided by the degrees of freedom.

F: The ratio of two mean squares. When the F value is large and the significance level is small (typically smaller than 0.05 or 0.01) the null hypothesis can be rejected. In other words, a small significance level indicates that the results probably are not due to random chance.

Sig.: The conditional probability that a relationship as strong as the one observed in the data would be present, if the null hypothesis were true. It is often called the p-value. Typically, a value of less than 0.05 is considered significant.

APPENDIX 10

Field observations of the pattern of flow recession in the seasonal channel

The two-stage pattern described below was observed on three occasions (September 1999, October 2000 and October 2001), occurring over the roughly the same timescale, and with the same configuration, in each case. However, in October 2000 the process did not progress beyond stage 1, as the intense autumnal rainfall produced early recharge that rapidly increased groundwater levels and re-established flow in the seasonal section of channel.

Stage 1

The channel started to dry out first between Lambourn and Eastbury. At this stage, there was still a small discharge from Lynch Wood springs, but this was lost downstream of Bockhampton via infiltration through the bed and by evaporation. Downstream of Eastbury the channel was dry continuously to East Garston, except for a pool at the ford of a track across the river, 200m downstream of Eastbury. The bed of the pool was some 0.2 to 0.3m lower than the river bed upstream or downstream, and showed that the water table was only at a very shallow depth beneath the bed. There was no evidence of upwelling at this location, and no discharge downstream of the pool, so it appeared to be solely a location where the water table was intersected, not a point of focused groundwater discharge.

At the upstream end of East Garston village, the channel was dry, but a small discharge could be observed in the middle of the village, upstream of the known spring discharge point, which was augmented by discharge from the spring itself. Downstream of this point, there was a small flow, but this gradually declined until the channel was dry again at the bridge at the downstream end of the village. The channel was dry from this location downstream to the point acting as the temporary head of the river, in the reach upstream of Maidencourt Farm, and below this point continuous flow was observed.

APPENDIX 10 (cont.)

Stage 2

At this later stage, occurring three to four weeks after the onset of stage 1, flow had ceased from Lynch Wood springs, although there was still a pool of water present. There was no water at all in the channel upstream of East Garston, and here it was restricted to a small discharge from the main spring that was supporting a pool in the river channel adjacent to the spring discharge point. The discharge from the main spring at East Garston was not observed to cease over the period of field monitoring for this study. Downstream of the spring-fed pool, the channel was again dry all the way to Maidencourt Farm, where the river head had moved downstream some 150m to a position adjacent to the farm buildings. The channel downstream of Maidencourt Farm was never seen to be dry during the period of monitoring, but was dry in August 1976 when flow as far downstream as East Shefford weir ceased for a short period.

From the observed pattern of recession, it is clear that Lynch Wood spring is a major focus for regional scale groundwater discharge, it being able to maintain a flow even when the channel has dried up some 6km downstream. Meanwhile, the rapid cessation of flow over the length of channel from below Lambourn as far as Maidencourt Farm indicates the weak groundwater inputs that occur in this section, excluding the minor (but consistent) spring at East Garston. The lack of groundwater input between Lambourn and Eastbury is not due to the bed being of very low permeability, as during the early stages of flow recession, the small discharge from Lynch Wood is lost over this section, dominantly by infiltration. This finding was supported by work undertaken during groundwater scheme investigations in October 1975, when 0.05 cumecs of pumped groundwater was discharged into the dry channel of the river immediately downstream of Lambourn village, with a loss of 0.02 cumecs occurring in the 900m section downstream to Eastbury (Greenfield & Child, 1976).

References:

Greenfield, B.J. and Child, S.C., 1976. Upper Lambourn Group Pumping Test 1975. Volume IV Hydrological Aspects. Thames Water – Thames Conservancy Division.

Copy of journal article submitted to Hydrological Processes

Dynamics of River – Aquifer interactions along a Chalk stream:
the River Lambourn, UK.

T.R. Grapes, C. Bradley and G.E. Petts
School of Geography, Earth and Environmental Sciences,
The University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK

ABSTRACT.

This paper describes the spatial and temporal pattern of groundwater flow accretion to the River Lambourn, a 234km^2 chalk catchment of the West Berkshire Downs, UK, which has been largely unaffected by groundwater abstraction. Variations in the discharge measured at four fixed gauges in the catchment, coupled with information on the length of flowing channel over the period 1983-2001, are used to describe regional patterns in flow accretion: mean catchment accretion generally exceeds 0.15m^{3}s^{-1}km^{-1}, but there are significant differences between perennial reaches indicating how the combination of local structural controls and seasonal changes in the drainage net affects flow accretion. Data from current meter surveys were used to determine the spatial variability in flow accretion: 505 paired observations along 12 reaches between 1and 2.95km in length indicated a consistent spatial trend in accretion, which was highest in the upstream and downstream channel reaches, but also in middle reaches where dry valleys intersected the main valley. A flow accretion index was developed to describe the relationship of flow accretion in each of the 12 study reaches to catchment discharge. The relationship varied from being strongly correlated with catchment discharge (2 reaches), weakly correlated (3 reaches), strong negative correlation (2 reaches), and no relationship to catchment discharge (4 reaches). The results highlight the need to reconsider the usual assumption of uniform, or uniformly increasing, flow accretion in chalk catchments, they emphasise the importance of catchment topography, and illustrate how flow accretion in individual reaches may vary between high and low groundwater levels.

Keywords:

Chalk streams; Flow Accretion; River – aquifer interaction;

INTRODUCTION.

Groundwater dominated streams in chalk catchments are important in a number of respects. They are associated with a diverse flora and fauna, but are vulnerable to periods of drought and groundwater abstraction (Wood & Petts, 1999). The Chalk aquifer provides distinctive spatial and temporal controls on the manner of groundwater – river interaction, but this is frequently difficult to represent appropriately in catchment models, especially as chalk streams are characterised by two extremes of hydrological behaviour: they exhibit considerable variability in flowing channel length on a seasonal basis, and display very low variability in catchment discharge per unit area. Both attributes reflect the degree to which chalk streams rely upon groundwater discharge for much of their flow. Although chalk streams typically exhibit ephemeral flow in their headwaters, within perennial channel reaches flow variations are buffered by continuous groundwater seepage that sustains flow, even during periods of low rainfall. As a result, chalk catchments are characterised by a substantial groundwater contribution that may comprise 80-95% of total flows (Sear *et al*. 1999). Many chalk streams have been severely impacted by groundwater abstraction, and by point and diffuse pollution from agricultural runoff (e.g. Neal *et al*. 2000) and water treatment works (Jarvie *et al*. 2002). These problems are compounded during periods of drought when reduced base flow in perennial channel reaches, whether reflecting reduced recharge and/or increased abstraction (e.g. Agnew *et al*. 2000), may increase pollutant loadings.

At present, management of surface-water and groundwater resources in these catchments is severely compromised by a number of uncertainties concerning the mechanisms of groundwater – river exchange. This is illustrated by the difficulty that Jones & Lister (1998) have described in accounting for aquifer storage in chalk catchments when relating precipitation to river flow. Although some success has been achieved with simple models of aquifer / river exchange, that take into account the variable transmissivity of the chalk aquifer (Cooper *et al.* 1995), typically water resources management relies heavily upon the output of regional-scale models that describe river-aquifer exchange at a catchment-scale. As a result, the representation of river-aquifer exchange is highly generalised, and has been poorly simulated. This represents a problem, even where there has been a detailed investigation of the

regional hydrogeology, as Rushton *et al.* (1989) have demonstrated for the Berkshire Downs. In such catchments, regional groundwater flows are determined by features such as topographic lows along principal valley axes (e.g. along the Thames and Kennet floodplains in Berkshire), whilst local variability in the Chalk accounts for the spatial and temporal patterns of groundwater discharge to perennial and ephemeral channel sections (Bradford, 2002). Generally, studies have focussed upon regional determinants of groundwater flow and have failed to describe the significant spatial and temporal variability in groundwater – river exchange that is important to understanding local controls on river flow.

This paper seeks to determine the degree to which groundwater – river exchange varies at a local scale, by describing recent work undertaken in the Berkshire Downs that sought to characterise the flow regime of a chalk stream unaffected by abstraction: the River Lambourn. We use a variety of data sources to investigate the dynamics of groundwater seepage to the River Lambourn, and describe the variability of flow accretion over short distances; and the potential for rapid groundwater flows to contribute to river discharge. These observations are based upon the results of a two-year field programme , with additional data from long running monitoring programmes.

Groundwater – Surface-water Interactions

The relationship between groundwater seepage and river flow in chalk catchments follows a clear seasonal cycle. Rising groundwater levels in the autumn produce a headward extension from the perennial channel, such that bourne (or spring) flows occur over significant areas of a chalk catchment. When groundwater levels are at their winter maximum, usually between February and April, chalk streams tend to respond rapidly to precipitation, as rapid water flow occurs through fractures in the Chalk (e.g. MacDonald *et al*. 1998), although inevitably some dry valleys remain where the water table fails to intersect the ground surface. As the regional water table falls through the spring and summer, flow will cease in ephemeral channel sections, but groundwater seepage will sustain flows in the perennial channel. Seepage between aquifers and rivers is likely to occur continuously wherever the water table intersects the surface, with flow volumes that are determined by the regional hydraulic gradient, the hydraulic conductivity of near-surface deposits, and the permeability of

the river-bed (Kirk & Herbert, 2002; Calver, 2001).

The annual cycle of groundwater level fluctuation, its relationship to river flow, and the degree to which it determines the quantity of seepage to or from the river must be represented appropriately in numerical models (albeit usually at the catchment scale). Seasonally, seepage will reflect regional water levels; their relationship to river stage, and in some cases the possible contribution of water from impermeable areas of the catchment (e.g. Bradbury & Rushton, 1998). However, comparatively few studies have documented field observations of groundwater seepage to chalk streams that may be used to verify modelled predictions, although data from adjacent river gauging sites enable groundwater accretion to be estimated. Clearly, supplementary field surveys are needed in many cases: for example, Rushton & Tomlinson (1995) suggest that flow gauging at intervals of no more than 3km is necessary to estimate infiltration near abstraction boreholes. In such situations systematic flow gauging along the river profile provides a useful indication of the variability in flow accretion, and although the results from occasional surveys have been presented in the literature (e.g. Oakes & Pontin, 1976; Connorton & Hanson, 1978; Wyness *et al.*, 1994; Wilson & Akande, 1995), they have been used solely as calibration tools for regional groundwater models, and interpretation of the accretion profiles themselves has been almost totally neglected. Inevitably, seepage rates are likely to differ markedly over distances of around 1km, reflecting the local hydrogeology, the extent of floodplain and alluvial deposits, and the degree to which a river may have incised into an underlying aquifer. It is also possible for both influent and effluent reaches to occur under certain circumstances, although the temporal and spatial variability of such flows and the hydraulic controls, are poorly understood. Seepage rates will also vary considerably at a smaller scale, of between 10-100m: influent and effluent flows may occur across a pool-riffle boundary, with downward flow at the riffle head and upward flow at the riffle tail, although this may be limited to the inflow or outflow of local surface waters.

THE RIVER LAMBOURN, BERKSHIRE

The catchment of the River Lambourn extends over 234km^2 of the West Berkshire Downs, UK (Figure 1), with elevations ranging from 261m OD in the northwest to around 70m OD in the southeast. The Chalk outcrops over much of the

catchment, and is around 200m thick. It dips at an angle of c. 0.6° to the South East and has been subdivided into three units: the Lower Chalk, Middle Chalk and Upper Chalk. It is locally overlain by periglacial deposits, 'clay with flints' and sediments of Eocene age in the lower catchment, with 1-2m of alluvial silt/clay and occasional peat lenses infilling areas of the valley floor. The seasonal head of the river lies near the village of Lambourn, from where the river flows southeast to the River Kennet. There is only one significant tributary: the Winterbourne Stream that joins the Lambourn near Newbury.

The landscape is classic chalk downland: rolling, grass-covered hills, which are dissected by a network of dry valleys, some of which experience ephemeral flows in their lower sections. Some of the dry valleys are clearly defined by the 150m contour line in Figure 1: they include three dry valleys near the seasonal head of the river, close to the village of Lambourn, two dry valleys that intersect the main valley c. 3km and 6km below Lambourn village (the lower of which exhibits ephemeral flows); a further dry valley 2km below the gauge at Welford, and a dry valley extending above the Winterbourne tributary.

The River Lambourn is relatively unaffected by groundwater abstraction and is characterised by a semi-natural flow regime with peak flows coinciding with maximum winter groundwater levels. The mean annual flow was 1.69 m^3s^{-1} over the period 1962 – 2000 (NRFA, 2001), with a base flow index of 0.96 (Gustard *et al*. 1992). Much of the channel remains geomorphologically diverse with a gravel bed, and the river was notified as a Site of Special Scientific Interest[1] in 1995 as a classic example of a lowland chalk river.

An extensive instrumentation network was installed in the Lambourn catchment during the West Berkshire Groundwater Scheme (WBGS) (Owen, 1981). This scheme was designed to enable groundwater abstraction to augment river flows, but has only been used very occasionally (for flow augmentation from August to November 1976 and from 4th to 27th September 1989). Flow gauges have been maintained at East Shefford, Welford and Shaw; and on the Winterbourne Stream at Bagnor (Figure 1). A total of 43 abstraction boreholes and 67 observation boreholes were drilled in the catchments of the Pang and Lambourn between 1967 and 1974 for

[1] A Site of Special Scientific Interest (SSSI) is designated by English Nature to provide legal protection for an area of recognised conservation interest.

the WBGS (Brettell, 1971; Hardcastle 1978), and the groundwater level records from these and other boreholes enable the groundwater catchment to be estimated. The figure for mean groundwater catchment obtained was 168km^2, which represents 72% of the surface-water catchment.

The relationship between observed groundwater levels from boreholes close to the River Lambourn, and the river profile are summarised in Figure 2, using data based on weekly measurements (monthly for SU/76B and SU38/72B) from the early 1970s to the late 1990s. The range between minimum and maximum groundwater level varies by as much as 25m upgradient from the village of Lambourn, with a comparable inter-quartile range (between the 25-75% percentiles) approaching 8m. The inter-quartile range is much lower for the two boreholes adjacent to the upper, seasonal, section of the river (SU37/60 and SU37/36), and is less than 5m. In the middle channel section, water levels in boreholes SU37/63 and SU47/26 correspond closely with the river profile, and their inter-quartile ranges are consistently higher than the riverbed elevation. The relationship between extreme groundwater levels and the river profile is also of interest: under conditions of a very high water table it is possible to envisage a very rapid response to further precipitation, as some groundwater levels near the river in the middle channel reaches are considerably above the elevation of the river channel. Conversely, under extremely low water table conditions, the levels of all boreholes illustrated in Figure 2 lie below the river profile, suggesting the likely cessation of river flows.

FLOW ACCRETION DYNAMICS

Estimates of river flow accretion (albeit spatially averaged) can be readily derived for channel sections between gauging stations by dividing the change in discharge by the channel length between the two gauges. However, estimates of catchment-scale accretion and accretion above the highest gauging station rely upon the availability of data on the length of contributing river channel. Information on the presence or absence of channel flow is available for the River Lambourn from 1983-1998, from Pike (1998); and was collected routinely from 1999-2001 as part of the study described here. Longitudinal variations in flow accretion have been assessed using two primary sources: records from gauging stations on the River Lambourn, and data from current meter surveys along the river. The availability of data for the four gauges

on the Lambourn and Winterbourne tributary are summarised in Table 1. Although only the gauges at Bagnor and Shaw have a continuous record, the East Shefford gauge was reopened in May 1999 as part of the current study, thus giving two periods with complementary data: 1966–1983; and 1999-2001.

Catchment-scale Accretion

Estimates of spatially averaged catchment accretion rates for the Lambourn catchment based on the record from Shaw gauging station, situated just above the confluence of the Lambourn with the Kennet, are shown in Figure 3, together with catchment discharge and estimates of the length of contributing channel over the period 1984-2002, while summary statistics are given in Table 2. There is a close relationship between catchment discharge and flow accretion, although changes in the length of contributing channel attenuate the accretion pattern, reducing mean accretion rate at high flows, while increasing mean accretion at low flows. Exceptions to this trend occurred in late 1986 (1); 1987 (2) and 1998 (3); when short-term reductions in channel length appear to produce peaks in the mean accretion rate, and in early 1991 (4) when a rapid expansion in the drainage network led to a decline in mean accretion. Some of these changes, for example, 3, are clearly a result of the method of calculation, and highlight the importance of accurate data on variations in the flowing channel length.

Typically, peak accretion rates occur between January and March and seldom exceed 0.2 $m^3s^{-1}km^{-1}$. However, there were periods of increased accretion particularly during the winters of 1995/96 and 2000/01. These were associated with high precipitation between September and December, which totalled 350mm in 1995, and 460mm in 2000, compared to a long-term mean of 250mm for the equivalent months in the period 1964-2000. Minimum rates of flow accretion were consistently c. 0.05 $m^3s^{-1}km^{-1}$, which thus represents the seepage rate that sustains river base flows when groundwater levels are at their seasonal minimum. Generally, however, the variation in accretion is rather limited: this reflects consistent groundwater discharge to the river, and the ability of delayed groundwater flows to attenuate any short-term fluctuations arising from significant precipitation events. This is a commonly cited characteristic of groundwater-dominated rivers, but the data presented here illustrate the close relationship between channel length and peak accretion rate, to the extent

that the mean catchment accretion rate generally exceeds 0.15 $m^3s^{-1}km^{-1}$ when there are flows in the highest ephemeral section of the river. This most probably reflects a combination of high accretion in the upper, ephemeral, channel sections, coupled with increased accretion in the lower catchment sustained by the higher regional hydraulic gradient. Both processes are likely to be important, acting together they apparently reduce the variability in mean catchment accretion, but there is also the likelihood of varying accretion totals in middle reaches which cannot be identified at this scale.

Flow Accretion Rates between gauging stations

Clearly, there are likely to be considerable variations in actual accretion rates within the catchment-scale figures presented above. This is indicated by further analysis of the Lambourn data, focussing on accretion between adjacent gauging stations, and above the upstream gauge at East Shefford. The estimated accretion totals are summarised in Table 3, firstly, on a volumetric basis, and secondly, as a percentage of catchment discharge, for the period June 1966 to September 1983 (continuous gauged records are only available for all four gauging weir sites during this period).

At this scale it is possible to distinguish between ephemeral and perennial channel reaches, with ephemeral reaches characterised by significantly greater variability in accretion, their coefficients of variation (in volumetric terms) exceeding 50%. Accretion in the ephemeral reaches of the Lambourn above the gauge at East Shefford ranges from zero in August 1976, to a peak of 2.46m^3s^{-1} on 7/2/69 and on the Winterbourne tributary above the gauge at Bagnor from 0.01m^3s^{-1} (on 1/11/69) to 0.55m^3s^{-1} (on 15/3/82). The perennial reach between East Shefford and Welford shows the least variability in flow accretion, with a coefficient of variation of 31.5%, but this reach has relatively small mean accretion rates. In contrast, the second perennial reach between Welford and Shaw has a significantly higher standard deviation with the total increase in flow varying from 0.073 to 1.48m^3s^{-1}. These differences in accretion indicate the degree to which local structural controls, coupled with seasonal changes in the drainage net, modify flow accretion dynamics at a local scale.

Further information on the variability of flow accretion is presented in Figure 4 which gives the cumulative frequency distribution for flow accretion along the four

channel sections; with the flow duration curve for the same gauges plotted in the lower figure. The data highlight the extent to which flow accretion above East Shefford is characterised by a significantly more uniform gradient, indicating an even distribution of discharges across the range of flows, in contrast with accretion in the two perennial sections of the Lambourn (between East Shefford and Welford and between Welford and Shaw), and on the Winterbourne. This reflects the buffering effect of the seasonal extension of the flowing channel above East Shefford, and the increase in groundwater seepage in this section, driven by the higher hydraulic gradients as groundwater levels rise (c.f. Figure 2). Figure 4 demonstrates that for approaching 50% of the time, almost half of the total accretion to the River Lambourn occurs above the gauge at East Shefford, which clearly demonstrates the importance of flow accretion in the seasonal section of the channel. Accretion in the East Shefford to Welford reach is very consistent at around $0.3m^3s^{-1}$, (Q_{25} being c. $0.25m^3s^{-1}$ and Q_{95} c. $0.4m^3s^{-1}$), but much higher rates of accretion do occur in this reach, albeit very infrequently (less than 5% of the time) as Q_{99} is c.100% higher than Q95 at c.$0.9m^3s^{-1}$.

The extent to which accretion varies locally, and through time, is demonstrated by considering the contribution of each reach as a proportion of catchment discharge. There are significant differences in the timing of the maximum contribution of each section to catchment discharge. Maximum accretion rates for the two ephemeral sections on the Lambourn (i.e. above East Shefford) and on the Winterbourne stream to Bagnor, total 96.6% of catchment discharge, while maximum flow contributions from the perennial channel sections total 118.7% of total catchment discharge. This suggests that there are systematic variations in flow accretion dynamics through the catchment, which is supported by the coefficients of variation. The greatest variation in the proportional contribution of flows appears to be in the reach between East Shefford and Welford (54.9%); whereas the remaining three channel sections range from 40% for the ephemeral section above East Shefford to between 22.1% and 28.4% for the other two sections.

i. Flow accretion in Ephemeral Reaches.

Further information on the patterns of flow accretion in the ephemeral channel section above the East Shefford gauge is presented in Figure 5 which gives mean accretion rates in the ephemeral section above East Shefford over the period June

1999 to October 2001, an estimate of the catchment-wide accretion rate above the downstream gauge at Shaw, and the approximate length of the active channel above East Shefford between June 1999 and September 2001. Discharge measured at both stations is given in the lower figure. Annual minimum flows typically occur between October and November and are ~$1m^3s^{-1}$ at Shaw, and ~$0.2m^3s^{-1}$ at East Shefford. Flows increase any time between November and January; the timing and extent of the increase depending upon the quantity and duration of precipitation and groundwater recharge. For example, in the winter of 1999/2000 the increase in flows was small: from 1 m^3s^{-1} in December to $3.5m^3s^{-1}$ in May at Shaw, and from 0.2 to $2m^3s^{-1}$ at East Shefford. The maximum flows recorded in 2000 were also small: $3.80m^3s^{-1}$ at Shaw and $1.92m^3s^{-1}$ at Shefford (both flow maxima were observed on the 28th May 2000. However, in 2001 high autumn precipitation produced maximum flows exceeding $4m^3s^{-1}$ and $6.5m^3s^{-1}$ at East Shefford and Shaw respectively. Mean daily catchment discharge between January and July 2001 was $2.57m^3s^{-1}$, 47% higher than the long-term average of $1.75m^3s^{-1}$, reflecting higher than average precipitation, including some extreme events. For example, rainfall totalled >150mm in April 2000, and produced an unusually late peak in the annual hydrograph, while intense precipitation, totalling 388mm from October to December 2000 (inclusive), representing 207% of the long term mean (1964-2000) for the same 3-month period of 188mm, produced a 40-year peak discharge at Shaw of $6.67m^3s^{-1}$.

As would be expected, discharge dynamics are closely associated with the spatial and temporal variability in flow accretion through the catchment, but there are some differences between accretion in the ephemeral and perennial reaches. This is seen firstly, in the period October to December 1999, when the length of contributing channel above East Shefford fell to below 3km, which produced an increase in mean accretion rate to East Shefford. Secondly, during flow recession from August 1999 to October 1999; August 2000 to November 2000; and August 2001 to October 2001 when there was a gradual decline in mean accretion above East Shefford to a minimum of c. $0.025m^3s^{-1}km^{-1}$. During these three periods the rate at which accretion fell in the ephemeral section was significantly higher than for the whole catchment, to the extent that mean accretion in the ephemeral channel was between 30-50% of the catchment mean from October to November. Thirdly, during the increase in flows in December 2000, when high precipitation produced peak observed accretion rates

above East Shefford of c. 0.4 $m^3s^{-1}km^{-1}$.

Figure 5 demonstrates that estimates of mean accretion rate in ephemeral reaches are particularly sensitive to changes in channel length, whether arising under high or low flow conditions. For example, evidently the increase in mean accretion rate above East Shefford between October and December 1999 is an artefact of a reduced length of active channel. In these circumstances there may be little change in the total volume of flow accretion in the ephemeral channel reaches, which indicates the extent to which accretion is concentrated at the sub-reach scale. Thus, during the period from October to December 1999, there was an 83% reduction in the length of flowing channel above East Shefford, associated with the migration of the river head downstream to the perennial source, but this had no impact on river discharge. The implication is that at this state of flow, discharges at East Shefford are mainly derived from seepage flows to the river along the 1.5km length of perennial channel immediately above the gauging station. However, significant changes in the channel network will also take place under high flow conditions: for example, in December 2000, the drainage network expanded considerably with flows occurring in normally dry chalk valleys. This produced a pronounced peak in estimated accretion rates above East Shefford of ~0.4$m^3s^{-1}km^{-1}$, which although of short duration, contributed to substantially higher seasonal accretion in 2000/2001 compared with the previous year.

The flow data emphasise the limited differences between mean catchment accretion, and accretion within one ephemeral channel section. For much of the year, there is little difference in accretion rates to East Shefford and to the catchment gauge at Shaw, and as noted above, differences between the two data series are only discernible at extreme flow conditions, particularly during low flows. It is important to note, however, the importance of local controls upon accretion. This is suggested by a number of occasions when 'accretion pulses' occurred, these appear as sharp spikes on the accretion plots and apparently represent episodes of rapid throughflow from precipitation either, through the chalk (*sensu* MacDonald *et al.* 1998) or over the surface, at points where the water table lies close to the ground surface. Accretion pulses may be identified in both the ephemeral channel reach above East Shefford, and at a catchment-scale above Shaw. For example two distinct pulses (numbered 1 and 2 on Figure 5) occurred in November and December 1999 above East Shefford, although only the first was also associated with a very small pulse in catchment

accretion. Smaller pulses (3 to 11) can be identified at a catchment scale, of which 5, 6, and 7 appear to be associated with changes in channel length. Of the remaining accretion pulses, only pulse 8 was associated with an increase in accretion in the ephemeral reach, suggesting that pulses 3,4, 9, 10 and 11 arose from episodes of localised intense precipitation elsewhere within the catchment which gave rise to rapid runoff. Clearly, therefore, there is strong evidence for local controls upon accretion rates and variability, only some of which is seen in the main ephemeral reach above East Shefford.

ii. Flow Accretion in Perennial Reaches

Differences in the pattern of flow accretion rates between gauging stations on the two perennial reaches of the Lambourn between East Shefford and Welford, and between Welford and Shaw, and their relationship to catchment discharge, are presented in Figure 6. The data are summarised as three-monthly moving averages for the period from 1966 to 1984, when data from the Welford gauge are available and the catchment discharge is also presented for the same period. The two channel sections behave in markedly different ways. In most of the years, the lower section between Welford and Shaw is characterised by accretion rates that are closely associated with discharge at Shaw: peak accretion rates for the most part occur close or immediately following peak catchment discharge, although there are notable exceptions in 1967 and 1968 when peak accretion in the lower reach corresponds to the period of minimum catchment discharge. With the exception of this period, accretion between Welford and Shaw appears to be closely related to catchment-scale accretion and discharge, which is particularly clear from 1974 onwards.

In contrast, significantly different patterns and quantities of flow accretion occur in the upstream section between East Shefford and Welford, where accretion is generally higher than in the lower section between Welford and Shaw, particularly when catchment discharge is low. The differences between accretion rates in the two perennial sections is indicated by the out-of-phase relationship between accretion rates in the two channel sections for much of the period 1966 - 1980. Over this period also, for much of the time, accretion rates in the upper perennial section between East Shefford and Welford were inversely proportional to catchment discharge. There are exceptions to this pattern: for example, in late 1967, 1971/72 and 1972/73 peak accretion in the Welford reach coincides with peak catchment discharge.

In several years, peak accretion in the upper reach occurred on the rising limb of the catchment hydrograph, illustrating a possible structural control on accretion: groundwater might be locally confined, for example by a hard ground in the chalk. Under conditions of a rising groundwater levels, seepage rates in the upper reach first increase in proportion to the hydraulic gradient, until the water table rises above the 'confining' layer (which coincides with flow in ephemeral channel sections). This effect is not seen in the lower perennial channel section which may be sustained by deeper groundwater flow, and, as noted above, is more characteristic of regional groundwater flow patterns. Any explanation is largely speculative, however, and is further affected by possible impacts from groundwater abstraction through the Lambourn Valley Pilot Scheme in the early years of the period shown in Figure 6

In any event, differences in the behaviour of the two perennial reaches are confirmed by the scatter plot in Figure 6 which shows the relationship between accretion in the perennial reaches: East Shefford to Welford; and Welford to Shaw, and catchment discharge. While there is a clear linear relationship between accretion in the lower channel section (between Welford and Shaw), there is no correlation between accretion in the section between East Shefford and Welford. The implication is that there are distinct, and differing, controls on accretion in the two reaches, which are considered in detail below.

High spatial resolution accretion identified by current meter surveys.

Analysis of accretion patterns using records from fixed gauges indicates the extent of accretion varies locally, which is difficult to predict. This can be investigated further by systematic current meter surveys, which have been undertaken in the Lambourn catchment on several occasions: a series of current meter surveys were completed as part of a programme of groundwater investigation from 1964 to 1979, while supplementary surveys were undertaken from 1999-2001. Analysis of these data has identified a total of 505 pairs of readings that were situated on the upstream and downstream limits of 12 reaches along the River Lambourn, shown in Figure 1. The reaches varied from 1.00km to 2.95km in length, and extended from just below the seasonal source to the lowest gauging station. Most of the data were collected in three years of above average discharge: 1966, 1967 and 1975, but as most current meter surveys were undertaken in summer months, discharges were not unusually high.

The estimates of accretion are summarised in Table 4, and Figure 7, and confirm the variability in flow accretion. There is a distinct spatial trend in accretion along the channel profile, consisting of moderate but declining accretion from reach no. 1 to reach no. 3; negligible accretion from reach 3 to 4; increasing accretion to reach no. 6; decreasing accretion from reach 6 to a minimum at reach 11. The smooth and spatially consistent trend in accretion suggests that the main control on accretion can be identified at a scale of about 3 km, indicating the limitations of estimating accretion solely on the basis of existing gauging station records. Greatest accretion rates occurred in the upstream and downstream channel reaches, but also in certain middle reaches that corresponded with the intersection of major dry valleys. A number of reaches are characterised by flow loss (negative accretion or influent seepage) under low flow conditions, although only one reach (no. 11) has an average accretion rate of below zero.

The resulting flow accretion profile, and its relationship to the mean catchment accretion rate is shown in the lower graph of Figure 7. This confirms the importance of accretion in reaches 1-2, 6-8 and 12, with negligible accretion in reaches 3-4 and negative values for reach 11 indicating influent condition in this reach (i.e. loss of river-water). The data demonstrate the degree to which flow accretion is focussed on certain reaches, most particularly reach 6, which is immediately above the gauge at East Shefford.

Temporal Dynamics of Reach Flow Accretion.

The description of flow accretion patterns presented above, whilst clearly demonstrating the variability in accretion, is limited by the extent to which temporal variations in flow accretion are identified. This is likely to be significant, as suggested by considering accretion as a proportion of catchment discharge in Table 3. The location of maximum accretion is likely to vary in a systematic manner, reflecting both the seasonal rise and fall of the water table, and the expansion and contraction of the channel network. The available current meter dataset is unevenly distributed through time, which complicates any attempt to determine the temporal dynamics of flow accretion. However, by plotting a measure of reach flow accretion against catchment discharge, it is possible to suggest how individual reaches vary on a seasonal basis. The flow accretion index was devised to express the proportional contribution of

increasing discharge (Q) in each reach, and its contribution to total catchment discharge:

$$FAI = \frac{Increase\ in\ Q\ along\ reach\ as\ proportion\ of\ Catchment\ Q}{Reach\ length\ as\ proportion\ of\ total\ active\ channel\ length}$$

The index was produced by determining the increase in flow per unit length for each reach and dividing by the catchment mean accretion rate:

$$FAI = \frac{Reach\ Gain\ /\ Reach\ Length}{Catchment\ Discharge\ /\ Total\ active\ channel}$$

If identical accretion rates (in $m^3s^{-1}km^{-1}$) occurred throughout the active channel at any point in time, and varied directly in proportion to discharge, the Flow Accretion Index would be a constant value of 1. However, differences in the FAI for the 12 reaches along the Lambourn shown in Figure 1, and their relation to catchment discharge, are given in Table 4 (with plotted data for reaches 1, 4, 6 and 7 in Figure 8) and confirm the importance of local controls on flow accretion. The results suggest that characteristic reaches can be identified where there is a reasonably strong correlation between reach accretion and total catchment discharge (reaches 1 & 4), reaches with a weak positive correlation between reach accretion and total catchment discharge (reaches 2, 3 & 5), reaches with a strong negative correlation between reach accretion and total catchment discharge (reaches 7 & 8), and reaches where accretion displays no discernible relationship with catchment discharge (reaches 9, 10, 11 and 12).

Generally, the relationships identified in the Table display a systematic variation in the proportional contribution of reaches to catchment discharge along the river profile. Upper reaches above East Shefford (nos. 1 to 6) display a positive relationship with catchment discharge. These reaches are ephemeral (although reach no. 6 is only marginally ephemeral) and contribute significantly to catchment discharge as the seasonal water table rises. Conversely, the proportional contribution from reaches in the mid-course of the Lambourn (7 and 8) show a negative relationship to catchment discharge. Whilst the ***actual*** magnitude of flow accretion

may not vary significantly, the proportion of total catchment discharge that arises as seepage from these reaches declines seasonally, as the drainage net expands. In contrast the proportional contribution from reaches further downstream (nos. 9 to 12) shows no relationship with catchment discharge: reach 9 has a consistent FAI of around 1 indicating accretion that for much of the time is around the catchment mean. Reaches 10 and 11 have FAI's that are more variable and are negative at times of low catchment discharge indicating influent seepage (i.e. seepage from the river into the underlying aquifer). Finally reach 12 above the Shaw gauging station has a FAI that is consistently above 1, indicating relatively high accretion that is sustained under all flow conditions (i.e. proportionally high accretion under low flow conditions; and increasing total accretion – or continued proportion of total flow – under high flow conditions).

There are several important points to highlight: the positive relationship between FAI and catchment discharge in reaches 1 and 4 reflects the presence of distinct springs within these reaches. As a result, discharge is closely related to the catchment average water table, that is itself proportional to the catchment discharge. In contrast, reach 7, near Weston, has a strong negative correlation indicating an inverse relationship to catchment discharge, and suggesting that this reach provides a consistently high contribution to catchment discharge under low flow conditions, but as catchment discharge increases the proportional contribution declines. Significantly, the FAI for reach 7 rarely falls below a value of 1 indicating that under high flow conditions, accretion in this reach approximates the mean value, and implying that the actual accretion rate in reach 7 is relatively constant.

Accretion in reach 6, immediately upstream, is distinctly different in that the proportional contribution of this reach displays no trend with catchment discharge. On five occasions, a FAI of 0 (or just below 0) was observed when catchment discharges were between 1 and $3m^3s^{-1}$, while for much of the time the FAI was between 2 and 4, although a maximum value of >5 was observed on one day (corresponding to a catchment discharge of just under 2 m^3s^{-1}). Clearly, for the majority of the time, accretion in this reach is significantly above the catchment average, and periods of negligible flow are associated with the occurrence of a very low regional water-table.

DISCUSSION

The results described in this paper are significant, in that they contradict the usual assumption of uniform, or uniformly increasing, accretion in Chalk catchments. This raises an important question concerning the manner of groundwater accretion, and specifically whether the mechanism of groundwater seepage to chalk streams predominantly comprises local point-source flows, i.e. groundwater springs discharging to the river, or if diffuse inputs are most important. The data presented here also demonstrate the degree to which interpretations of flow accretion may differ when they are inferred from detailed current meter surveys, at a scale of 1-3km, compared with the analysis of discharge data from fixed gauges, at a scale of 10km, and highlight the need to take surface topography into account wherever possible.

Although the general results indicate that flow accretion is scale dependent, there is an underlying systematic variation in accretion along the profile of the river Lambourn. This may indicate an underlying, geological, control upon groundwater – river exchange, but may also reflect the influence of the dry valleys indicated in Figure 1. An example of a geological control on flow accretion would be sub-horizontal (i.e. parallel to the bedding plane) features with a vertical spacing of c. 50-70m. Assuming a combined angle of dip and channel slope of 1°, this would equate to a distance along the channel of between 2.8 and 4km. Accretion patterns are also likely to be influenced by local hard grounds, such as the Chalk Rock, which occurs at the boundary of the Upper and Middle Chalk. The Chalk Rock outcrops immediately south of Lambourn village, and the reach where it is present at a shallow depth coincides with the low accretion rate section in reaches 3 and 4. At Shefford Church (between reaches 5 and 6), the Chalk Rock lies at a depth of 30m, and seems to form the base of the active flow zone, with effectively no significant groundwater flow occurring beneath it. This suggests that the Chalk Rock has a very low vertical permeability, and in this case, there may be a point between Lambourn and Shefford Church where the Chalk Rock establishes control over the vertical location of the base of the active flow zone. At this point, groundwater flow changes from being predominantly beneath the Chalk Rock, to being exclusively above it.

The likelihood of discontinuities in the Chalk focussing river – aquifer exchange at specific points has been suggested by a number of studies. An extreme

example of this was described by Banks *et al.* (1995) in the Chalk of the Berkshire Downs, but the underlying control on the highly transmissive pathway identified from tracer testing was not explicitly identified. More generally, studies of the temporal and spatial variability in groundwater – river exchange have been limited by the resolution of longitudinal river stage data and groundwater level observations, to the extent that the nature of flow interaction, and particularly whether it is occurring in a uniform or point-source manner, cannot be readily determined. Further quantification of these flows requires an appreciation of the inter-relationship between channel bed permeability and the combined nature and distribution of the valley floor alluvial deposits. There have been only limited field investigation of both parameters in chalk streams: Younger *et al.*'s (1993) study of streambed sediment focussed on the River Thames, and the hydraulic characteristics of such sediments in tributary streams has not been adequately studied. Similarly, whilst Grey *et al.* (1995) highlighted the paucity of studies describing valley floor hydrogeology, there has been little recent progress. This is important as any permeable alluvial horizons may represent pathways of preferential flow through the catchment that will complicate further the pattern of groundwater accretion.

The detailed accretion data-set implies that catchment topography, and specifically the location of dry valleys, has a significant control on the distribution of flow accretion. It is very noticeable, for example, that all the high accretion reaches are adjacent to, or immediately upstream of, the junction of major dry valleys with the main valley of the Lambourn. These are: i. the Lynch Wood springs above Lambourn village, ii. the West Shefford to East Shefford reach which corresponds to the Great Shefford dry valley, iii. the reach to Shaw which includes the Winterbourne valley. It is interesting to speculate on possible explanations for these observations: the likelihood of dry valleys exhibiting enhanced permeability, relative to interfluve locations, is generally recognised (e.g. Allen *et al.* 1997) but this by itself is insufficient to explain enhanced accretion rates at their confluence with the main valley, as over time the main valley transmissivity should have developed to accommodate the additional flow volume without increasing seepage to the river. There are two possible explanations: the enhanced volume of groundwater flow from the dry valleys may actually be responsible for the observed high accretion rates in certain reaches, in which case the development of the chalk fissure system that

accounts for the transmissivities of the main and dry valleys have yet to reach an equilibrium state for current environmental conditions. Alternatively, it may not specifically be the dry valleys that represent the key control on accretion, but rather the underlying geological/ structural control on the dry valley development that also influences the direction and rate of groundwater flow.

The extent to which dry valleys may influence the spatial distribution of accretion is also illustrated by the behaviour of the reach immediately downstream of East Shefford area, where accretion is inversely proportional to catchment discharge. This might be explained if the Great Shefford dry valley were to capture an increasing proportion of regional scale groundwater flows as the water-table rises. One effect of this would be to restrict any increase in the water-table immediately downstream of East Shefford, thereby producing a reduction in accretion rates in this reach as groundwater levels and catchment discharge increase. Clearly, however, this is largely speculative, and requires further investigation, for example, explicitly including the effects of dry valleys in regional catchment models and supports Bradford's (2002) argument that a 'process-based' approach that links the distribution of aquifer properties and discharge zones is required to advance our knowledge of chalk hydrogeology. This is particularly important if we are to understand the response of such catchments to future environmental change and especially to changes in the frequency of extreme events, such as prolonged drought, with reduced recharge, low groundwater levels and changing patterns of accretion, and equally the behaviour of the catchment when prolonged precipitation corresponds to period of high groundwater levels, when chalk rivers may exhibit a 'flashy response' leading to groundwater floods.

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List of Figures:

Gauge number	Source	Date	Summary Flow Data			Distance above Kennet confluence (km)	Comments
			Q10	Mean	Q95		
39033	Winterbourne at Bagnor G/S	6/62 → present	0.317	0.17	0.051	n/a	Good rating curve
39019	Lambourn at Shaw G/S	6/62 → present	2.9	1.75	0.761	2.6	Good rating curve
39031	Lambourn at Welford G/S	6/62→10/83	1.67	1.02	0.414	12.5	Variable rating curve: affected by summer macrophyte growth
39032	Lambourn at East Shefford G/S	4/66→11/85; 10/99→10/02	1.57	0.76	0.113	15.8	Good rating curve
	Current Meter Records	1/62 → 11/79; 10/99 → 10/02					

Table 1; Sources of Flow Data for the Lambourn Catchment:

	Discharge at Shaw (m^3s^{-1})	Length of River Lambourn contributing to flow (km)	Mean catchment flow accretion ($m^3s^{-1}km^{-1}$)
Minimum	0.411	13.95	0.029
Mean	1.746	19.02	0.088
Maximum	6.670	23.35	0.286
Standard Deviation	0.883	3.458	0.033
Coefficient of variation	50.6%	18.2%	37.5%

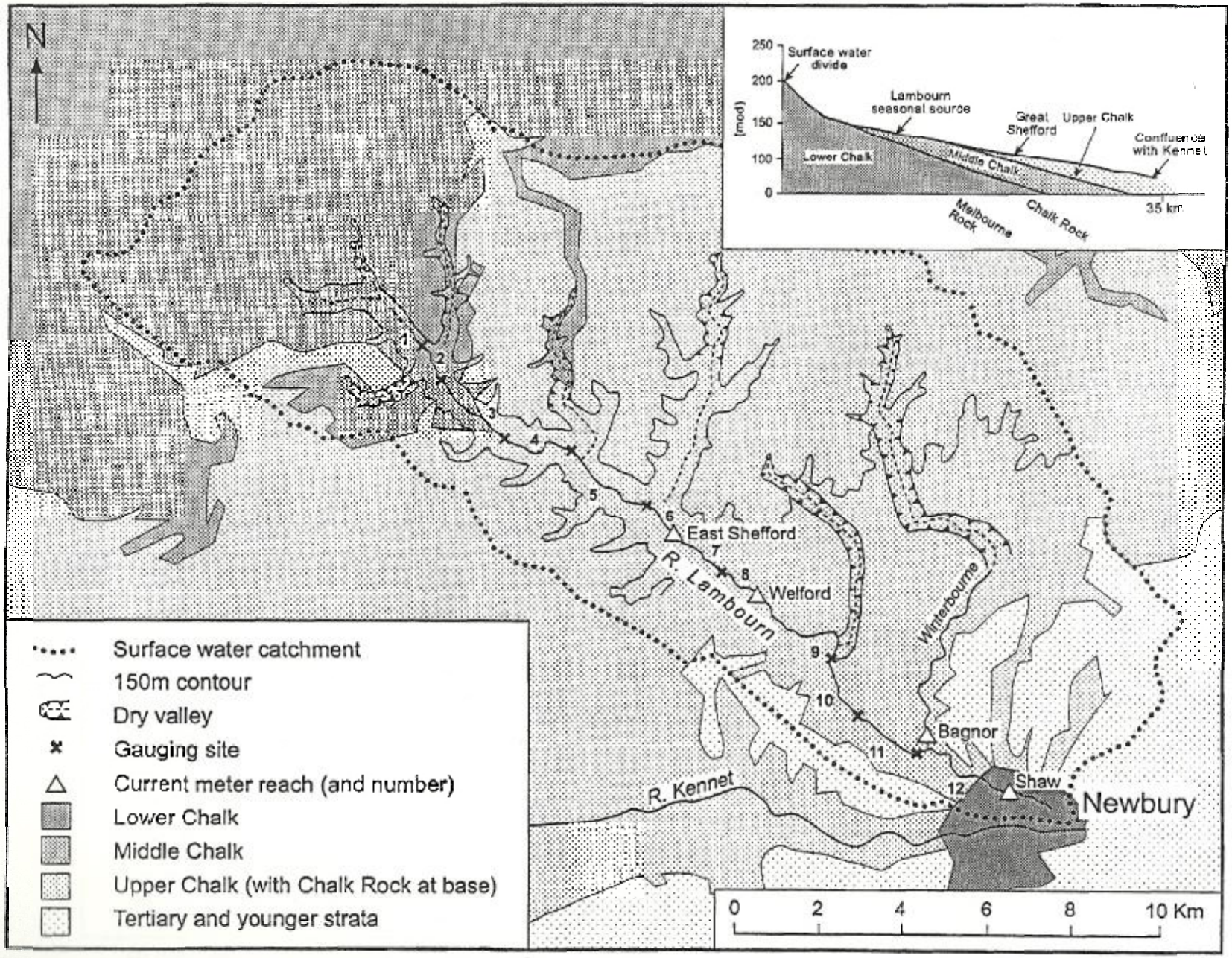
Table 2: Summary statistics for catchment-scale accretion above the gauging station at Shaw for the period 1983-2001.

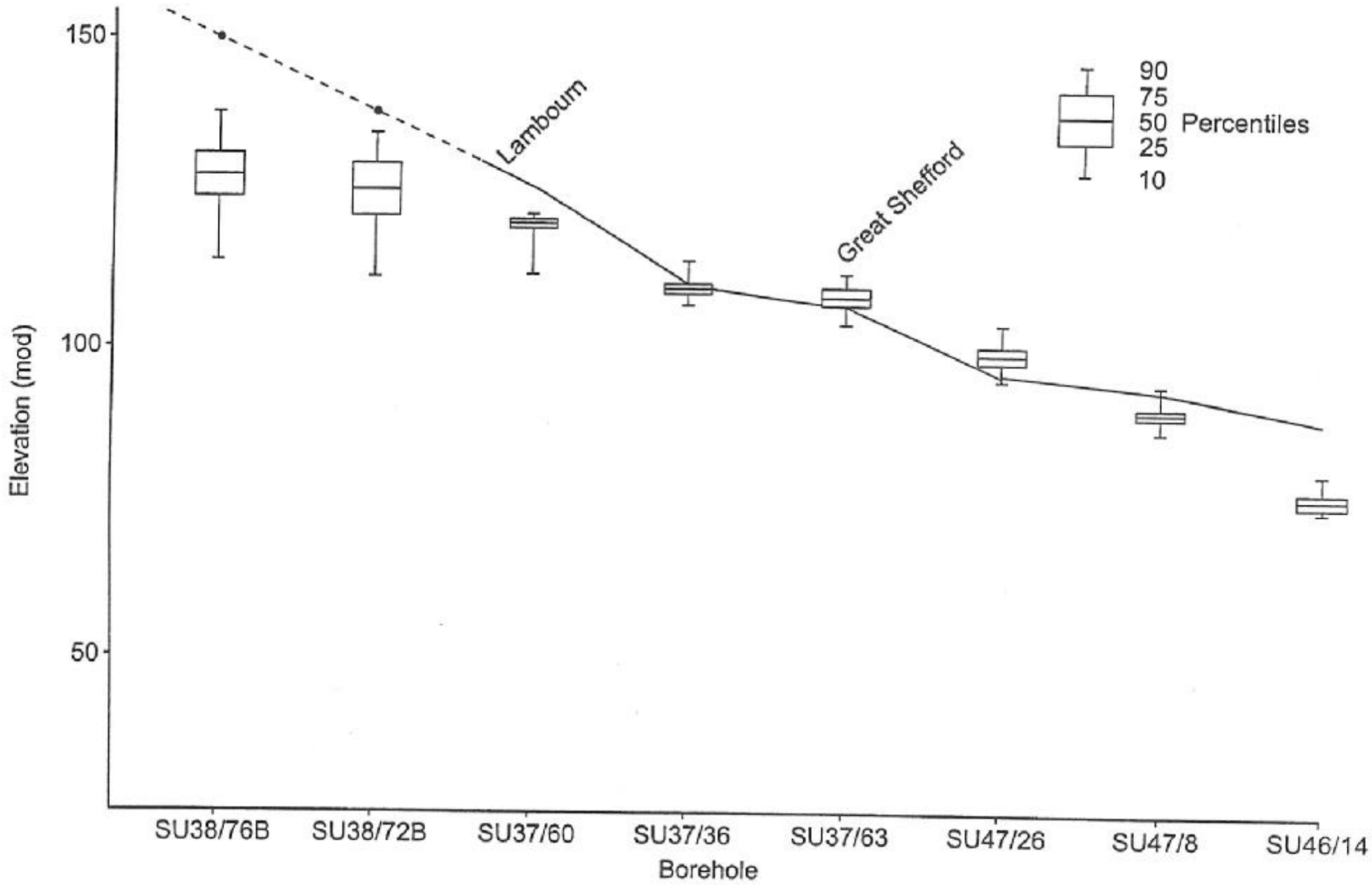
Accretion expressed in volumetric terms:						
	Accretion to East Shefford (m^3s^{-1})	Accretion between East Shefford and Welford		Accretion between Welford and Shaw		Accretion on the Winterbourne to Bagnor (m^3s^{-1})
		m^3s^{-1}	$m^3s^{-1}km^{-1}$	m^3s^{-1}	$m^3s^{-1}km^{-1}$	
Minimum	0	-0.23	-.08	0.07	0.01	0.01
Mean	0.76	0.29	0.10	0.55	0.06	0.18
Maximum	2.46	0.91	0.31	1.48	0.16	0.55
Standard Deviation	0.55	0.09	0.03	0.21	0.02	0.10
Coefficient of Variation	71.5%	31.7%		38.6%		53.7%
Accretion expressed as percentage of catchment discharge:						
Minimum	0%	-8.3%		4.8%		1.0%
Mean	37.2%	20.3%		32.6%		9.9%
Maximum	69.0%	55.6%		63.1%		27.6%
Standard Deviation	14.9%	11.1%		7.2%		2.8%
Coefficient of Variation	40.0%	54.6%		22.1%		28.4%

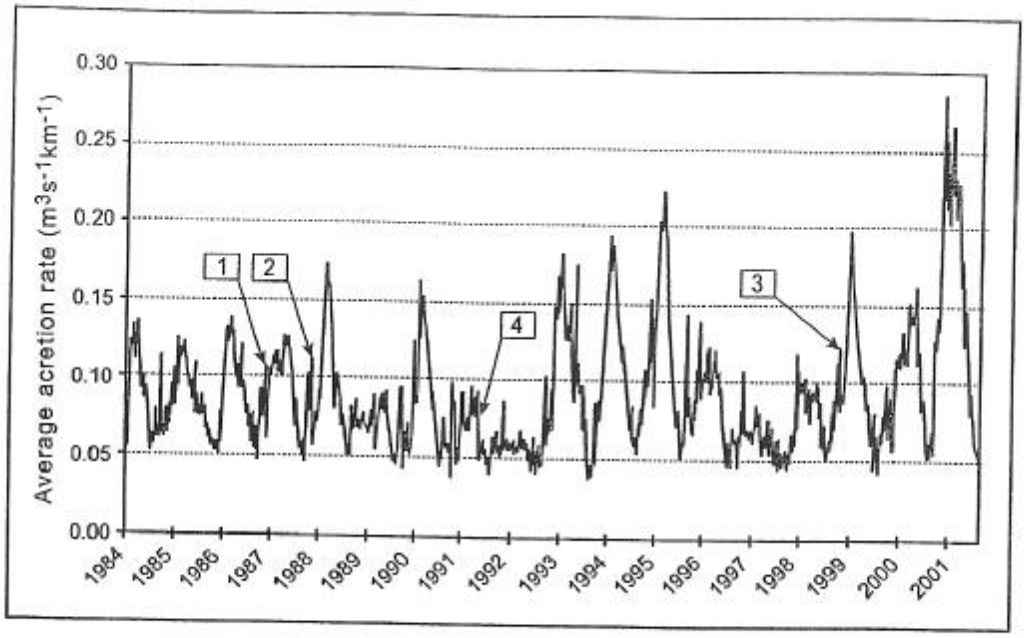
Table 3. Estimated quantity of flow accretion occurring between gauging stations, expressed as total flows in m^3s^{-1}, and as a proportion of catchment discharge, for the period June 1966 to September 1983.

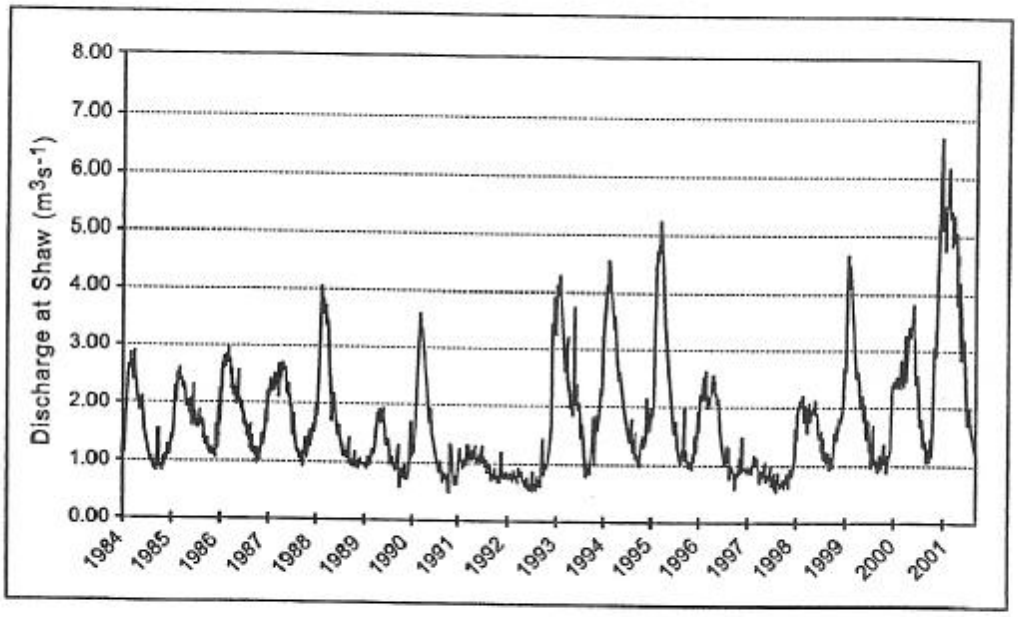
Reach No.	Distance below source (km)	No. of paired data points	Minimum	Mean	Maximum	Standard Deviation	Relationship between FAI in reach to Shaw Discharge (Q);	
1	**0.95 ® 1.95**	**72**	**0.0**	**0.129**	**0.480**	**0.121**	**0.87Q + 0.032 (41%)**	**+++**
2	1.95→3.10	49	0.0	0.086	0.383	0.085	0.34Q + 0.451 (12%)	+
3	3.10→5.10	44	-0.090	0.020	0.115	0.034	0.14Q – 0.039 (18%)	+
4	**5.10 ®7.55**	**55**	**-.0040**	**0.024**	**0.135**	**0.032**	**0.25Q – 0.218 (46%)**	**+++**
5	7.55→9.40	54	-0.049	0.063	0.195	0.048	0.12Q + 0.062 (12%)	+
6	**9.40®10.90**	**68**	**-0.014**	**0.211**	**0.560**	**0.129**	**0.13Q + 2.283 (1%)**	**O**
7	**10.90®12.85**	**37**	**0.072**	**0.139**	**0.338**	**0.052**	**-0.92Q + 3.81 (56%)**	**---**
8	12.85→13.85	36	-0.080	0.123	0.490	0.082	-.90Q + 3.497 (26%)	--
9	13.85→16.50	18	-0.045	0.068	0.162	0.053	0.10Q + 0.601 (2%)	O
10	16.50→18.65	16	-0.042	0.054	0.251	0.073	-0.08Q + 0.824 (0.4%)	O
11	18.65→20.40	28	-0.217	-0.019	0.114	0.073	0.08Q – 0.349 (0.4%)	O
12	20.40→23.35	28	0.018	0.152	0.380	0.089	0.01Q + 1.892 (0)	O

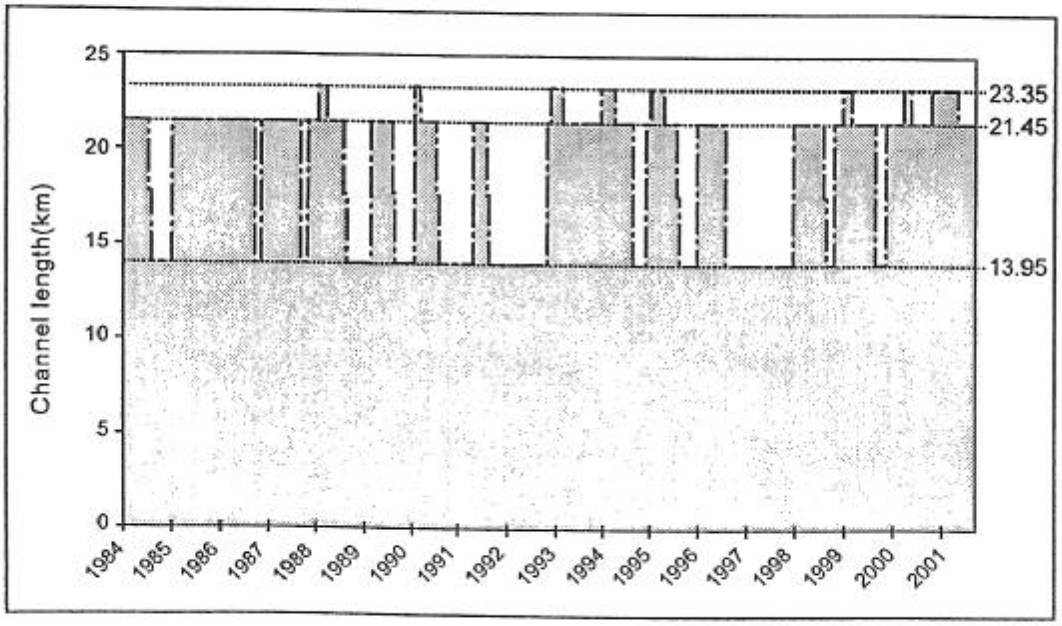
Table 4: Estimates of accretion rate (in $\mathbf{m^3s^{-1}}$) for 12 reaches along the River Lambourn; and their relationship to catchment discharge. .

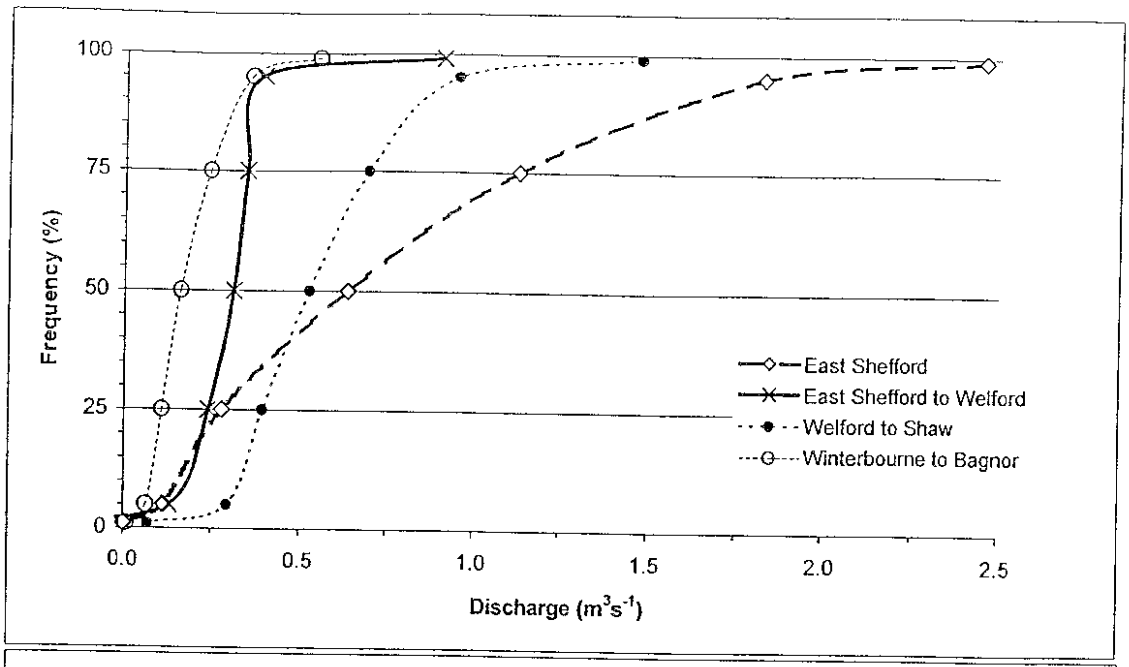

N
Surface water divide
Lambourn seasonal source
Great Shefford
Upper Chalk
Confluence with Kennet
Lower Chalk
Middle Chalk
Melbourne Rock
Chalk Rock
35 km
250
200
150
100
0
(mod)
East Shefford
Welford
R. Lambourn
Winterbourne
Bagnor
Shaw
Newbury
R. Kennet
1
2
3
4
5
6
7
8
9
10
11
12
Surface water catchment
150m contour
Dry valley
Gauging site
Current meter reach (and number)
Lower Chalk
Middle Chalk
Upper Chalk (with Chalk Rock at base)
Tertiary and younger strata
0
2
4
6
8
10 Km

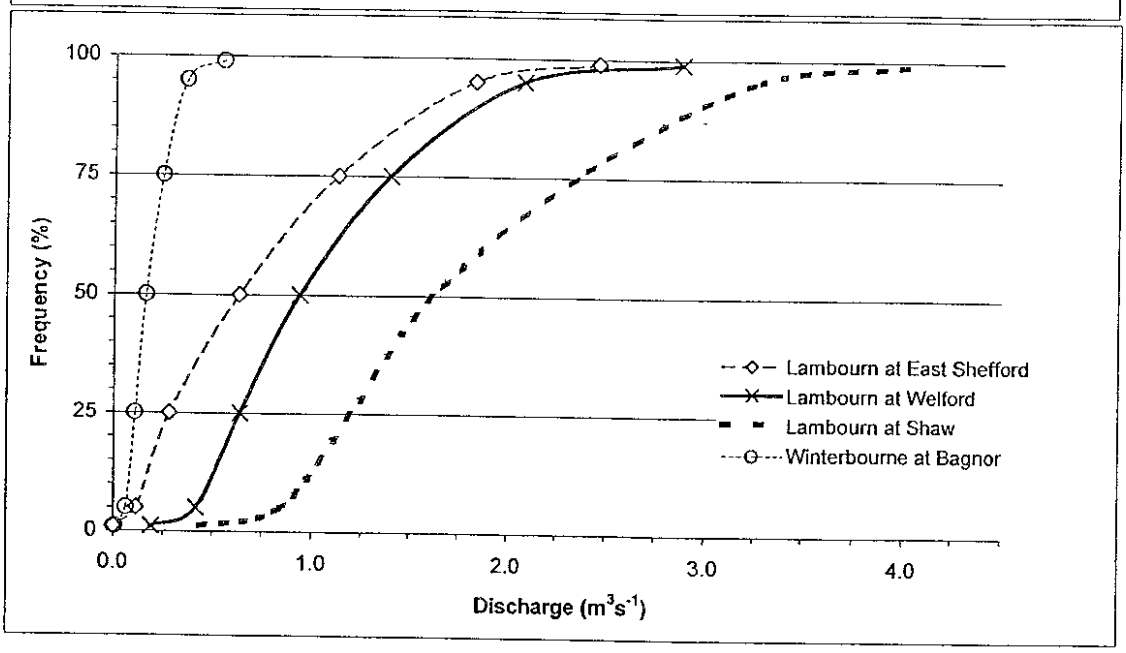

150
100
50
Elevation (mod)
Lamboum
Great Shefford
90
75
50
25
10
Percentiles
SU38/76B
SU38/72B
SU37/60
SU37/36
SU37/63
SU47/26
SU47/8
SU46/14
Borehole

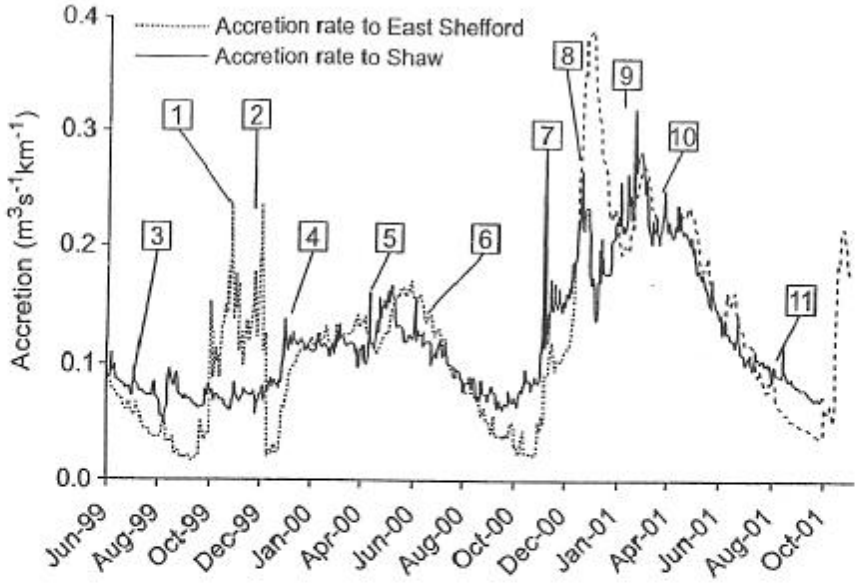

Average acretion rate (m3s-1km-1)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
1
2
3
4
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001

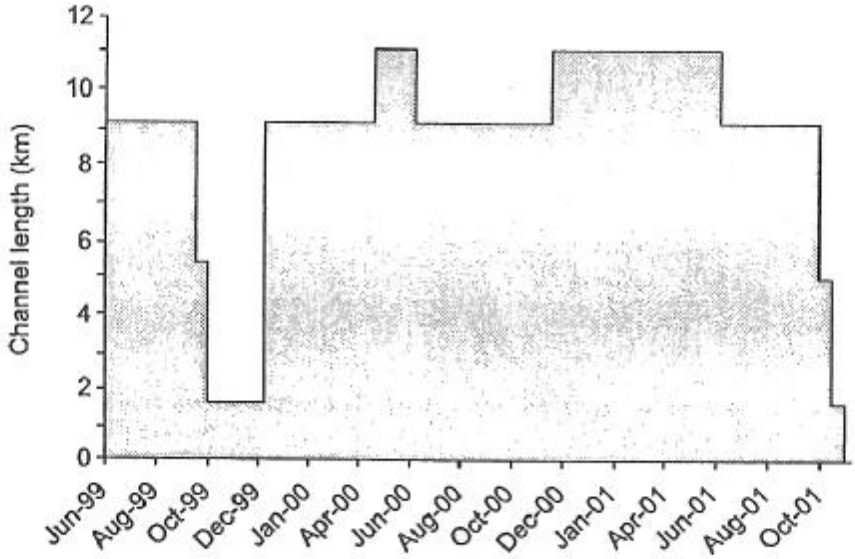

Discharge at Shaw (m3s-1)
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001

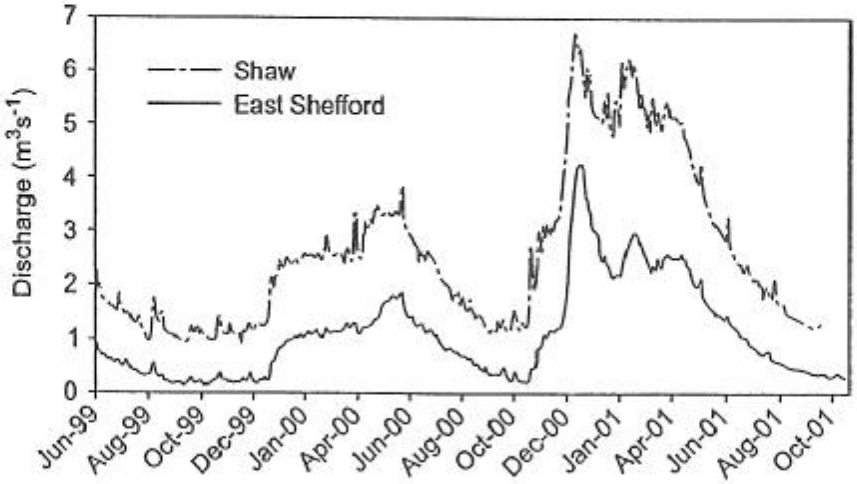

Channel length(km)
25
20
15
10
5
0
23.35
21.45
13.95
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001

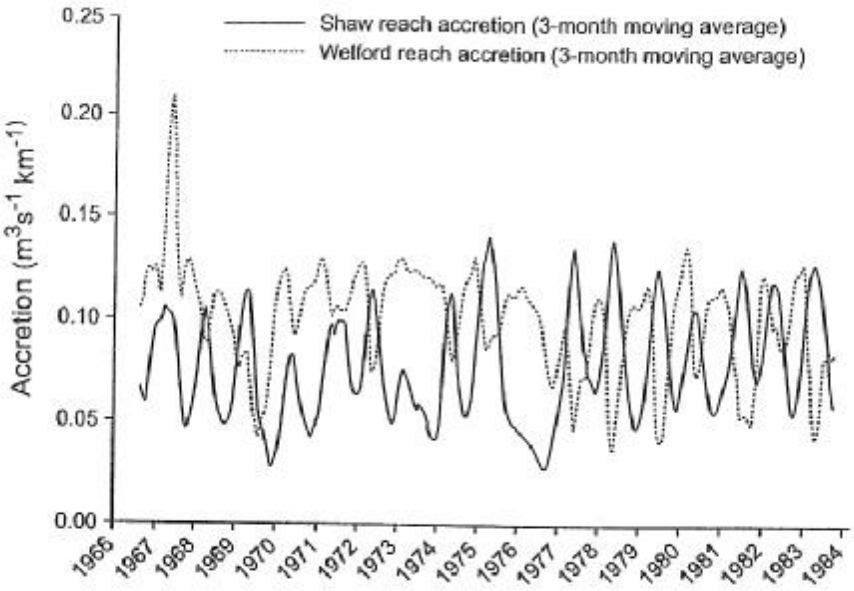

100
75
50
25
0
Frequency (%)
0.0
0.5
1.0
1.5
2.0
2.5
Discharge (m3s-1)
East Shefford
East Shefford to Welford
Welford to Shaw
Winterbourne to Bagnor

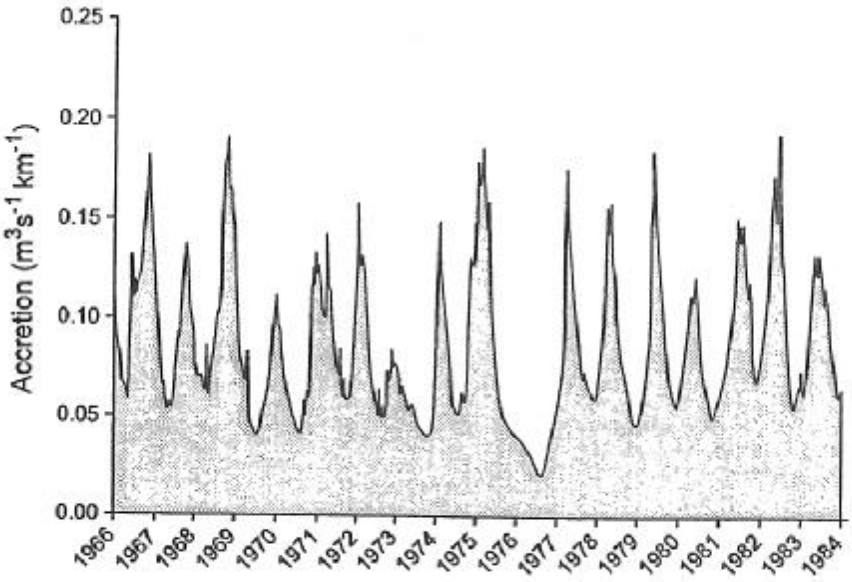

100
75
50
25
0
Frequency (%)
0.0
1.0
2.0
3.0
4.0
Discharge (m3s-1)
Lambourn at East Shefford
Lambourn at Welford
Lambourn at Shaw
Winterbourne at Bagnor

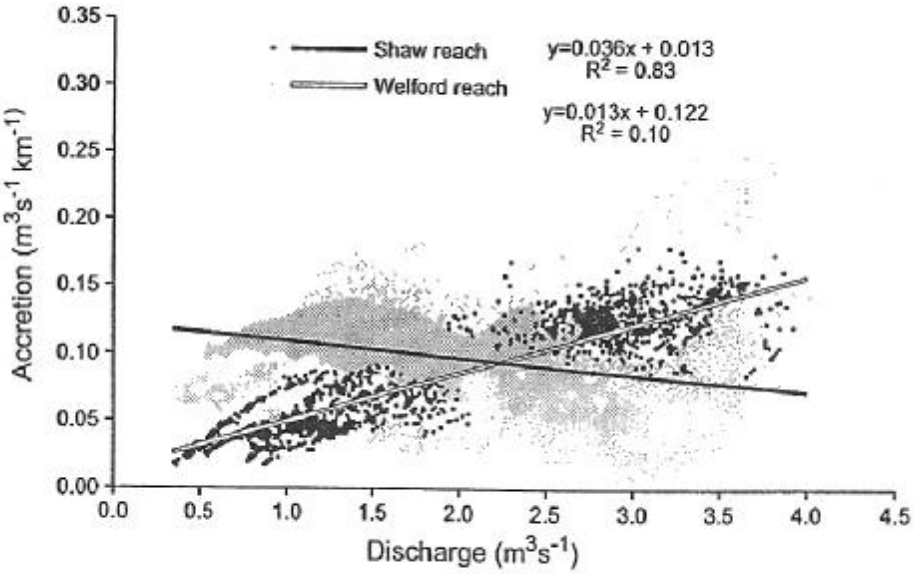

Accretion rate to East Shefford
Accretion rate to Shaw
Accretion (m3s-1km-1)
0.4
0.3
0.2
0.1
0.0
1
2
3
4
5
6
7
8
9
10
11
Jun-99
Aug-99
Oct-99
Dec-99
Jan-00
Apr-00
Jun-00
Aug-00
Oct-00
Dec-00
Jan-01
Apr-01
Jun-01
Aug-01
Oct-01

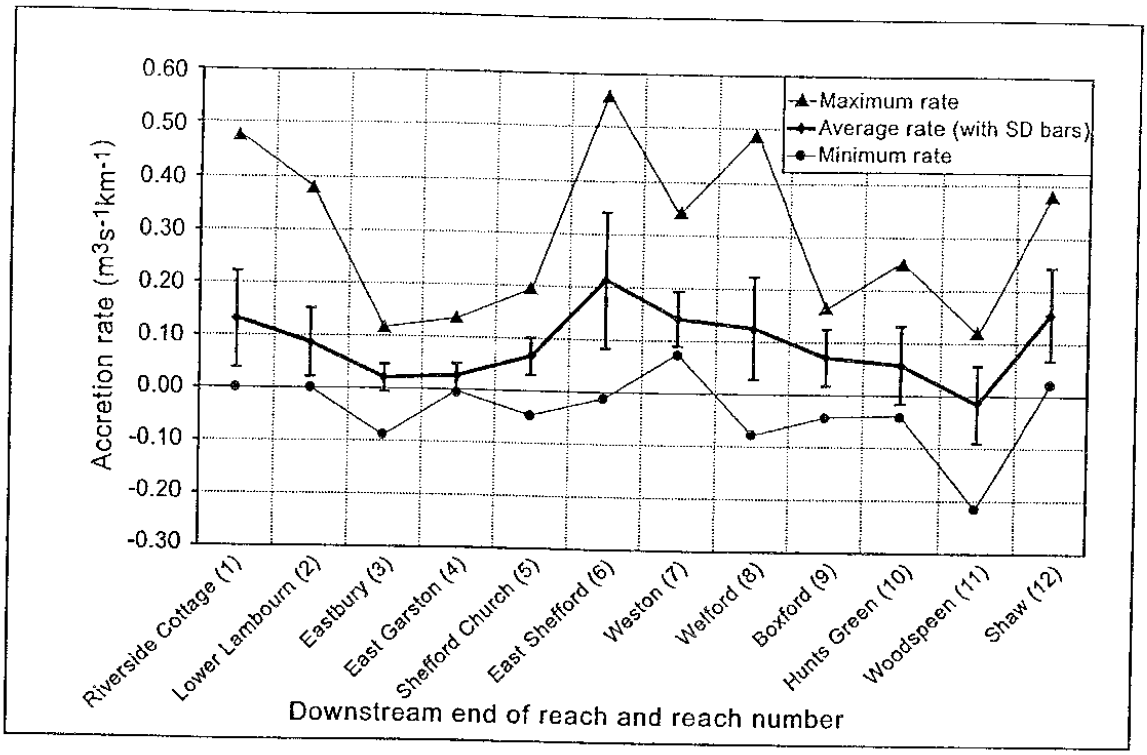

Channel length (km)
12
10
8
6
4
2
0
Jun-99
Aug-99
Oct-99
Dec-99
Jan-00
Apr-00
Jun-00
Aug-00
Oct-00
Dec-00
Jan-01
Apr-01
Jun-01
Aug-01
Oct-01

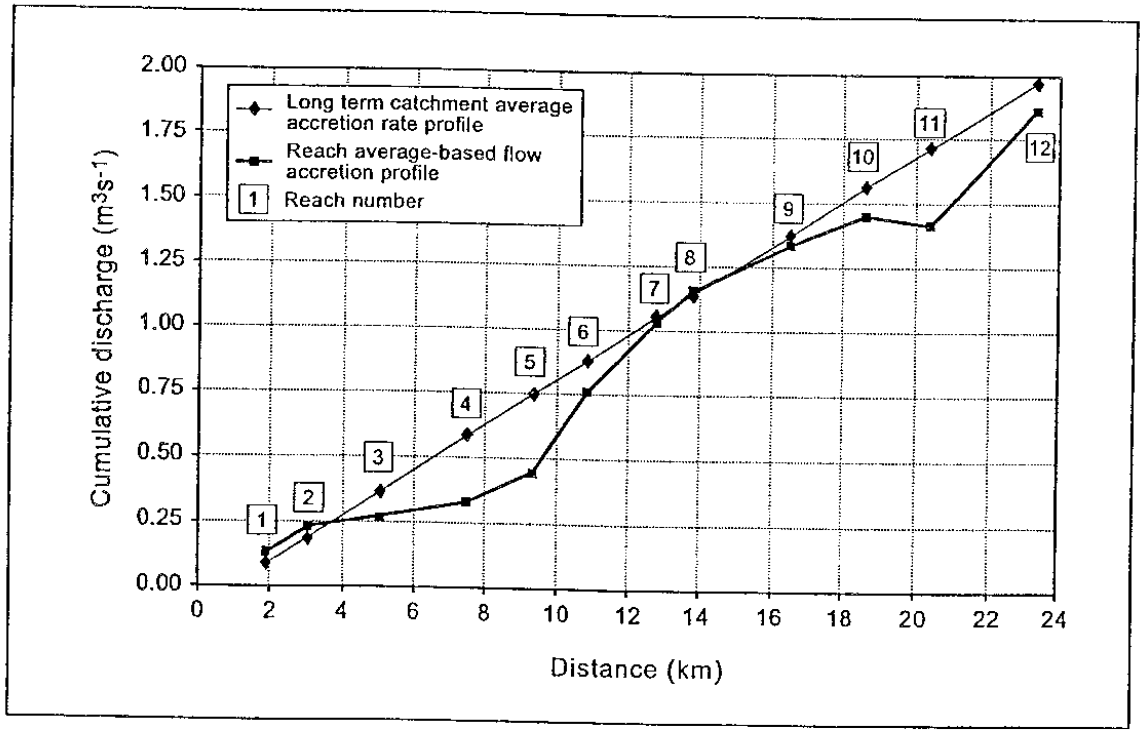

Shaw
East Shefford
Discharge (m3s-1)
7
6
5
4
3
2
1
0
Jun-99
Aug-99
Oct-99
Dec-99
Jan-00
Apr-00
Jun-00
Aug-00
Oct-00
Dec-00
Jan-01
Apr-01
Jun-01
Aug-01
Oct-01

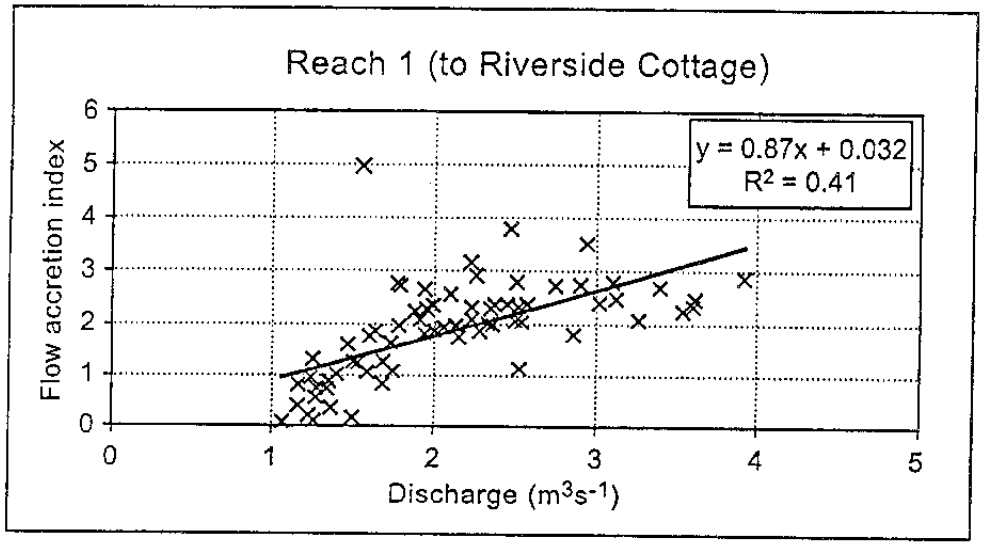

Shaw reach accretion (3-month moving average)
Welford reach accretion (3-month moving average)
Accretion (m3s-1 km-1)
0.25
0.20
0.15
0.10
0.05
0.00
1966
1967
1968
1969
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984

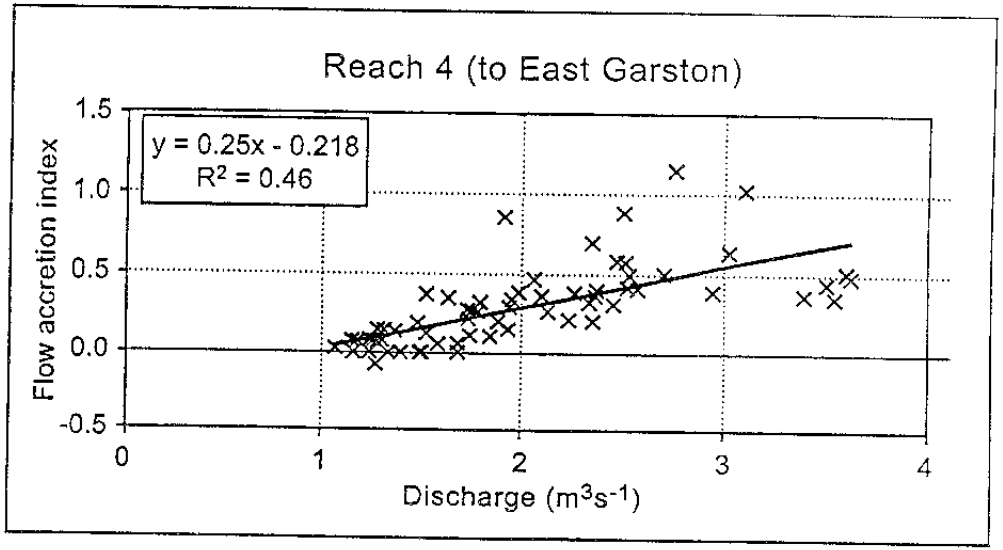

Accretion (m3s-1 km-1)
0.25
0.20
0.15
0.10
0.05
0.00
1966
1967
1968
1969
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984

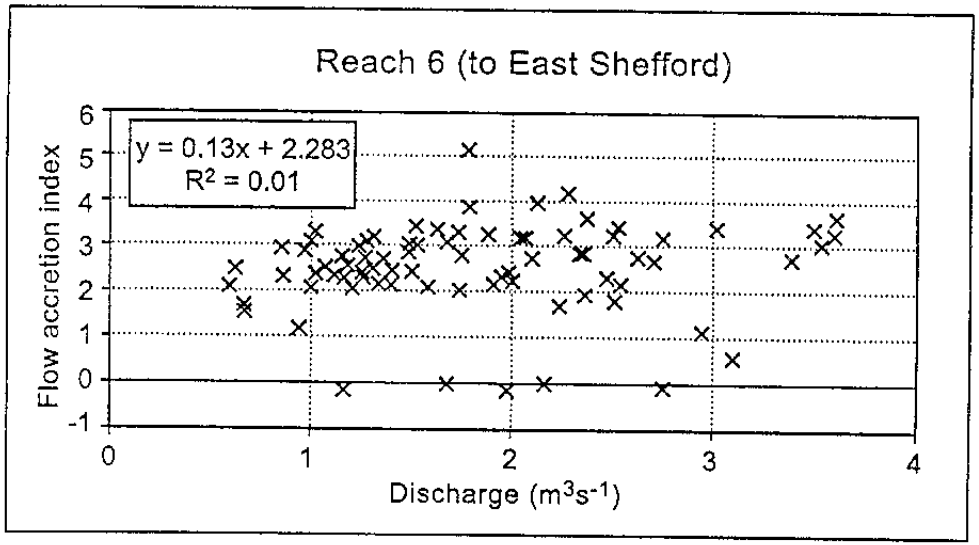

Shaw reach
Welford reach
y=0.036x + 0.013
R2 = 0.83
y=0.013x + 0.122
R2 = 0.10
Accretion (m3s-1 km-1)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Discharge (m3s-1)

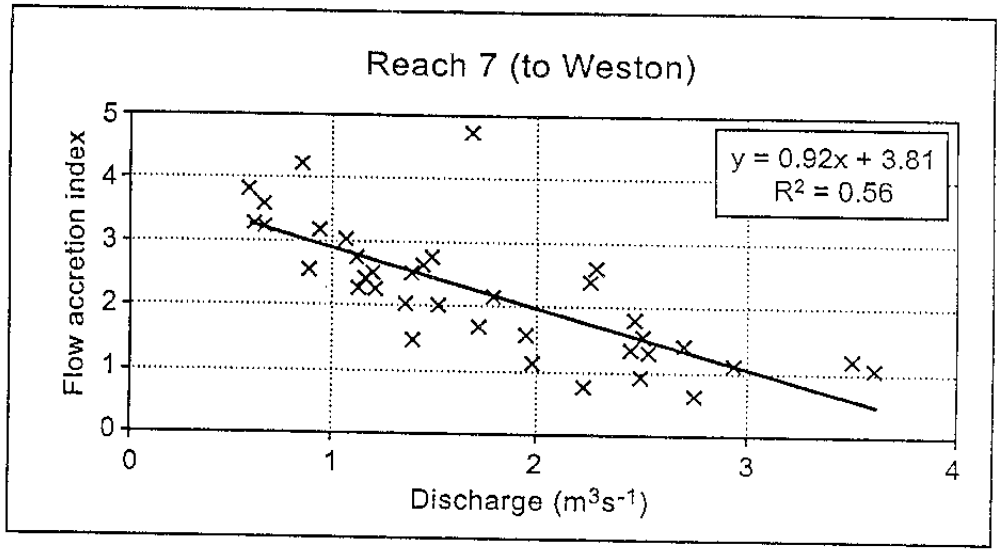

Maximum rate
Average rate (with SD bars)
Minimum rate
Accretion rate (m3s-1km-1)
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.10
-0.20
-0.30
Riverside Cottage (1)
Lower Lambourn (2)
Eastbury (3)
East Garston (4)
Shefford Church (5)
East Shefford (6)
Weston (7)
Welford (8)
Boxford (9)
Hunts Green (10)
Woodspeen (11)
Shaw (12)
Downstream end of reach and reach number


Long term catchment average accretion rate profile
Reach average-based flow accretion profile
1 Reach number
Cumulative discharge (m3s-1)
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
0
2
4
6
8
10
12
14
16
18
20
22
24
Distance (km)


Reach 1 (to Riverside Cottage)
y = 0.87x + 0.032
R² = 0.41
Flow accretion index
Discharge (m³s⁻¹)
0
1
2
3
4
5
6


Reach 4 (to East Garston)
y = 0.25x - 0.218
R² = 0.46
Flow accretion index
Discharge (m³s⁻¹)
1.5
1.0
0.5
0.0
-0.5
0
1
2
3
4


Reach 6 (to East Shefford)
y = 0.13x + 2.283
R² = 0.01
Flow accretion index
Discharge (m³s⁻¹)
6
5
4
3
2
1
0
-1
0
1
2
3
4


Reach 7 (to Weston)
y = 0.92x + 3.81
R² = 0.56
Flow accretion index
Discharge (m³s⁻¹)
5
4
3
2
1
0
0
1
2
3
4