CONCEPTUAL AND DIGITAL GEOLOGICAL MODELS OF CHALK CATCHMENTS IN NORTHERN FRANCE AND SOUTHERN ENGLAND

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A thesis submitted in partial fulfilment of the requirements of the University of Brighton for the degree of Doctor of Philosophy

December 2014

University of Brighton
Abstract

The conceptual geological model is a fundamental component in any engineering geological or hydrogeological project. Three dimensional (3D) digital geological models and visualisations, which represent not only the 3D stratigraphical model but also 3D non-stratigraphical features (e.g. the weathered zone), are relatively uncommon despite a progressive increase in the use of desktop GIS and geological modelling software. In light of this, the objectives of this research were to investigate and characterise the field geology of the study areas, the Hallue and Patcham Chalk groundwater catchments in northern France and southern England, and to develop representative 3D digital geological models. These groundwater catchments, also the focus for the FLOOD1 research project, had experienced groundwater flooding in the winter of 2000-2001. The stratigraphical framework for the Chalk of southern England was utilised to map and correlate the Chalk exposed in the research catchments. These data were used to evaluate the structural geology of the research catchments in terms of folding and faulting. Scanline and borehole optical televiewer surveys were undertaken to characterise the fracturing of the rock mass throughout the stratigraphical sequence, and the relationship between vein fabrics, within the Chalk matrix, and fractures was evaluated. The local variation in Quaternary geology, geomorphology and soil properties was also investigated in the vicinity of the Patcham Catchment FLOOD1 recharge site and documented at exposures in Hallue Catchment. The data from the field investigations were synthesised into 3D digital geological models of the research catchments using GIS (ArcGIS 9.0) and geological modelling software (GSI3D). Borehole data, from ground investigations on areas of Chalk outcrop, were used to supplement the field data and produce a predictive model for the base of the weathered zone (engineering rockhead). Surfaces for the base of the weathered zone, water tables and discrete marker horizons were incorporated, with the geological models, into standalone subsurface viewers. These models allowed the geological differences between the research catchments to be considered and the hydrogeological implications conceptualised. The methods presented in this research may be applied to other areas of Chalk outcrop to aid hydrogeological conceptualisation.
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Acknowledgements

The work presented in this thesis was undertaken in conjunction with the INTERREG III-A FLOOD1 research project. FLOOD1 was a tripartite research project comprising the Bureau Recherches Géologique et Minières (BRGM), the British Geological Survey (BGS) and the University of Brighton. The FLOOD1 project managers were Marie-Luce Noyer (BRGM), Brian Adams (BGS), Professor Rory Mortimore and Dr David Pope. The research opportunity and financial support of the FLOOD1 project is gratefully acknowledged.

Colleagues from BGS and BRGM provided much support and guidance during this undertaking for which I am grateful. Christian Nail (BRGM), Arnaud Wuilleumier (BRGM) and Pierre Chrétien (BRGM) from the BRGM Amiens office provided access to data and assistance with organising fieldwork in the Hallue Catchment. Christian Robelin (BRGM) provided support with understanding the Paris Basin Chalk stratigraphy, assistance with fieldwork and access to the Hallue FLOOD1 recharge site borehole cores. Dr Donald Aldiss (BGS) provided training in the BGS method of Chalk mapping and advice on research writing. David Buckley (BGS) and Alex Gallagher (BGS) coordinated and undertook geophysical surveying in boreholes in the Patcham Catchment. Helen Rutter (BGS), Holger Kessler (BGS) and Ricky Terrington (BGS) gave access to data and assistance with the GSI3D modelling software.

I would like to thank Professor Rory Mortimore for his supervision, advice and encouragement. I would also like to thank Dr Martin Smith for his supervision and assistance with field and lab research techniques. Thanks go to Ian Molyneux for the many hours of discussion and for his patient assistance with fieldwork. I would also like to thank Dr David Pope for his continued support and assistance during the research and also in the final stages of submission. Thanks go to Dr Stewart Ullyott who provided advice and access to data. Jessica Flynn and Emily Riddiford provided assistance with fieldwork, Chris and Simon Cook provided advice at key points during preparation of the thesis and Imogen Privett provided assistance with figures and proof reading. Many other colleagues from the University of Brighton provided assistance in some form during this work for which I am grateful.
In the final stages of this undertaking, my employers, CH2M Hill (formerly Halcrow) and Thames Tideway Tunnel (project of Thames Water Utilities Limited), have been particularly supportive. From these organisations, I would like to thank Iain Tromans (CH2M Hill), Des Andrews (CH2M Hill), Colin Warren (CH2M Hill), John Harris (Thames Tideway Tunnel) and Tim Newman (Thames Tideway Tunnel).

Lastly, I would like to thank my parents and friends for their encouragement and patience - it would not have been possible without their support.
Declaration

I declare that the research contained in this thesis, unless otherwise formally indicated within the text, is the original work of the author. The thesis has not been previously submitted to this or any other university for a degree, and does not incorporate any material already submitted for a degree.

Signed

Dated
Chapter 1 Introduction

1.1 Research Context

The Chalk Group is the principle aquifer in both England and France. The area of the Chalk outcrop is approximately 21,500 km$^2$ in England (Monkhouse and Richards, 1982) and 70,000 km$^2$ in France (Crampon et al., 1993). As an aquifer, it provides over 50% of the groundwater supply in England. The total volume of water contained within the Chalk is between $2.02 \times 10^{12}$ and $2.63 \times 10^{12}$ m$^3$ - although only a small proportion ($0.4 \times 10^9 - 1.0 \times 10^9$ m$^3$) of this is drainable (Lewis et al., 1993). In addition to water draining from the saturated zone during seasonal water level fluctuations, it is estimated that the unsaturated zone could contribute 80% of baseflow to rivers and streams, or dynamic storage, due to slow drainage (Lewis et al., 1993). Its occurrence in the south and east of England, where population density is high and there is a large demand for water from industry and agriculture, make it strategically important.

The Chalk aquifer, as well as being an important resource, may also pose a hazard during periods of high groundwater level. For example, during the winter of 2000-2001, large floods occurred in northern France and in southern England, particularly in valleys developed on Chalk outcrops. In many of these regions, a sudden rise of groundwater level was recorded just before the floods, and the flooding typically had a long duration – often lasting weeks or months after rainfall had ceased. Groundwater flooding events in the INTERREG III-A region (Figure 1.1) at this time resulted in damage costing £1 million in the Brighton area and tens of millions of Euros in the Somme Basin (Anon, 2004).

The understanding of Chalk geology has advanced considerably in the last 30 years with the advent of the revised Chalk lithostratigraphy (Mortimore, 1986; Mortimore et al., 2001; Hopson, 2005; Mortimore, 2011), the changes in BGS Chalk mapping techniques (Bristow et al., 1997) and new BGS maps e.g. Chichester and Bognor, Salisbury, Newbury (British Geological Survey, 1996, 2005, 2006b). This revised lithostratigraphical framework has also been utilised widely in hydrogeology and engineering geology in the United Kingdom. Examples of recent construction
projects which have utilised it include the Channel Tunnel Rail Link, Crossrail and Thames Water’s Lee and Thames Tunnel.

Figure 1.1 INTERREG III-A funding region 2000-2008. Green indicates the core funding area and yellow indicates the extended funding area.

The Chalk lithostratigraphy in Southern England comprises nine formations which denote broad lithological changes in the Chalk and are constrained by a series of distinct lithological and fossil marker horizons. These horizons have allowed stratigraphical precision to metre, and sometimes centimetre, accuracy where both lithological and fossil marker horizons are present (Mortimore, 2011). In addition, within the Chalk lithostratigraphical framework local variation in lithological and physical properties due to structural, sedimentological and geomorphological variations may be more easily recognised and accounted for.

Over the same period as the developments in Chalk stratigraphy, there have been advances in fields associated with the Chalk Group. This includes Upper Cretaceous tectonics (e.g. Mortimore and Pomerol, 1991a; Mortimore and Pomerol, 1997; Mortimore et al., 1998); Upper Cretaceous eustatic sea level change (Haq et al., 1987, 1988; Mortimore and Pomerol, 1991b; Voigt and Hilbrecht, 1997; Hancock, 2000); Cenozoic denudation and landscape evolution (e.g. Jones, 1999a, b); Quaternary deposits associated with Chalk landscapes (e.g. Catt, 1986; Antoine et al., 2003a; Laignel et al., 2003; Quesnel et al., 2003; Ulycott et al., 2004); the hydrogeology of the Chalk aquifer (e.g. Barker, 1993; Jones and Robins, 1999; Price et al., 2000; Mathias et al., 2005) and the engineering geology of the Chalk (e.g. Spink and Norbury, 1990; Bowden et al., 2002; Lord et al., 2002; Spink, 2002). This
has led to progressively more advanced conceptual models of the Chalk as a rock mass and as an aquifer (Figure 1.2).

![Conceptual ground model of a Chalk valley](figure12.png)

Figure 1.2 Conceptual ground model of a Chalk valley (Mortimore et al., 1996; Lord et al., 2002)

The conceptual ground model shown in Figure 1.2 demonstrates the 3-D complexities that are associated with a valley in an area of Chalk outcrop. These complexities may have a significant influence on the engineering and hydrogeological behaviour of the Chalk rock mass and aquifer. The representation of complexities such as these are likely to become more common in 3-D digital geological models as modelling tools develop (Turner, 2006). Examples of models developed for areas of Chalk outcrop include the 3-D conceptualisation of the central South Downs aquifer (Robins, 2001; Robins et al., 2003), the Pang-Lambourn Catchment Model (Aldiss et al., 2002) and the London Basin Chalk Model (Royse, 2010). The advantage of presenting conceptual models in a 3-D digital format is that dimensions and inter-relationships can start to be measured e.g. volume of a geological unit and its extent below a water table. Digital models may also be used to predict ground conditions. In the simplest digital model, this may be to provide a prediction of the stratigraphical sequence in an area of unexplored ground but, if the model is attributed (e.g. Royse et al., 2009), it may also be used to predict engineering parameters.
1.1.1 FLOOD1 Research Project

The research presented in this thesis was undertaken to support the hydrogeological investigations of the FLOOD1 project and was conducted as part of the author’s role as a research assistant on the project. FLOOD1 was a tripartite research project funded by the European Regional Development Fund to investigate the role of groundwater in flooding events on Chalk catchments of the INTERREG III-A region (Figure 1.1). The FLOOD1 project partners comprised Bureau Recherches Géologique et Minières (BRGM), the British Geological Survey (BGS) and the University of Brighton.

The FLOOD1 research catchments comprised the Hallue groundwater catchment, northeast of Amiens, in the Department of the Somme – Picardy, northern France and the Patcham groundwater catchment, north of Brighton, in Sussex southern England (Figure 1.3).

The research catchments were located on areas of Chalk outcrop which had been affected by groundwater flooding in the winter of 2000-2001. The area of the Hallue groundwater catchment was approximately 220 km² during the flooding. It is situated, however, within the larger Somme Basin which has an area of approximately 7,380 km². The area of the Patcham groundwater catchment was approximately 40 km² during the flooding. It is situated within the larger Brighton aquifer block of the South Downs which has an area of approximately 139 km² (Jones and Robins, 1999) (Figure 1.4).
The objectives of the FLOOD1 research project were to understand the hydraulic behaviour of water flow in the unsaturated zone of the Chalk aquifer in relation to groundwater flooding; to develop unsaturated zone monitoring techniques; and to produce more appropriate methodologies and tools for forecasting groundwater flooding events. To meet these objectives, experimental recharge sites (Figure 1.5) were installed at selected locations within the Hallue and Patcham research catchments near to the areas of groundwater emergence. A third comparison site was also installed in the Pang Catchment, west of the village of East Ilsley, in Berkshire (Adams et al., 2008).
The recharges sites, designed by the Centre for Ecology and Hydrology (CEH), BGS and BRGM, contained raingauges, near-surface purgeable tensiometers, equitensiometers, EnviroSMART probes and deep-jacking tensiometers which were logged every 15 minutes (Figure 1.5). The deep boreholes also contained Diver data loggers in the saturated zone to measure groundwater level. The instruments were installed at regular intervals from 0.10 to 60 m BGL to provide a detailed profile and monitor the process of groundwater recharge through the unsaturated zone to the saturated zone of the Chalk aquifer - and the resulting evolution of the water table.

As only one recharge site was planned for each research catchment, the location of the site was critical. To select the locations for the recharge sites the following criteria had to be evaluated at each potential location:

(i) Could the deep unsaturated zone and water table be monitored?
(ii) Was the location near to and up hydraulic gradient from the groundwater flooding discharge point?
(iii) Would the shallow instruments be installed in the Chalk and not in Palaeogene deposits, Quaternary deposits or in a karst setting?
(iv) Would the instruments be installed in the Chalk units which experienced groundwater fluctuation during episodes of groundwater flooding?
To complement the data collected from the experimental recharge sites, a programme of laboratory testing and field investigation was also undertaken in the research catchments. The results from these field investigations, and the subsequent geological modelling, are presented in this thesis.
1.2 Research Objectives

The overall hypothesis of this study was to show whether sufficiently representative geological models of the Hallue and Patcham catchments can be constructed to improve the understanding of the aquifer and its hydrogeological behaviour. To address this hypothesis, the objectives of this thesis were:

- To determine the stratigraphical range and lithological characteristics of the Chalk in the research catchments from collation and presentation of field data. Where appropriate, to develop frameworks to compare the stratigraphical and lithological characteristics of the Chalk between the research catchments.
- To identity the geological structures in the research catchments and compare characteristics of these structures between the research catchments in the context of the regional geological setting.
- To assess the Chalk discontinuity (fracture) characteristics, which influence the behaviour of the Chalk rock mass and aquifer, in the research catchments through collation and analysis of field, industrial and published data.
- To assess the relationship between stratigraphy, geological structure, discontinuity characteristics and geomorphology of the Chalk in the research catchments.
- To review the local relationship between geomorphology and bedrock geology on soil characteristics and the implications of this for the wider research catchments.
- To develop conceptual and digital geological models of the research catchments to synthesis and present the data collected.
- To utilise the digital geological models of the research catchments to assess the potential impact on the aquifer of stratigraphy, geological structure and geomorphology, and compare these findings between the research catchments.

This work was intrinsically linked to the Interreg IIIa FLOOD1 research project and a parallel PhD research project, conducted by the second research assistant on FLOOD1, into the hydrogeological characterisation of the Chalk aquifer with specific reference to unsaturated zone behaviour (Molyneux, 2012).
1.3 Research Methods

To achieve these objectives, the lithostratigraphical framework developed by Mortimore (1986) and Mortimore et al. (2001), and the field mapping techniques developed by the BGS (Bristow et al., 1997) were employed to survey and assess exposures in the research catchments. Lithostratigraphical data were also obtained from logging the FLOOD1 recharge site borehole core and from down-hole geophysical surveying of monitoring boreholes. These data were synthesised to produce revised geological maps and structure contours for the research catchments. Scanline and optical televiewer surveys were utilised to collect discontinuity data from selected exposures and boreholes in the research catchments. To investigate the localised relationship between geomorphology, bedrock geology and soil characteristics, differential GPS, electromagnetic (EM31) and field permeameter surveys were undertaken and combined with laboratory mineralogical (X-ray diffraction) and particle size analysis of soil samples. Digital geological models of the research catchments were developed using a combination of GIS (ArcGIS 9.0) and geological modelling (GSI3D 1.5.2) software (Kessler et al., 2004; Kessler et al., 2008). As part of the modelling process, borehole discontinuity profiles from industrial datasets and published discontinuity profiles were analysed in relation to geomorphology to develop a predictive model for the base of the weathered zone. The digital geological models for the research catchments were combined with the predicted surface for the base of the weathered zone and surfaces for typical water tables in standalone model viewers (GSI3D subsurface viewers). The digital geological models were then used to compare the research catchments and demonstrate how geological field observations and geological modelling may be used to enhance understanding of the aquifer and its hydrogeological behaviour.

1.4 Thesis Structure

Chapter 1 is an introduction to the research. It outlines the research context for the work presented in the thesis and the remit of the FLOOD1 research project. The objectives of the work are stated and the methods employed to meet these objectives are discussed. Finally, the thesis structure is presented.
Chapter 2 outlines the historical background literature to the research. Important information concerning the concepts and methods involved in the research are presented. Specifically the topics of geological and geomorphological evolution of southern England and northern France, Chalk stratigraphy and geological modelling and visualisation are reviewed.

Chapter 3 introduces the fieldwork aspect of the research. The different methods employed in each research catchment are discussed. The results from these field investigations are presented and the key information synthesised at the end of the chapter.

Chapter 4 presents the interpretation of the structural geology of the research catchments and discusses this interpretation in the context of the regional geological setting. The results from fracture surveys and vein fabric analysis in the research catchments are also presented and compared to the larger scale fold and fault structures.

Chapter 5 presents the findings from the study of geomorphology, Quaternary geology and soil characteristics surrounding the FLOOD1 recharge site in the Patcham Catchment. The results from this study are discussed in the context of current literature and the potential influence on the shallow instrumentation present at the recharge site.

Chapter 6 presents the methods, data and results from constructing the geological models of the research catchments. In particular, this chapter focuses on the processes involved in the construction of the models, the results from the modelling process and the constraints of the models.

Chapter 7 presents a discussion on how the geological models of the research catchments may be applied to aid hydrogeological conceptualisation of the aquifer. In particular, this chapter focuses on application of the geological models to aid conceptualisation of the unsaturated zone, and discussions are presented in the context of observations from long term groundwater monitoring in the catchments and the findings from the FLOOD1 research project.
Chapter 8 concludes the thesis by defining the results from the work and presenting the final conceptual and digital geological models of the research catchments. The limitations of the work are also discussed and recommendations for further work are made.
Chapter 2 Background Concepts

2.1 Introduction

This chapter presents key background information relating to the research areas on the topics of regional geological and geomorphological evolution, chalk lithology; stratigraphy of the Chalk Group in the UK and France, engineering and hydrogeological characteristics of the Chalk and geological modelling and visualisation.

The key research areas for this thesis in England and France involved the Chalk and overlying deposits. The extent of the Chalk outcrop is approximately 21,500 km² in England (Monkhouse and Richards, 1982) and 70,000 km² in France (Crampon et al., 1993) and is subject to continued construction and development. The Chalk is also the principle aquifer in both countries. Natural extreme events such as groundwater flooding have a significant impact on infrastructure and, with the pattern of recharge changing and the frequency of short term heavy rainfall events increasing, these events are likely to continue to occur and may become more frequent (Packman, 2007). It is essential, therefore, to have a detailed understanding of the geology of the aquifer to aid hydrogeological conceptualisation of groundwater processes, and potentially aid prediction, of these events.

The Chalk rock mass varies regionally in relation to sedimentary, tectonic, diagenetic and geomorphological history (Mortimore et al., 1990b; Mortimore and Pomerol, 1998). This regional variation in turn influences the hydrogeological and engineering characteristics of the Chalk. Comprehension of the regional geological and geomorphological evolution is fundamental to understanding local variation in the Chalk stratigraphy and rock mass prior to fieldwork and geological modelling.
2.2 Regional Geological and Geomorphological Evolution

The two catchments studied in detail, the Patcham Catchment and the Hallue Catchment, are located in the South Downs in southern England and in the Somme–Picardy, northern France respectively. This places the catchments on the southern margin of the former Weald Basin in the Southern Province of the Chalk in England and within the Paris Basin situated to the north of the main basin axis and Hampshire-Dieppe-Bray High in France (Figure 2.1).

The main phase of extension and subsidence, which formed the Weald and Paris basins, occurred in the Jurassic and Cretaceous (Gallois, 1965; Pomerol, 1980; Ziegler, 1990; Hamblin et al., 1992; Guillocheau et al., 2000). The Weald and Paris basins were periodically isolated throughout the Mesozoic until the end of the Lower Cretaceous Barremian stage (Figure 2.2). From the Aptian stage, rising sea levels, possibly relaxation of the lithospheric stresses and thermal anomalies led to re-establishment of shallow-marine connections between the Weald and Paris Basin (Ziegler, 1990). At the start of the Upper Cretaceous, eustatic rise in sea level (Haq et al., 1988; Hancock, 2000) and continued regional tectonic subsidence caused expansion of chalk sedimentation over the whole of the submerged region - termed the ‘Cenomanian Transgression’ (Figure 2.3). Climatic conditions during this period were warm and stable which had a twofold effect of increasing oceanic productivity and sedimentation rates of coccoliths and to limit the terrigenous input to the shallow basins due to a lack of runoff from the available landmass under a non-seasonal, possibly arid, climatic regime. Furthermore, Milankovitch cycles may have also had a subtle control on sedimentation, leading to the development of marl and limestone couplets corresponding with low and high solar input and oceanic carbonate production respectively (Felder, 1981; Mortimore, 1986; Gale, 1989, 1995).

The Weald and Paris Basin constituted one depositional centre at this time, the Anglo–Paris Basin. The exact limits of the continental seas are unknown because in many areas subsequent erosion removed shoreline facies (Hancock, 1993). Sea level fluctuation and tectonic events occurred throughout deposition of the chalk in the Late Cretaceous (Figure 2.3).
Figure 2.1 Broad structural features affecting sedimentation of the Upper Cretaceous deposits in the British Isles. Based on British Geological Survey 1:1 000 000 maps of the Geology of the UK, Ireland and Continental Shelf, North and South Sheets and derived from Mortimore et al. (2001). WB denotes the Weald Basin and PB the Paris Basin. The locations of the Hallue and Patcham catchments are indicated by red boxes.
The combined interaction of these processes on chalk sedimentation is complex but Mortimore (2011) inferred that sea-level changes played an important role in the deposition of Cenomanian, Turonian and Early Coniacian sediments and less so in the Late Coniacian, Santonian and Campanian sediments of southern England. During these latter stages, Mortimore (2011) inferred that the effects of the Subhercynian (Figure 2.2) tectonic events were getting stronger. The Subhercynian phases of compressional tectonics, recognised by Stille (1924), Voigt (1963), Ziegler (1975a; 1975b; 1987, 1990), have been directly linked by Mortimore and Pomerol
(1991a; 1997) and Mortimore et al. (1998) to sedimentary variation and the development of geological structures in the Chalk (Figure 2.3). Based on these observations, Mortimore (2011) presented the following summary of the sedimentotectonic history of southern England and northern France:

- Cenomanian to Lower Coniacian narrow elongate, asymmetric basins parallel to the southern edge of the Weald with sedimentary thicknesses and lithologies influenced by growth of en echelon folds.
- An Upper Turonian uplift and erosional event, partly related to sea-level fall (Early Ilsede phase).
- Middle Coniacian conspicuous erosional events and slumping (Ilsede phase of Stille, 1924).
- A Santonian to Lower Campanian shift in sedimentation associated with a more conspicuous variation in lithology and thickness and the growth of faults and folds and a special style of fracturing with conspicuous development of sheet flint (Wernigerode Phase of Stille, 1924). Strong hiatuses with >50% loss of section are present along tectonic axes (Mortimore and Pomerol, 1991b, 1997) and in the Paris Basin (Mortimore and Pomerol, 1987).
- A later Lower Campanian second phase of major channel formation and slumping seen on Portsdown (Peine Phase of Riedel, 1940, 1942) and possibly the eastern Paris Basin.
- End Cretaceous (Laramide) uplift which is strongest adjacent to edge of the Weald especially in the East Sussex Downs and the development of broader basins.

Hancock (2000) indicated a fall in sea level from 68 Ma with the Chalk probably becoming emergent by 65 Ma. At the point deposition ceased, a continuous, up to 550m thick, sheet of chalk had been deposited (Jones, 1999a).
The Laramide tectonic phase (Figure 2.2) led to the majority of France and southeast England being uplifted above sea level (Pomerol, 1980; Ziegler, 1981). Danian and Selandian deposits are not represented in the research areas as a result of the Laramide phase of uplift. Erosion, during the Palaeocene, resulted in the rapid removal of around 350 m of Chalk (Jones, 1999a). From the Thanetian to the Lutetian, the Anglo-Paris Basin experienced marine incursions (Figure 2.4 and Figure 2.5). These periodic transgression and regression cycles during the Palaeogene resulted in lithologically variable facies composed of gravels, sands and clays, deposited in fluvial, estuarine and marine settings, overlying the Chalk (Figure 2.2). The inversion of the Mesozoic basins (e.g. the Weald Basin) (Lake and Karner, 1987; Chadwick, 1993; Hawkes et al., 1998) and initiation of Cenozoic basins (e.g. Hampshire-Dieppe and London Basins) during these transgression and regression cycles lead to cyclic accumulation of Palaeogene sediments in Cenozoic basins and contemporaneous pulses of accelerated denudation on uplifted areas (Jones, 1980; Small, 1980; Ziegler, 1990; Jones, 1999a). These cycles led to the margins of the

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**Figure 2.3** Sea-level curve of Hancock (2000) compared with southern English Chalk stratigraphy and Cenomanian to Maastrichtian global events - from Mortimore (2011)
Cenozoic basins being progressively overstepped. The sub-Palaeogene erosion surface that formed is therefore a multifaceted or polycyclic diachronous marine trimmed surface (Wooldridge and Linton, 1939, 1955; Pinchemel, 1954; Jones, 1980, 1999a). Jones (1999b) models for the Cenozoic evolution and denudation of southern England assumed the highest denudation rates occurred during the Early Palaeogene and were up to 20.0 m Ma\(^{-1}\) (Figure 2.6). Deposition occurred in both research areas during this time with the earliest marine deposits being of Thanetian age. Sedimentation was likely to have continued until the mid Eocene (Lutetian).

Figure 2.4 Generalised distribution of land and sea from the Late Cretaceous to the Pliocene adapted from Bignot (1974), Pomerol (1980; 1982) and Ziegler (1990). 1 = Coniacian to Campanian, 2 = Late Thanetian, 3 = Ypresian (Cuisien), 4 = Lower Lutetian, 5 = Middle and Upper Lutetian, 6 = Oligocene, 7 = Miocene and 8 = Pliocene. Areas of land are white and areas of sea are blue.

The Eocene Alpine tectonic phase led to further uplift, faulting and folding in northern France and southern England and, despite a further marine transgression into the Anglo-Paris Basin, the Hallue and Patcham catchments were likely to have experienced subaerial conditions from the Oligocene onwards. The drainage pattern
Figure 2.5 Eustatic sea level and ocean-bottom water temperature during the Cenozoic. Based on Haq et al. (1987) and Savin (1977).

of southern England, which is radial and concordant with macrostructure (e.g. the Weald-Artois Anticline) probably initiated on the flexured land surface after recession of the Palaeogene sea (Jones, 1999a). Palaeoclimatic studies indicate warm climatic conditions (Figure 2.4) from the late Palaeocene to the early Oligocene (Savin, 1977; Buchardt, 1978; Collinson and Hooker, 1987). The presence of sarsen stones and palaeo-silcretes on the South Downs has been used as evidence for duricrusted low relief land surfaces subjected to a sub-tropical to tropical seasonal climate (Summerfield, 1979; Summerfield and Goudie, 1980). Later work by Ullyott et al. (2004), however, casts some doubt on this interpretation and has suggested that silcretes may have formed as a result of silicification during the Neogene or Quaternary, in association with acid leaching of Lambeth Group sediments. Despite continued pulses of uplift, Jones (1999b) assumed the rate of denudation on the South Downs reduced to 1.3 - 2.7 m Ma\(^{-1}\) in the Late Palaeogene.
Figure 2.6 Patterns of denudation for the crest of the South Downs adapted from Jones (1999b). 1 = onset of sub-aerial denudation of the Chalk, 2 = onset of sedimentation in Thanetian 3 = cessation of sedimentation and onset of Eocene sub-aerial denudation, 4 = increase in rate of denudation during the Miocene associated with increased tectonic activity, 5 = increase in rate of denudation in Quaternary associated with Pleistocene periglacial conditions. Area shaded grey indicate thickness of Palaeogene cover.

Subaerial conditions persisted during the Miocene (Figure 2.4) in the location of the research catchments despite sea level fluctuations in the Langhain-Serravalian and in the Tortonian (Larsonneur, 1971; Van Vliet-Lanoë et al., 1998; 2000a). The Miocene Alpine tectonic phase led to pronounced deformation and development of regional structural patterns to virtually their present form (Jones, 1999a). The uplift of areas on major inversion axes, such as the Weald-Artois Anticline, is likely to have generated both relief and erosion in northern France and southern England (Jones, 1999a). To reflect this increase in tectonic activity, Jones (1999b) assumed the Neogene rate of denudation in the area of the South Downs increased to 3.9 - 4.3 m Ma⁻¹ (Figure 2.6).

The area of the research catchments would have continued to remain above sea-level during the Pliocene despite a further marine transgression which affected the London Basin (Mathers and Zalasiewicz, 1988) and parts of the Channel (Figure
The oldest Clay-with-flints or “Formations résiduelles à silex” deposits in the area of the research catchments may have begun forming in the Pliocene (Table 2.1) where the Palaeogene deposits overlying the Chalk became thin enough to become permeable (Quesnel, 1997; Quesnel et al., 2003). The main period of Clay-with-flints formation, however, was the Pleistocene (Hodgson et al., 1967; Catt and Hodgson, 1976; Quesnel et al., 2003). Many authors recognise a Late Pliocene-Early Pleistocene development of drainage networks and tectonic movements in northern France and southern England which lead to exhumation of the Chalk and escarpment development. Guillocheau et al. (2000) indicated reorganisation of the rivers in the Paris Basin occurred during the Pliocene-Early Pleistocene and Van Vliet-Lanoë et al. (2000b) suggested a period of subsidence in the area of the Somme during the Middle Pliocene with renewed uplift and incision during the Pleistocene around 1 - 0.8 Ma. This uplift and incision was also recognised by Pomerol (1980), who suggested 100-200 m of uplift for the Plio-Quaternary, and Antoine et al. (2000; 2003b) who recognised 55-60 m of incision in the last 1 Ma to form the Pleistocene river terraces of the Somme. In the western South Downs, Small and Fisher (1970) indicated that the rivers had cut down to 100-150 m OD by the beginning of the Pleistocene - thereby implying 50-100 m of uplift in the Late Pliocene. Further to this, Jones (1999b) and Preece et al. (1990) suggested Pleistocene differential uplift for southern England, after 2 Ma, of 250 m and 400 m respectively. Coupled with this uplift, further fluctuations in sea level were experienced (Figure 2.5).

The area of research catchments, from the middle Pleistocene to the Holocene would have been affected by periglacial and temperate interglacial climatic conditions (Table 2.1). In the periglacial periods, permafrost conditions dominated with ground covered in snow or ice and perennially frozen to depth. The average temperatures were low and fluctuated above and below freezing causing frost shattering and brecciation of the Chalk (Williams, 1980, 1986, 1987; Murton, 1996; Murton and Lautridou, 2003). Mass movement of frost shattering material occurred via solifluction processes and meltwater (French, 1996). In the temperate interglacial periods, it is likely that there was a return to typical denudation processes such as fluvial action, soil creep and hill wash.
Under the periglacial conditions, in the area of the research catchments, a new drainage network developed due to incision from surface run-off during periods of melting with the Chalk frozen at depth and effectively impermeable (Reid, 1887; Bull, 1940; Morgan, 1971). Relatively rapid valley incision would have been facilitated by frost brecciated chalk. Wind, snow and differential mass wasting at the time of incision probably led to the development of valley asymmetry with north-west facing slopes steeper than south-east facing slopes (Ollier and Thomasson, 1957; Clark, 1965; French, 1972; Williams, 1986). When permafrost degraded, the Chalk regained its permeable properties and left the coombs and valleys mostly dry (French, 1996, 2007).

<table>
<thead>
<tr>
<th>MARINE OXYGEN ISOTOPE STAGES</th>
<th>AGE (Ka)</th>
<th>CHRONOSTRATIGRAPHY</th>
<th>SOUTHERN ENGLAND</th>
<th>NORTHERN FRANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>LATE</td>
<td>10-13</td>
<td>HOLOCENE FLANDRIAN</td>
<td>TEMPERATE</td>
<td>Submerged peats in estuaries and off coasts</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Valley mouths drowned, peats and submerged forests preserved below sea level Solent River floodplain, formation of Yeo Solent, Christchurch Bay, Poole Harbour</td>
<td></td>
</tr>
<tr>
<td></td>
<td>120</td>
<td>DEVENSIAN WEICHSELIAN</td>
<td>PERIGLACIAL</td>
<td>Periglacial head and bess formation in France and Channel Islands</td>
</tr>
<tr>
<td></td>
<td>130</td>
<td>IPSWICHIAN (EEMIAN)</td>
<td>TEMPERATE</td>
<td>Ancient La Hauteville and Grandcamp formations marine interglacial raised beach deposits at up to +1.5m Lyres Formation with peat</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>VOLSTOMIAN (STAALIAN)</td>
<td>PERIGLACIAL</td>
<td>Formation d’Hennecque marine interglacial raised beach at up to +13m</td>
</tr>
<tr>
<td></td>
<td>440</td>
<td>HOXNIAN (HOLSTEINIAN)</td>
<td>TEMPERATE</td>
<td>Formation d’Ursel marine interglacial raised beach at up to +13m</td>
</tr>
<tr>
<td>MIDDLE</td>
<td>560</td>
<td>ANGLIAN (ELSTERIAN)</td>
<td>PERIGLACIAL</td>
<td>Formation du Valois heads and gravelly sands (periglacial)</td>
</tr>
<tr>
<td></td>
<td>770</td>
<td>&quot;CROMERIAN COMPLEX (CROMERIAN)&quot;</td>
<td>COLD</td>
<td>Formation du Marni Exant heads affected by ice wedges</td>
</tr>
<tr>
<td></td>
<td>18-40</td>
<td>BEESTONIAN TO PRE-LUGHAMON (MENAPIAN TO PRAETIANI)</td>
<td>BECOMING COLD</td>
<td>Formation de Roumois lacustrine and fluvial, Ice wedges and cryoturbation</td>
</tr>
<tr>
<td></td>
<td>2080</td>
<td>PUOCENE</td>
<td>TEMPERATE</td>
<td>Saint Étienne Sands, marine, 120/130m above present Maximum transgression</td>
</tr>
</tbody>
</table>

Table 2.1 Quaternary history of southern England and northern France. Based on Gallois (1965), Edmonds et al. (1975), Melville and Freshney (1982) and Lautridou et al. (1986b). Absolute ages and marine oxygen-isotope stages taken from Shotton (1986), Šibrava (1986) and Bowen et al. (1986).

Solifluction debris - coombe or head deposits, sorted or stratified muds and solifluction gravels and loessic deposits are the three main types of periglacial deposits found on the chalk in northern France and southern England (French,
Solifluction debris or head deposits consists of a heterogeneous material composed of coarse angular fragments of chalk within a fine calcareous matrix. Solifluction or head deposits mainly relate to cold and damp conditions during the late-middle Devensian - MOIS (marine oxygen isotope stage) 4 and 2 and locally 8 or 6 (French, 1996; Bates et al., 2003; Murton and Lautridou, 2003).

In northern France, in the vicinity of the Hallue catchment, loess is typically between 2-4 m thick and locally may be more (Figure 2.7). It mantles plateau areas and is the main component in Limon and Colluvion. In southern England, loess is generally thin and discontinuous (Catt, 1985). It veneers exposed upland surfaces and, where present in valleys, is usually reworked by either soliflution or meltwater into Brickearth, buff or brown, generally structureless, non-calcareous loam or silt (Young and Lake, 1988), or Head deposits - unstratified homogeneous brown, silty or sandy loams commonly containing worn flints and sandstone fragments (Young and Lake, 1988). In both northern France and southern England, the most extensive and continuous loess unit is dated to a period of between 30 and 15 ka in

Figure 2.7 Map of the loess and coversands in northern France and southern England derived from Antoine et al. (2003a)
the Late Devensian – MOIS 2 and end of 3 (Table 2.1) (French, 1996; Antoine et al., 2003a; French, 2007). Late Saalian loess, MOIS 6, is also well developed in northern France but older loess deposits, in both countries, are much less widely distributed. Studies on the mineralogy of the loess indicate it has been derived from the outwash sediments in the North Sea, English Channel palaeovalleys and southern North Sea fluvial network, and transported by northeast winds in southern England and northwest to north-northwest winds in northern France (Lautridou, 1985; Antoine et al., 2003a) (Figure 2.7).

Clay-with-flints in southern England and northern France, in the vicinity of the research catchments, are likely to have developed to almost their current form in the Pleistocene by interglacial weathering and periglacial disturbance (cryoturbation) of a thin veneer of the Palaeogene deposits present on the sub-Palaeogene erosion surface (Quesnel et al., 2003). The dominant processes of soil formation in this veneer were decalcification, rubification and illuviation of clay into spaces generated by dissolution of the underlying Chalk. The mixture of clay illuviated from the Palaeogene veneer, and flints and other insoluble chalk residue released by subsurface dissolution, accumulated on the upper surface of the Chalk to form a thin layer. During the cold stages of the Pleistocene this layer was mixed with the Palaeogene veneer by cryoturbation and the flint nodules were frost-shattered into angular fragments; the mixed layer was often moved laterally by solifluction and loess was often deposited on the surface (Avery et al., 1959; Hodgson et al., 1967; Catt and Hodgson, 1976; Quesnel et al., 2003). Due to these repeated oscillations from periglacial to temperate conditions in the Pleistocene producing numerous episodes of intense denudation, in combination with assumed uplift at 2 Ma, Jones (1999b) estimated rates of Pleistocene and Holocene denudation for the South Downs ranging between 20-145 m Ma⁻¹ (Figure 2.6).

In summary, both research catchments in northern France and southern England and have experienced a complex history of deposition and erosion from the Late Cretaceous to present (Figure 2.6). Variation in the pattern of erosion and deposition through time is likely to be closely associated with the structural development of the region (Figure 2.8). These structures divide up the region into morphotectonic zones (Jones, 1999a) which each have slightly different structural and geomorphological
histories with varying rates of denudation – from low normal to morphostasis (Green, 1985). In the present day, the Hallue Catchment in the north of the Paris Basin has the Chalk present at outcrop, retains locally small pockets of Palaeocene-Eocene sands and Formations résiduelles à silex. A cover of Pleistocene loessic deposits, Limon and Colluviums, are also present over the majority of the catchment. The
Patcham Catchment has the Chalk present at outcrop and is near to Palaeocene-Eocene Lambeth Group deposits present in the synclines at Falmer and Hove. A thin cover of Pleistocene and Holocene deposits formed from the sub-aerial denudation of the bedrock formations, such as Head, Brickearth, Clay-with-flints and Coombe deposits, are also present in the Patcham Catchment.

2.3 UK Southern Province Chalk Lithostratigraphy

The lithostratigraphy of the Chalk Group of southern England has been revised substantially over the last thirty years. The current lithostratigraphical framework (Figure 2.9) is based on broad changes in physical properties of the rock mass combined with laterally continuous marker horizons such as marl seams, flint bands, layers of nodular chalk and well-defined trace fossil horizons (Mortimore, 1983a, 1986).

The British Geological Survey mapping technique for areas of Chalk outcrop involves a combination of landform, field brash and biostratigraphical evidence to map the Chalk units typically at formation or member level (Bristow et al., 1997). Mortimore (1983a, 1986) has also demonstrated that discrete marker horizons (e.g. marl seams, flint bands) and broad physical changes may be recognised in down-hole geophysical logs. Using this technique some horizons maybe correlated over large distances within the Anglo – Paris Basin (Mortimore and Pomerol, 1987).

The Brighton Chalk block of the South Downs in Sussex was remapped for Southern Water plc and the Environment Agency by the British Geological Survey between 1999 and 2001 from a combination of remote sensing data, the field slips of Christopher Gaster, field notes and logs of R.N. Mortimore and a series of reconnaissance surveys (Aldiss, 2007; Hopson, 2009). The Chalk formations present in the Patcham Catchment comprise the West Melbury Marly Chalk, the Zig Zag Chalk, the Holywell Nodular Chalk, the New Pit Chalk, the Lewes Nodular Chalk, the Seaford Chalk and the Newhaven Chalk (Figure 2.9). The stratigraphical and lithological characteristics of the chalk formations are outlined in the following sections.
Figure 2.9 UK Southern Province Chalk Lithostratigraphy. Subgroups, formations and members are those used by the BGS for mapping purposes. Traditional zones are also shown (Mortimore, 1983a, 1986; Bristow et al., 1997)
2.3.1 West Melbury Marly Chalk Formation
The West Melbury Marly Chalk Formation is a subdivision of the Grey Chalk Subgroup. It forms a narrow outcrop of buff, grey and off-white, marly chalk. It contains local beds of hard chalk, and these give rise to a ‘spiky’ gamma-ray signature. In Sussex the West Melbury Marly chalk begins at the Neostlingoceras carcitanense Subzone of the M. mantelli Zone, and it extends to the base of the Middle Cenomanian Acanthoceras rhotomagense Zone (Bristow et al., 1997).

2.3.2 Zig Zag Chalk Formation
The Zig Zag Chalk Formation is a subdivision of the Grey Chalk Subgroup. It consists of firm, pale grey to off-white, blocky chalk. The lower part has rhythmic alternations of marls or marly chalk and firm white chalk (Jukes-Bowne Bed 5). Within the Zig Zag Chalk there is a unit of gritty, silty chalk with lenticular, laminated calcarenite, filled lenses (Jukes-Browne Bed 7). This forms a marker separating a lower unit of blocky white chalk with Inoceramus atlanticus in the highest 2 m, from a poorly fossiliferous upper unit with a few amphidonteine oysters and Inoceramus pictus. The Zig Zag Chalk spans the interval from the base of the Middle Cenomanian A. rhotomagense Zone up to a horizon near the top of the Upper Cenomanian Metoicoceras geslinianum Zone (Bristow et al., 1997).

2.3.3 Holywell Nodular Chalk Formation
The Holywell Nodular Chalk Formation is the lowest subdivision of the White Chalk Subgroup. It comprises the Plenus Marls-Melbourn Rock interval with the shell debris derived from Inoceramus pictus plus related groups, and the overlying shell-detrital chalks with debris of the Mytiloides species.

In Sussex there is a seven metre interval between the Melbourn Rock and the beds with abundant Mytiloides. Immediately succeeding the Melbourn Rock are the lower Holywell Beds comprising a series of plexus or griotte marls, 15-30 cm wide, recurring at intervals of 30-60 cm at the base of the succession, broadening to 1-1.3m intervals upwards, and red, iron-stained patchily developed nodular beds or hardgrounds (Mortimore, 1986).
The middle Holywell Formation (11-15 m thick) is distinguished by an abundance of bivalve debris (mostly *Mytiloides*), associated with sediments that are nodular and contain more closely spaced griotte marls. Sinuous, cylindrical (2-3 mm diameter) burrows thread vertically through these sediments (Mortimore, 1986).

The upper Holywell Formation represent a return to the condition of the lower beds with more massive, less gritty, uniform chalk containing relatively fewer *Mytiloides* and more broadly spaced griotte marls. These beds are some 10-13 m thick and are terminated by the first conspicuous discrete marl (Mortimore, 1986).

Three distinctive suites of marls, which may be used for detailed correlation, are recognised in the Holywell Nodular Chalk Formation. These are the three pairs of Meads Marls at the base, followed by the Holywell Marls and the Gun Garden Marls (Mortimore, 1986).

### 2.3.4 New Pit Chalk Formation

The New Pit Chalk Formation is a subdivision of the White Chalk Subgroup. Its base coincides with the incoming of firm, smooth, white, flaggy chalk and loss of nodular and shell-detrital Chalk. There tends to be little topographic expression at this boundary, although in the Patcham catchment area it was recognised by a negative break of slope. Thick shelled, well-preserved *Mytiloides* of the Holywell Nodular Chalk are replaced by thin-shelled *Mytiloides* preserved as moulds typically lacking shell. Well developed marl seams are characteristic of this unit, particularly the New Pit Marls and Glynde Marls near the top, which have distinct wireline log signatures. The Glyndebourne Flints are developed at the base of the New Pit Chalk in Sussex. The New Pit Chalk spans the Middle Turonian *Collignoniceras woollgari* Zone. The base of the traditional *Terebratulina lata* Zone is a variable distance above the base of the New Pit Chalk and ranges into the overlying Lewes Nodular Chalk (Mortimore, 1983a, 1986; Bristow *et al.*, 1997).

### 2.3.5 Lewes Nodular Chalk Formation

The Lewes Nodular Chalk Formation is a subdivision of the White Chalk Subgroup. The nodularity of the Lewes Nodular Chalk begins a short distance above the base of the Lewes Chalk as originally defined (Glynde Marl 1 in Sussex or one of the higher Glynde Marls elsewhere in the Glynde-Southerham Marl interval). In more
complete basinal facies of Hampshire, Sussex and Kent, thin, sporadic, occurrences of nodular chalk are found lower in the succession. The onset of nodularity approximates to the first conspicuous flints in the basinal sections, and thus marks the beginning of markedly flinty chalk in the Southern Province. The Lewes Nodular Chalk comprises the higher part of the *Terebratulina lata* Zone, and the *Stemotaxis plana* and *Micraster cortestudinarium* zones. The top of the Lewes Nodular Chalk is slightly diachronous (Mortimore, 1983a, 1986; Bristow *et al.*, 1997).

### 2.3.6 Seaford Chalk Formation

The Seaford Chalk Formation is a subdivision of the White Chalk Subgroup. It is fine-grained, soft to firm, flinty white chalk. Its base is taken at Shoreham Marl 2 in the type locality in Sussex. Conspicuous, semi—continuous bands of large nodular flints are a feature of this formation. With the exception of the Belle Tout Marls in the lower part, Seaford Chalk wireline geophysics signatures are subdued because of the near absence of marl seams. In the stratotype section at Seaford Head, the formation coincides with the *M. coranguinum* Zone and is delimited upwards by the entry of marls seams marking the base of the succeeding Newhaven Chalk. The Seaford Chalk is distinguished by its fine-grained slabby brash contrasting with the harder, coarse, nodular gritty brash of the Lewes Nodular Chalk. The lower beds of the Seaford Chalk (Belle Tout Beds) are characterised by *Platyceramus* and *Volviceramus* shell detritus and marl seams. There is rarely a consistently developed topographical expression at the base of the formation. The Seaford Chalk is generally coextensive with the *Micraster coranguinum* Zone (Middle Coniacian to Middle Santonian inclusive). Inoceramid shell fragments are conspicuous at various levels in the brash, core and rock face. Thick-shelled *Platyceramus* and *Volviceramus* characterise the Belle Tout Beds; thin-shelled, pink *Cladoceramus undulatoplicatus* are found at the base of the Santonian in the middle part of the formation, and thick-shelled *Platyceramus* accompanied by *Sphenoceramus* are common in the upper bed. A generally barren interval (i.e. with rare shell debris layers), the Cuckmere Beds, separates the *Cladoceramus* concentrations from the *Platyceramus* in the Belle Tout Beds (Mortimore, 1983a, 1986; Bristow *et al.*, 1997).

### 2.3.7 Newhaven Chalk Formation

The Newhaven Chalk Formation is a subdivision of the White Chalk Subgroup. It is a unit of firm, white, predominantly marly chalk with widely spaced flints and
common marl seams. At the type locality at Seaford Head, Sussex, the base is taken at the base of Buckle Marl 1, and the base of the overlying Culver Formation is taken at the base of Castle Hill Marl 2. These marl seams, however, may virtually disappear over structural highs. On these structural highs, the BGS map the marl-free chalk with the Seaford Chalk. There is also local lithological variation, such as the occurrence of phosphatic chalk cuvettes within the Newhaven Chalk Formation. In trough areas, such as Brighton, not only are marl seams in the Newhaven Chalk better developed, but strong marl seams (such as the Pepper Box Marls) occur above the Castle Hill Marls. In such situations, the upper limit of the Newhaven Chalk is sharply defined both in the field sections and in boreholes and the boundary is taken at this higher level. Where there are no exposures, the base of the Newhaven Chalk is mapped in Sussex along a negative topographic feature, which occurs at the base of a secondary escarpment west of the river Adur (Jones and Robins, 1999), and a subtle change in field brash including the relative increase in the abundance of zoophycos flints. In some areas, the topographic feature at the base of the Newhaven Chalk is more subdued and difficult to follow. Where most complete, the Newhaven Chalk spans the crinoid and Offaster pilula zones, together with the lower part of the Hagenowia blackmorei Subzone of the Goniotheuthis quadrata Zone (Mortimore, 1983a, 1986; Bristow et al., 1997).

2.4 Paris Basin Chalk Biostratigraphy

Chalk stratigraphical units, differentiated on current BRGM 1:50,000 geological maps of the Hallue Catchment, are based on the benthonic foraminifera succession and zonation of Monciardini (1978, 1980). The first appearance, last appearance and assemblage of benthic foraminifera define the biozones and map units. To produce the geological maps, chalk samples, collected from field exposures and quarries, were used to determine the foraminifera assemblage and biozone. The line work was then defined based on these control points. In the Hallue Catchment, the biozones mapped at outcrop range from Upper Turonian (T/c) to Lower Campanian (S/f) (Figure 2.10).

Lithostratigraphical mapping had never previously been attempted for the Chalk in the area of the Hallue Catchment as it was thought unfeasible (Robelin, 2006). Mortimore and Pomerol (1987), however, demonstrated that lithological and
biostratigraphical marker horizons, used in the UK southern province Chalk lithostratigraphy, could be correlated to the Chalk of northern France. Pomerol et al. (1987), Pomerol (1988a, b; 1996) and Robaszynski et al. (2005) demonstrated the relationship of these marker horizons to the stratigraphical biozones developed by Monciardini (1978, 1980) (Figure 2.10). A combined litho and biostratigraphical framework was then applied for mapping purposes on the BRGM 1:50,000 maps for Bléneau (Pomerol, 1988c), Courtenay (Pomerol, 1988d), and Arcis-sur-Aube (Pomerol, 1996b). Mortimore (2001b) also successfully used lithostratigraphy for mapping the coastline of northern France, between Port du Havre-Antifer and Ault, for BRGM and as part of the INTERREG II ROCC (Risk of Cliff Collapse) research project.

The following sections outline the foraminifera succession of the mapped units of the Amiens, Albert, Baupaume 1:50,000 BRGM geological maps (Dupuis et al., 1972a; Mennessier et al., 1976a; Delattre and Mériaux, 1977) as originally defined by Monciardini (1978, 1980) with discussion on the corresponding UK stratigraphy. The corresponding map notation is indicated in parenthesis next to the foraminifera biozone. Biozones with the prefix “T” are Turonian and biozones with the prefix “S” are Senonian (Coniacian to Campanian).

2.4.1 Upper Turonian to Lower Coniacian (C3c-4a)

According to Monciardini (1978, 1980), the last appearance of Gavelinella cf. tourainensis marks the top Turonian T/c biozone (C3c). Pomerol et al. (1987) recorded that Gavelinella cf. tourainensis occurred immediately below and above the Lewes Marl (Figure 2.9) at Puys, Bois de Cise and Ault in northern France. This species were not identified, however, in the Poigny borehole (Figure 2.10).

The T/c biozone is followed by the T/S transitional zone between the Upper Turonian and Lower Coniacian. According to Monciardini (1978, 1980), the T/S transitional zone is marked by the occurrence of Reussella cf. kelleri (Figure 2.10).
Figure 2.10 Benthonic foraminifera zonation of the Chalk of the Paris Basin adapted from Robaszynski et al. (2005). Biostratigraphy and lithostratigraphy shown is from the Poigny (Craie 701) borehole. On the right are the foraminifera biozones which approximate to those defined by Monciardini (1978, 1980) with the mapped units from the Hallue Catchment represented in colour. The vertical ranges of key foraminifera species shown in the centre were identified and defined by Robaszynski and Bellier (2000). On the left are lithological descriptions, marker beds and UK formations/subgroups as correlated to the Paris Basin by Mortimore and Pomerol (1987), Pomerol et al. (1987), Pomerol (1988a, b; 1996).
Pomerol et al. (1987) noted the occurrence of *Reussella cf. kelleri* in the Cuilfail Zoophycos at Shoreham quarry. The base of the T/S transitional zone may also approximate to the base of the UKB 10 interval zone of Hart et al. (1989) due to the occurrence of *Globorotalites gr. Michelinius* at this boundary in the Poigny borehole (Figure 2.10).

The base of the biozone S/a biozone (C4a), according to Monciardini (1978, 1980), is recognised by the first appearance of *Reussella kelleri, Gavelinella vombensis, Osangularia cordieriana, Gavelinella thalmanni* and *Stensioenina praexsculpta*. Hart et al. (1989) also recognised the occurrence of *Reussella kelleri* in the Lower Coniacian (UKB 11 zone). Pomerol et al. (1987) noted that *Reussella kelleri* occurs above the Navigation Hardgrounds at Shoreham quarry and at St-Julien-du-Sault in the stratotype area. *Gavelinella vombensis* is indicated as *Gavelinella arnagerensis* by Robaszynski et al. (2005) and in Figure 2.10. Hart et al. (1989) did not refer to *Gavelinella vombensis* but do indicate the presence of *Lingulogavelinella cf. L. vombensis* in the Lower Coniacian. Hart et al. (1989) did not identify *Osangularia cordieriana* this low in the UK succession. Likewise, Robaszynski et al. (2005) recognised *Osangularia* species in the S/a biozone but not specifically *Osangularia cordieriana* in the Poigny borehole (Figure 2.10). Pomerol et al. (1987) indicated that *Stensioenina praexsculpta* was synonymous with *Stensioenina granulata granulata* (*Stensioenina praexsculpta*) (Figure 2.10). *Gavelinella thalmanni* and *Stensioenina granulata granulata* (*Stensioenina praexsculpta*) are also recognised by Hart et al. (1989) but not in the Lower Coniacian.

### 2.4.2 Middle and Upper Coniacian - Lower Santonian (C4bc)

The base of the biozone S/b (C4b), according to Monciardini (1978, 1980), is marked by the continued presence of *Gavelinella vombensis, Osangularia cordieriana, Gavelinella thalmanni* and *Stensioenina praexsculpta* and the last appearance of *Reussella kelleri. Gavelinella thalmanni* and *Stensioenina granulata granulata* (*Stensioenina praexsculpta*) are recognised by Hart et al. (1989) as middle Coniacian (UKB 12). Pomerol et al. (1987) noted the base of biozone S/b (C4b) coincides with the Shoreham Marl 1 at Shoreham quarry. This marl is a key lithological marker in the UK Southern Province lithostratigraphy at the boundary between the Lewes Nodular and Seaford Chalk Formations (Figure 2.9).
The macrofossils *Platyceramus sp.*, *Volviceramus cf. involutus*, *Micraster turonensis*, and the associated lithological marker horizon of the Seven Sisters Flint band, from the Belle Tout Beds (Figure 2.9) of the Seaford Chalk Formation were found to occur close to the S/b (C4b) - S/c (C4c) biozone boundary in the Paris basin (Pomerol et al., 1985; Mortimore and Pomerol, 1987). *Micraster coranguinum* was also found to occur consistently throughout the Anglo-Paris basin at the base of biozone S/c (C4c) (Pomerol et al., 1987; Pomerol, 1996).

The base of biozone S/c (C4c), according to Monciardini (1978, 1980), is marked by the appearance of *Stensioina laevigata*, *Stensioenina exsculpta gracilis*, *Reussella cushmani* and *Bolivinitella (Loxostomum) eleyi*. Pomerol et al. (1987) indicated that *Stensioenina exsculpta gracilis* and *Stensioina laevigata* are synonymous with *Stensioenina exsculpta exsculpta* and *Stensioenina granulata polonica* (Figure 2.10) respectively. *Stensioenina exsculpta exsculpta* (*Stensioenina exsculpta gracilis*), *Stensioenina granulata polonica* (*Stensioina laevigata*) and *Bolivinitella (Loxostomum) eleyi* are also recognised by Hart et al. (1989) as upper Coniacian (UKB 13). Pomerol et al. (1987) found that *Stensioenina exsculpta exsculpta* (*Stensioenina exsculpta gracilis*) appears around the position of the Belle Tout Marls in the Belle Tout Beds (Figure 2.9) of the Seaford Chalk Formation. Hampton et al. (2007) found the first appearance of *Stensioenina granulata polonica* (*Stensioina laevigata*) at Seaford Head occurred above the Cuckmere Sponge Bed within Cuckmere Beds (Figure 2.9) of the Seaford Chalk Formation. *Reussella cushmani* is not recognised by Hart et al. (1989) in the UKB 13 zone or Robaszynski et al. (2005) in the Poigny borehole (Figure 2.10) although other species of *Reussella* are present. *Bolivinitella (Loxostomum) eleyi* was not clearly linked to the occurrence of any lithostratigraphical marker horizon by Pomerol et al. (1987) although Hart et al. (1989) indicated its appearance is closely related to the appearance of *Stensioenina exsculpta exsculpta* (*Stensioenina exsculpta gracilis*) which would indicate an association with the Belle Tout Beds of the Seaford Chalk Formation.

The boundary between S/c (C4c) - S/d (C5d) biozones was thought to coincide with the Coniacian - Santonian boundary (Monciardini, 1980) - as indicated on the Amiens and Albert geological maps. Pomerol (1986) and Mortimore and Pomerol (1987), however, found occurrences of the base Santonian index macrofossil
Cladoceramus undulatoplicatus within the S/c (C4c) biozone. Pomerol et al. (1987) also highlighted that if Micraster coranguinum occurs at the base of S/c (C4c) biozone, it cannot occur at the base of S/d (C5d) biozone and therefore the S/c (C4c) - S/d (C5d) boundary cannot correlate with the Coniacian - Santonian boundary. Hampton et al. (2007) found that the last appearance of Stensioenina granulata granulata (Stensioenina praeexsculpta) at Seaford Head occurs just below Coniacian - Santonian boundary and the entry of Cladoceramus undulatoplicatus.

2.4.3 Santonian (C5d-e)

The base of the biozone S/d (C5d), according to Monciardini (1978, 1980), is marked by the appearance of Ressuella sjanochaee and Eponides concinnus and the last appearance of Gavelinella vombensis. The occurrence of Eponides concinnus, as well Ressuella sjanochaee prepraecursor (Figure 2.10), is also recognised by Hart et al. (1989) as Santonian (UKB 14). Hampton et al. (2007) found the first appearance of Ressuella sjanochaee prepraecursor at Seaford Head occurred around the Short Brow Flint in Haven Brow Beds (Figure 2.9) of the Seaford Chalk Formation.

The base of the biozone S/e (C5e), according to Monciardini (1978, 1980), is marked by the first appearance of Gravelinella cristata and the last appearance of Stensioenina praeexsculpta and Stensioina laevigata. Gravelinella cristata is also recognised by Hart et al. (1989) as Santonian (UKB 14). Hampton et al. (2007) found the first appearance of Gravelinella cristata (Gravelinella cristata brotzeni) at Seaford Head just below the Exceat Flint within the Haven Brow Beds (Figure 2.9) of the Seaford Chalk Formation. This places the base of the biozone S/e (C5e) within the middle Santonian.

2.4.4 Upper Santonian/Lower Campanian (C5f)

The base of the biozone S/f (C5f), according to Monciardini (1978, 1980), is marked by the first appearance of Bolivinoides strigillatus; last appearance of Ressuella sjanochaee (Figure 2.10). Bolivinoides strigillatus is also recognised by Hart et al. (1989) as upper Santonian/lower Campanian (UKB 15). Hampton et al. (2007) found the first appearance of Bolivinoides strigillatus at Seaford Head above the Hawks Brow Flint and just below the Brighton Five Marls in the Splash Point Beds (Figure
2.9) of the Newhaven Chalk Formation. This places the base of the biozone S/d (C5d) within the lower Campanian.

### 2.5 Engineering Geology of the Chalk Group

As an engineering material, the Chalk is generally regarded as a weak rock and comprises clay or silt-sized calcite particles. It is an ultra-fine-grained limestone composed of very pure, low magnesium calcite, consisting largely of coccoliths and coccolith fragments. In spite of this, it has not recrystallized significantly since the Cretaceous under depths of burial less than 1000 m (Downing et al., 1993; Price et al., 1993). It retains high porosity and high moisture content (close to saturation value). It has dual porosity comprising both fine pores in the rock material and larger voids along fractures. The combination of high porosity with a high degree of saturation makes soft chalk frost susceptible and causes chalk to slurry during engineering operations (Higginbottom, 1966; Lord et al., 2002).

The heterogeneities of the chalk mass influence its engineering behaviour. An appreciation of the sedimentary, diagenetic, tectonic and geomorphological history, as well as the stratigraphical framework, is required to understand the geological setting and predict the character of the heterogeneities. Hardness, bedding/discontinuity spacing, bedding/discontinuity pattern and the discontinuity aperture are the heterogeneities which have been identified as most likely to influence the engineering behaviour of the chalk mass (Lord et al., 1994). The most easily measured property of the chalk which is indicative of its mass behaviour is dry density (or porosity) (Clayton, 1990; Mortimore and Fielding, 1990; Greenwood, 1993; Matthews et al., 1993). The typical index properties of the chalk are listed in Table 2.2.

In the last 30 years, the lithostratigraphy of the Chalk group has been substantially revised – see Section 2.3 (Mortimore, 1986; Mortimore, 1987; Bristow et al., 1997). This lithostratigraphy provides a classification that reflects physical properties of the Chalk – such as dry density. Generally, much of the Grey Chalk Subgroup is of very high density (intact dry density $\gamma_d > 1.95 \text{ Mg/m}^3$). The chalk in the New Pit Formation is of medium density ($\gamma_d = 1.55-1.70 \text{ Mg/m}^3$) and the overlying formations vary
between “low” and “medium” density ($\gamma_d = 1.55 \text{ and } 1.55 - 1.70 \text{ Mg/m}^3$ respectively) (Mortmore et al., 1990b; Mortmore et al., 1990c; Lord et al., 2002).

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
<th>Range</th>
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<tr>
<td>Dry density</td>
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<td>Mg/m³</td>
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<td>Porosity</td>
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<tr>
<td>Voids ratio</td>
<td>e*</td>
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<tr>
<td>Saturated moisture content</td>
<td>$m_{sat}$</td>
<td>%</td>
</tr>
<tr>
<td>Calcium carbonate content</td>
<td></td>
<td>%</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>$G_s$</td>
<td>% - 2.69 - 2.71</td>
</tr>
<tr>
<td>Plastic Limit</td>
<td>$W_p$</td>
<td>%</td>
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<tr>
<td>Liquid Limit</td>
<td>$w_L$</td>
<td>%</td>
</tr>
<tr>
<td>Plasticity index</td>
<td>$I_p$</td>
<td>%</td>
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<tr>
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<tr>
<td>Point load index</td>
<td>$I_{s(50)}$</td>
<td>MPa</td>
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<tr>
<td>Unconfined compressive strength</td>
<td>$q_u$</td>
<td>MPa</td>
</tr>
<tr>
<td>Slake durability index</td>
<td>$I_d$</td>
<td>%</td>
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Table 2.2 Typical range of index properties for the Chalk (Lord et al., 2002).

The Chalk contains a range of distinct lithologies. These include pure white chalk, discrete marl seams in chalk, marly chalk, flint bands in chalk, hardgrounds in softer low-density chalk and hard high-density chucks. These lithologies have distinct physical properties and relate to specific processes which occurred during and soon after deposition in the palaeoenvironment. Mortimore and Pomerol (1998), in the context of the depositional basin (Figure 2.11), considered the main controls on lithological properties of the Chalk related to:

- Milankovitch cycles which controlled the background alternating bedding and groups of beds (Felder, 1981; Mortimore, 1986; Gale, 1989, 1995) possibly also controlling aspects of nannoplankton productivity and clastic input;
- Global sea-level fluctuations during the Late Cretaceous sea-level high (Haq et al., 1987), which controlled the amount of land exposed (clastic input), organic productivity by influencing oceanic circulation and upwelling of nutrient rich waters (especially important in formation of flints);
- Late Cretaceous tectonic pulses (Subhercynian and Laramide phases) which caused (i) local changes to sea-bed topography on which sea level changes and currents operated (Mortimore and Pomerol, 1997) and (ii) more global changes to watermass and landmass distribution (e.g. pulsed opening of the Atlantic, closing of Tethys, early Alpine tectonism).
Diagenetic processes may also have influenced the physical properties of the Chalk. Hancock (1993) described the early stage intrinsic diagenetic processes which acted on the initial chalk-ooze deposited on the sea-floor and also non-intrinsic diagenesis related to depositional hiatus and hardground formation. A third form of late stage non-intrinsic diagenesis may relate to processes such as dolomitisation. Where the various chalk lithologies are present in the near-surface environment, they may also influence the characteristics of weathering and karst (Lord et al., 2002).

Figure 2.11 Schematic cross-section across the Anglo-Paris Basin illustrating the lateral and stratigraphical change in chalk lithologies from Mortimore et al. (1990b) and Mortimore and Pomerol (1998).

Pure white chalk is characteristic of the White Chalk Subgroup and in particular the Coniacian, Santonian and Campanian chalks (i.e. the Lewes Nodular, Seaford, Newhaven and Culver Formations). Pure white chalks contain around 95-98 percent calcium carbonate (Lord et al., 2002). The Seaford and Newhaven Formations in particular exhibit intervals of pure white chalk devoid of flints, marl seams and hardgrounds. These intervals tend to occur at a local scale due to palaeo-environmental factors relating to seafloor tectonics and sedimentation (Mortimore and Pomerol, 1991a; Mortimore et al., 1996).
Marl seams are thin calcareous clay layers (30-200mm thick). They occur episodically rather than periodically throughout the Chalk sequence and form key marker beds (Section 2.3). The Turonian marker marl seams in the New Pit and Lewes Nodular Chalk Formations (New Pit, Glynde, Southerham, Caburn, Bridgewick and Lewes) are derived from volcanic ash deposits (i.e. they are weathered tuffs) (Wray, 1999) and represent discrete sedimentary events outside of the background alternating bedding of more or less marl rich layers (Felder, 1981; Mortimore, 1986; Gale, 1989, 1995). Due to their origin they have large lateral extents and are used for correlation as they have distinct pronounced peaks on geophysical borehole logs (Gray, 1958, 1965; Mortimore, 1986; Woods and Aldiss, 2004). Marl seams may contain 10-30 per cent clay and this typically is composed of illites and smectites (monmorillonite) (Ward et al., 1968). Chalks with numerous marl seams (e.g. Holywell, New Pit and Newhaven Chalk Formations) tend to be characterised by conjugate fractures (Mortimore, 2011). The spacing of marls seams may also define mechanical units and control the spacing of fractures (Cooke et al., 2006). Furthermore, the removal of overburden may cause marl seams to swell, due to the nature of the clay minerals present, and fracture the Chalk above and below the marl seam. The clay content of marl seams also considerably reduces their permeability in comparison with the surrounding chalk (Duperret et al., 2002; Molyneux, 2012). This in combination with fracturing of the chalk above and below the marl often leads to zones of high seepage (Jones and Robins, 1999; Lord et al., 2002).

Chalk comprises a basic alternating rhythm (Mortimore, 1979, 1986) which is periodic and related to Milankovitch cycles (Felder, 1981; Ditchfield and Marshall, 1989; Gale, 1989, 1995; Gale et al., 1999). There is a general trend of alternating more and less marl rich layers averaging some 300 mm thick although the younger the chalk the purer a carbonate it is (Mortimore, 1986). These rhythms are the underlying cause of alternating physical properties such as calcimetry, intact dry density and porosity. This is more sharply defined in some chalk formations such as the West Melbury Marly Chalk and the Lewes Nodular Chalk although it is present throughout the Chalk group.
Flint is a microcrystalline rock made of silica. It occurs as bands of dispersed nodules or conspicuous tabular or semi-tabular bands within the Chalk. Flint bands formed approximately parallel to bedding and in rhythmic layers which relate to pulses of sedimentation. Flint is a very strong, brittle material in contrast to the Chalk. Uniaxial compressive strengths are in the order of 100-200 MPa for small 30-40 mm sized nodules and 600-800 MPa for large nodules 300-400 mm thick. Flint generally has a low porosity (<6 %). Some nodular and semi-tabular flint bands, like some marl seams, form marker horizons. Semi-tabular and sheet flints may form low permeability horizons. Evidence for this is seen in Dieppe, France above the Seven Sisters Flint of the Seaford Chalk Formation and near Brighton above sheet flints in the Newhaven Chalk Formation (Lamont-Black and Mortimore, 2000; Mortimore, 2001a).

Hardgrounds and nodular beds result from pauses in sedimentation or erosion on the palaeo seabed. These breaks in sedimentation allowed the seabed to be colonised by sponges with spicules made of either silica or calcium carbonate. Sponge concentrations in a layer often produced red iron oxide nodular bed. Nodularity was developed by calcium carbonate cements precipitating in the topmost 200-300 mm of sea-floor, nucleating around the sponges in the sponge-rich layer. The hardground surfaces maybe bored and mineralised with either iron, green glauconite or phosphate. Bedding related lithologies may be occluded by the development of hardgrounds e.g. marls and flints. The intact dry density of hardground intraclasts is typically higher than the surrounding matrix. Well-developed hardgrounds can form particularly strong and competent units and may be a focus for stress and brittle deformation leaving them more fractured than the surrounding chalk (Lord et al., 2002).

Discontinuities such as fracturing and faulting occur ubiquitously throughout the Chalk. Five main styles of discontinuities occur generally. These are vertical joints or joint sets; sub-horizontal joints and bedding planes; inclined conjugate joint sets and shears; faults and fractures. Due to surface weathering effects, discontinuity intensity generally decreases with depth. Discontinuity intensity may also relate to stratigraphy (Cooke et al., 2006), and large faults may cross cut entire Chalk sequences. Critical discontinuity properties that influence engineering behaviour,
are style, frequency, aperture and weathering (Lord et al., 2002). Discontinuity properties, especially style and possibly frequency, may be related to stratigraphy (Cooke et al., 2006; Mortimore, 2011). The Chalk formations and even beds may display a tendency towards a certain style of fracturing (Mortimore et al., 1990b; Mortimore, 1993, 2001a, 2011). Fracture style relates to inclination, e.g. sub-vertical as opposed to inclined, and form of preservation e.g. sheet flints are a form of silicified fracture.

The Chalk, where exhumed, has well-developed weathering profiles (Figure 2.12). These weathering profiles developed due to a number of weathering processes, such as spring sapping, river erosion, periglacial conditions, glacial conditions and plant growth. The Chalk is subject to both chemical and mechanical weathering. Chemical weathering occurs in the form of dissolution by acidic meteoric waters and mechanical weathering from plant roots and frost action. Freeze thaw cycles during the Pleistocene were responsible for significant weathering of the Chalk (Section 2.2) and under optimum conditions reduced the chalk to metastable silts (Fookes and Best, 1969). Chalk weathering is closely related to geomorphological setting – see Figure 2.12 (Lord et al., 2002).

![Figure 2.12 Schematic illustration of the relationship between weathering profile, engineering domain and associated Chalk downland geomorphology (Lord et al., 2002). Interfluves can be mantled with plateau drift with associated dissolution and this is controlled by altitude. Slopes gradients are dependent on altitude and aspect - as these affect thickness of head etc. The degree of in-situ disintegration and the quantity/thickness of head in the dry-valley floor is controlled by the size of valley and catchment.](image-url)
Lord et al. (1994) introduced the Chalk CIRIA Grading Scheme for logging and classifying chalk (Table 2.3 and Table 2.4). This classification scheme was developed to better distinguish the performance of different types of Chalk in engineering, and is additional to the standard engineering geological description. Lord et al. (1994) identified the factors most likely to influence the behaviour of the chalk mass as being the hardness/density/strength of the intact chalk, bedding/discontinuity spacing and pattern and discontinuity aperture. The first is a material property whereas the other two are mass properties. For comparison, standard rock discontinuity spacing descriptive terms (BSI, 2003) are also included in Table 2.4

<table>
<thead>
<tr>
<th>Grade</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Discontinuities closed</td>
</tr>
<tr>
<td>B</td>
<td>Typical discontinuity aperture &lt; 3mm</td>
</tr>
<tr>
<td>C</td>
<td>Typical discontinuity aperture &gt; 3mm</td>
</tr>
<tr>
<td>Dc</td>
<td>Structureless or remoulded melange. Clast dominated.</td>
</tr>
<tr>
<td>Dm</td>
<td>Structureless or remoulded melange. Matrix dominated.</td>
</tr>
</tbody>
</table>

Table 2.3 CIRIA classification of chalk by discontinuity aperture from Lord et al. (1994); (2002)

<table>
<thead>
<tr>
<th>Suffix</th>
<th>Typical discontinuity spacing (mm)</th>
<th>Discontinuity Spacing Descriptive Terms</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2000 &lt; t</td>
<td>Very Wide</td>
</tr>
<tr>
<td>1</td>
<td>600 &lt; t &lt; 2000</td>
<td>Wide</td>
</tr>
<tr>
<td>2</td>
<td>200 &lt; t &lt; 600</td>
<td>Medium</td>
</tr>
<tr>
<td>3</td>
<td>60 &lt; t &lt; 200</td>
<td>Close</td>
</tr>
<tr>
<td>4</td>
<td>20 &lt; t &lt; 60</td>
<td>Very Close</td>
</tr>
<tr>
<td>5</td>
<td>t &lt; 20</td>
<td>Extremely Close</td>
</tr>
</tbody>
</table>

Table 2.4 CIRIA subdivisions of grades A to C by discontinuity spacing from Lord et al. (1994); (2002) and discontinuity spacing descriptive terms from BSI (2003). Underlined discontinuity spacings subdivisions are specific to BSI (2003).

Mortimore (1996), based on Roberts and Preene (1990), also equated the Chalk CIRIA grades to permeabilities from pumping tests (Table 2.5)

<table>
<thead>
<tr>
<th>Munford Grade</th>
<th>Fracture Spacing (mm)</th>
<th>Permeability (m/s)</th>
<th>Dewatering Method</th>
<th>Equivalent CIRIA Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>VI</td>
<td>Unstructured, clasts in putty matrix</td>
<td>10^{-7} to 10^{-9} but dissolution or calcrete can be present</td>
<td>Dm</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>Unstructured, clasts in putty matrix</td>
<td>10^{-7} to 10^{-9} sometimes only light powdery fills with numerous open spaces and dissolution openings can be present</td>
<td>Dc</td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>&lt;60</td>
<td>10^{-7} to 10^{-9}</td>
<td>Wells or well points</td>
<td>C5</td>
</tr>
<tr>
<td>III</td>
<td>60-200</td>
<td>10^{-7} to 10^{-9}</td>
<td>Wells or well points</td>
<td>B3 to C3</td>
</tr>
<tr>
<td>II</td>
<td>&gt;200</td>
<td>Erratic due to solution widening</td>
<td>Sump pumps</td>
<td>A1 to A2</td>
</tr>
<tr>
<td>I</td>
<td>&gt;200</td>
<td>Erratic due to solution widening</td>
<td>Sump pumps</td>
<td>A1 to A2</td>
</tr>
</tbody>
</table>

Table 2.5 Permeability ranges for Munford Grades in the White Chalk Subgroup (Roberts and Preene, 1990; Mortimore, 1996)
The most easily measured material property of chalk, which is indicative of mass behaviour, is dry density (Clayton, 1990; Greenwood, 1993; Matthews et al., 1993). Mortimore et al. (1990c) and Greenwood (1993) developed a scale for classifying chalk in terms of laboratory derived intact dry density and suggested field identification criteria to correspond to these laboratory scales (Table 2.6). Bowden et al. (2002) further developed the field identification criteria (Table 2.6). The density scale is additional to the CIRIA grade in the engineering classification of chalk e.g. dry density + grade.

<table>
<thead>
<tr>
<th>Identification Method</th>
<th>Low density</th>
<th>Medium density</th>
<th>High density</th>
<th>Very high density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intact dry density</td>
<td>&lt; 1.55 Mg/m3</td>
<td>1.55-1.70 Mg/m3</td>
<td>1.70-1.95 Mg/m3</td>
<td>&gt;1.95 Mg/m3</td>
</tr>
<tr>
<td>Porosity n°</td>
<td>&gt; 0.43</td>
<td>0.43 – 0.37</td>
<td>0.37 – 0.28</td>
<td>&lt; 0.28</td>
</tr>
<tr>
<td>Saturated Moisture Content*</td>
<td>&gt; 27.5 %</td>
<td>27.5 – 21.8%</td>
<td>21.8 – 14.3%</td>
<td>&lt;14.3 %</td>
</tr>
<tr>
<td>Approximate UCS</td>
<td>&lt; 3 MN/m2</td>
<td>3-5 MN/m2</td>
<td>5-12.5 MN/m2</td>
<td>&gt;12.5 MN/m2</td>
</tr>
<tr>
<td>BS 5930 1999 Amendment I (Dec 2007) strength term</td>
<td>Extremely weak to very weak</td>
<td>Very weak</td>
<td>Weak</td>
<td>Weak</td>
</tr>
<tr>
<td>Ease of breaking fragments</td>
<td>30-40 mm thick fragments can be crushed between finger and thumb, and remoulded</td>
<td>30-40 mm-thick fragments can be broken in two using both hands, but cannot be crushed between finger and thumb</td>
<td>30-40 mm-thick fragments cannot be broken in two. Only thin slabs &lt; 10 mm thick, and corners and edges of lumps can be broken with difficulty using both hands</td>
<td>Cannot be broken by hand. 100 mm-diameter lump can be broken by a single hammer blow when held in the palm of the hand</td>
</tr>
<tr>
<td>150 mm nail penetration</td>
<td>&gt; 25 mm, putty formed around nail</td>
<td>15-25 mm</td>
<td>6-12 mm</td>
<td>&lt; 6 mm</td>
</tr>
<tr>
<td>Used hammer pick penetration</td>
<td>&gt; 30 mm, chalk splashes</td>
<td>11-30 mm</td>
<td>2-11 mm</td>
<td>&lt; 2mm</td>
</tr>
<tr>
<td>New hammer pick penetration</td>
<td>&gt; 35 mm, chalk splashes</td>
<td>18-35 mm</td>
<td>6-18 mm</td>
<td>&lt; 6mm</td>
</tr>
</tbody>
</table>

Table 2.6 Intact dry density scales of chalk (based on Mortimore et al., 1990c; Matthews et al., 1993) and field identification procedures for CIRIA chalk density (after Bowden et al., 2002)
2.6 Hydrogeology of the Chalk Group

The Chalk has a distinct set of hydrogeological characteristics. It forms a dual or double porosity aquifer. The dual porosity results from the porosity of the matrix and the porosity of the fractures. The matrix porosity is high, around 20 to 45 per cent, but the matrix permeability is low - around $10^{-9} - 10^{-8}$ m$^{-1}$ (10$^{-5}$ to 10$^{-4}$ md$^{-1}$) (Price et al., 1993). The fracture porosity, however, is low, around 0.01%, but fractured chalk has a permeability of around $10^{-5} - 10^{-3}$ m$^{-1}$ (10$^{-1}$ to 10$^1$ md$^{-1}$) (Price et al., 1993).

The Chalk of England functions effectively as an aquifer because of the higher permeability provided by fractures (Price, 1987). As described in section 2.5, the Chalk contains distinct sets of discontinuities or fractures. It is the set sub-parallel to bedding that are believed to be pervasive and most hydrogeologically significant (Bloomfield, 1996). Although, different authors have discussed fractures using classification such as “primary” and “secondary” (Price, 1987) or “micro-fissures” and “macro-fissures” (Reeves, 1979) there is, in reality, likely to be a continuum from sealed micro-fractures to greatly enlarged karstic features.

2.6.1 Unsaturated Zone

The unsaturated zone is defined as that part of the aquifer that lies above the deepest water table where the pore-water pressures are less than atmospheric pressure except locally where perched aquifers exist. As the Chalk aquifer tends to have low or moderate hydraulic gradients and therefore relatively flat water tables, but chalk landscapes may have marked relief, the unsaturated zone can vary in thickness between 0 m in river valleys to more than a 100 m under hills (Price et al., 1993; Jones and Robins, 1999). Local variations in water tables, however, are known to exist from construction projects and may be influenced by the geological structure of the Chalk (Headworth, 1972; Giles and Lowings, 1990; Mortimore, 1993).

The condition of the unsaturated zone at any point in time controls how much infiltration will reach the water table and thus how much will recharge the aquifer. The capillary fringe is the portion of the unsaturated zone where the pores are saturated but the pore water is at less than atmospheric pressure. The pores do not
typically drain because the pore water pressure does not fall below the air entry pressure. The air-entry pressure is lower (more negative) for fine-grained materials than for coarse-grained materials. As a result, fine-grained materials have a thick capillary fringe (Price et al., 1993).

Due to the dual-porosity nature of the Chalk aquifer, the capillary fringe exits in two parts – the capillary fringe of the matrix and the fractures. The matrix is very fine grained with the pore throats, which control the matrix air entry pressure, around 1 μm. The corresponding air-entry pressure produces a capillary fringe of more than 30 m. The fractures, however, are assumed to have apertures greater than 50 μm and the corresponding air entry pressure would produce a capillary fringe of approximately 0.5 m. Therefore, the pore spaces of the chalk matrix will be saturated to a height of about 30 m above the water table but the fractures will typically be saturated to a height of approximately 0.5 m above the water table (Price et al., 1993).

If the chalk matrix capillary fringe is assumed to extend to the ground surface or the unsaturated zone is at field capacity, i.e. no soil moisture deficit, then the maximum infiltration rate without fracture flow will be approximately equivalent to the saturated hydraulic conductivity of the matrix. If the infiltration rate is average or moderate, water will move through the unsaturated zone, from the soil into the matrix. When the infiltration rate exceeds the saturated hydraulic conductivity of the matrix and persists for several days then the fissure system will begin to fill and conduct water. If, for example, the saturated hydraulic conductivity of matrix is 3-5 x 10^{-3} md^{-1} then the infiltration rate threshold for fracture flow will be 3-5 mmd^{-1}. If flow is activated in the major fractures then velocities of the order of 50 md^{-1} could occur in the unsaturated zone (Price et al., 1993).

Until the late 1960s, flow in the unsaturated zone of the Chalk was believed to be predominantly via fractures. The rapid response of the water table to high intensity rainfall events and the appearance of bacteria in production boreholes were cited as evidence for this assumption. However, a study by Smith et al. (1970) on the tritium content in chalk pore-water concluded that 85% of the total flow through the unsaturated zone was by intergranular flow through the matrix at less than 0.9 m/yr.
This led to the development of the concept of “piston flow” whereby the rapid response of the water table was thought to be due to the piston-displacement of the water within the unsaturated zone rather than flow through it (Price et al., 1993).

Early work at various Chalk sites in the south-east England (Wellings, 1984) suggested that fracture flow was likely to occur when matric potentials rose above approximately – 50 hPa: above these potentials, there was observed to be a rapid increase in hydraulic conductivity which was interpreted as the fracture system conducting water. These observations were reinforced by analysis of lysimeter data from Fleam Dyke in Cambridgeshire (Jones and Cooper, 1998) which showed that rapid recharge (greater than 1 mm/d – the derived hydraulic conductivity of the matrix) occurred through the lysimeter when the 5 m profile was at potentials of greater than -50 hPa. The results from this site suggested fracture flow accounted for around 30% of the annual drainage. In contrast, at Bridget’s Farm in Hampshire (Wellings, 1984), where matric hydraulic conductivity was high (around 6 mm/d), matric potentials only rose above -50 hPa under exceptional rainfall events and it was assumed that fracture flow was a very rare event. The differences between these two sites demonstrated that fracture flow could account for anything between approximately 0 - 30% of annual recharge (at the near surface).

A study by Lewis et al. (1993) found that water draining from two chalk river catchments in recessions was significantly greater than could be explained by gravity drainage from porosity. It was concluded that this discrepancy was probably due to slow release of water by drainage of chalk in the unsaturated zone. They calculated that drainage of water equivalent to some 0.25-0.30% of the volume of rock in the unsaturated zone would be sufficient to account for the anomaly. Assuming that the fissure porosity would have drained completely and relatively quickly, the water was assumed to come from the matrix porosity.

This conclusion was at odds with the observation that the matric pore space does not drain to any significant degree due to the narrow throats of individual pores (Price et al., 1993). Following detailed experimental work, Price et al. (2000) concluded that the water responsible for the discrepancy in storage noted by Lewis et al. (1993) was located on the irregularities on fissure surfaces within the
unsaturated zone. This additional storage was also considered as the explanation for why the water table is slow to respond to recharge events for much of the recharge season, and why the chalk is so resilient to drought. The concept of filling and draining of irregularities on fissure surfaces lead to a new model for the generation of fissure flow in the unsaturated zone of the chalk (Price et al., 2000). According to this new model, fissure flow was not generated by water moving down a fissure from the soil, but by suction in the surrounding blocks falling to a level where first the irregularities on the surfaces of the blocks are filled with water and then the narrower fissure also become filled. Thus fissure flow could be generated at any depth in the profile and, in a sequence of uniform vertical permeability, is likely to originate near the water table rather than high in the unsaturated zone. An additional conclusion from this work was that there will be significantly more water in storage in the unsaturated zone at the end of a recharge season than at the beginning of the following one for the same level of the water-table. Thus it follows that the water table’s response to recharge events will be relatively quicker at the end of the recharge season than at the beginning.

Haria et al. (2003) showed that water could also be held in storage along horizontal fractures due to film generation at contact points between blocks vertically above each other and, at low drainage fluxes, the hydraulic conductivity at contact points between chalk blocks was sufficient to transmit water downward. As the recharge season progresses and downward flux increases, however the small contact area would becomes restrictive to vertical water movement. Consequently, a thin film develops at the contact points to accommodate the increased vertical flux (Hodnett and Bell, 1990). These water films increase in thickness so increasing the hydraulic conductivity by enlarging the cross-sectional water filled porosity thereby reducing the tortuosity of flow pathways. Thus the horizontal fractures are providing greater storage within the unsaturated zone in addition to that described by Price et al. (2000).

Where the chalk matrix permeability is low, evidence indicates that unsaturated zone fracture flow is a common occurrence - particularly in winter (Cooper et al., 1990). Adams et al. (2008), Rutter et al. (2012), Gallagher et al. (2012) and Molyneux (2012) also observed that the presence of marls seams in the Chalk
unsaturated zone significantly reduced matrix permeability and increased the frequency of unsaturated zone fracture surface film flow. Cooper et al. (1990) suggested that other components of the unsaturated zone such as the thickness of soil, superficial deposits and weathered chalk overlying the undisturbed chalk are an important control on the occurrence of fracture flow. The spread of pore sizes in these materials provides a buffer for storage of rainwater, delaying release into the undisturbed chalk and therefore reducing the frequency of fissure flow.

2.6.2 Saturated Zone

The saturated zone is that part of the aquifer which lies below the water table - where the pore water pressures are equal to or greater than atmospheric pressure. It is generally, the upper 50-60 m of the saturated zone that is the principal, or effective, aquifer. The permeability generally decreases with depth through the saturated zone as the fracture density and fracture aperture reduce (Price et al., 1993). Fractures, therefore, account for much of the water movement in the effective aquifer.

High transmissivity values, which make the Chalk such a productive aquifer, are due to the enlargement, by solution, of the primary fracture component (Foster and Milton, 1974; Price et al., 1977; Price et al., 1982). In the saturated zone, the hydraulic behaviour is dominated by the dual porosity interaction of the primary and secondary fractures. Evidence suggests that the secondary solution enhanced fractures are concentrated at present or palaeo- zones of seasonal water table fluctuation. The development of secondary solution enhanced fractures is due to solution by water containing dissolved carbon dioxide (Price et al., 1993). Mustchin (1974) documented the spacing of major solution enhanced water-yielding fissures in the adits systems near Brighton as being 10 m to 500 m with individual fissures able to yield very large flows of the order of 5000 to 15000 m$^3$ d$^{-1}$.

Another characteristic of the saturated chalk aquifer is the association of high permeability with valleys and lower permeability associated with interfluves - although interfluves vary depending on the presence or absence of localised major fractures. Transmissivity values can be of the order of 3 x 10$^{-2}$ m$^2$s$^{-1}$ in valleys but reduce to 2 x 10$^{-4}$ m$^2$ s$^{-1}$ beneath higher parts of the interfluves (Price et al., 1993). In the saturated zone the matrix makes a negligible contribution to the transmissivity
of the aquifer with the permeability of the unfractured matrix being around $10^{-8}$ ms\(^{-1}\) (Price et al., 1993). Several factors are responsible for the high permeability along valleys and these are summaries in Table 2.7.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure</td>
<td>Valleys have been interpreted as following lines of structural weakness, with a higher degree of fracturing (Ineson, 1962; Morgan, 1971; Crampon et al., 1993; Marsh, 1993; Mortimore, 2012).</td>
</tr>
<tr>
<td>Erosion</td>
<td>Erosion along valleys reduces effective stress which can lead to the opening of fractures (Ineson, 1962; Price, 1987; Price et al., 1993).</td>
</tr>
<tr>
<td>Concentration of groundwater flow and groundwater mixing</td>
<td>The concentration of groundwater flow towards valley discharge areas, and mixing of groundwaters which have different chemical compositions, and are undersaturated with calcite, can lead to chalk dissolution (Rhoades and Sinacori, 1941; Robinson, 1976; Connorton and Reed, 1978; Owen and Robinson, 1978; Price, 1987; Price et al., 1993).</td>
</tr>
<tr>
<td>Periglaciation</td>
<td>Repeated freezing and thawing within the active layer would have broken down the top few metres of chalk to a weathered mantle and potentially lead to fractures opening up to depths of 20 to 30 m (Higginbottom and Fookes, 1970; Williams, 1980; Gibbard, 1985; Williams, 1987). Also, where there was surface water, concentration of flow in the talik and colder waters may have increased dissolution (Younger, 1989).</td>
</tr>
</tbody>
</table>

Table 2.7 Summary of factors contributing to higher transmissivity and storage in valleys on Chalk outcrop

The Chalk also has lithological variation which has influenced the development of preferential flow pathways. For example, there is evidence of higher permeability associated with hardgrounds such as the Chalk Rock and the Melbourn Rock which have higher degrees of fracturing or with karstic features developed laterally along marl layers where these have restricted water movement vertically (Mortimore, 1993). Association with younger materials overlying the Chalk may also lead to preferential flow pathways. For example, solution pipes are commonly developed in the Chalk on the edge of Palaeogene as result of acidic runoff (Price et al., 1993; Macdonald et al., 1998).

### 2.7 Geological Modelling and Visualisation

Three dimensional geological modelling and visualisation are routine in the mineral resources sectors. Their application in engineering geology and hydrogeology, however, is less common despite the advantages (Hack et al., 2006). Published examples in the literature from these sectors of geoscience commonly present models developed to enhance conceptualisation in water resources or as a tool to aid assessment of contamination risk to aquifers e.g. Dumpleton et al. (2001), Robins et al. (2003) and Mende et al. (2007). The relative lack of examples of 3-D
geological models or visualisations used in engineering geology maybe due to the constrained areas of investigation of many civil engineering projects. Civil engineering projects, such as bridges, roads or tunnels, typically have narrow and linear areas of investigation. The conceptual ground models for such investigations are commonly presented as a series of 2-D profile sections.

Conceptually, the engineering geological model may be thought of lying centrally between a triangle of knowledge and understanding of geological processes, geological material and mass properties and engineering geological boundaries (Knill, 2003). As the geological processes inherent in a geological model are spatially variable, it seems appropriate to summarise the knowledge and understanding of these processes for non-specialists in a direct and clear manner. Traditionally, this may be achieved diagrammatically but progressively this may be achieved through interactive visualisation.

Culshaw (2005) demonstrated how the British Geological Survey has been developing their capability in this respect by applying geological modelling tools in hydrogeological and engineering geology projects. Recent published examples of the British Geological Survey’s geological modelling (Figure 2.13) can be seen in Ford et al. (2008; 2010) Royse et al. (2008; 2009) and Royse (2010). Examples specifically related to the Chalk Group in southern England include; the 3-D conceptualisation of the central South Downs aquifer (Robins, 2001; Robins et al., 2003), the LOCAR model of the Pang and Lambourn catchments (Aldiss et al., 2002), and the London LithoFrame50 Model (Ford et al., 2008; Royse, 2010). The latter has been developed from a number of smaller models in the London area using GSI3D (Geological Surveying and Investigation in 3-D), which is a geological modelling software package the BGS has adopted and further developed using its projects as a test bed (Kessler et al., 2004; Kessler et al., 2008).
The 3-D conceptualisation of the central South Downs aquifer was developed by the British Geological Survey (BGS) using Vulcan in 1999 for Southern Water. The model was developed to better understand the flow system within the aquifer by taking advantage of the development of the new lithostratigraphy and mapping on sheets 317/332 Chichester and Bognor Regis (British Geological Survey, 1996) and 318/333 Brighton and Worthing (British Geological Survey, 2006a). These data were supplemented with re-interpreted borehole logs, down-hole geophysical data and re-interpretation of existing seismic traverses (Robins, 2001). The model also covers the Patcham Catchment area.

The data used to construct the central South Downs aquifer 3-D model comprised OS digital contours, spot heights and control points; digital geological linework captured at 1:10,000 scale, drift and features such as landslips, worked ground and made ground; base of Chalk contours (derived from seismic interpretation); offshore bathymetry and sediment thickness; on-shore rock-head contours; transmissivity and storativity data; water table configuration, typical spring and autumn groundwater data and the distribution of springs, spring lines and dolines (Robins, 2001).

A digital terrain model (DTM) was created using the OS digital contours, spot heights and other control points at a 25 m spacing grid. Seismic data from hydrocarbon
exploration were reinterpreted to generate a digital contour map of the base of the West Melbury Chalk Formation supported by a limited number of deep boreholes through the base of the Chalk. Several deep hydrocarbon wells that penetrate the Chalk provided sonic and gamma ray geophysical logs (Robins, 2001).

These structure contours on the base of the West Melbury Chalk Formation were used as a structural framework to guide the construction of the geometry of the remaining Chalk formations. The seismic interpretation was adjusted at shallow depths (<50 m) where it was believed the original data (shot for deep exploration of oil reserves) were out of range. Further data for the Chalk formations came from selected boreholes from the BGS Wellmaster water borehole database and interpretations of downhole geophysical logs of boreholes from various sources. Hydrogeological data in the form of transmissivity, storativity and water level data were also imported into the model (Robins, 2001).

The model was constructed using Vulcan – a software package developed by KRJA Systems Limited. Vulcan was originally designed for the Australian mining industry to portray mineral lodes in 3-D and assist in optimum mining design. The BGS had previously used Vulcan to produce a 3-D visual model to evaluate the risk to the Permo-Triassic aquifer from rising minewater in the South Nottinghamshire Coalfield (Robins, 2001).

The software chosen for geological modelling on the FLOOD1 project was GSI3D 1.5.2. GSI3D was developed by Hans-Georg Sobisch at the Soil and Geological Survey of Lower Saxony and the University of Cologne (Hinze et al., 1999; Sobisch, 2000; Sobisch and Bombien, 2003), and was originally designed for modelling the near-surface environment (approximately the uppermost 100 m) and sedimentary geology (Culshaw, 2005). More recent versions of the software, however, can be used to model faulted strata (e.g. Aldiss et al., 2012)

The data utilised by GSI3D in the modelling process comprises topographic maps and DTMs (digital terrain models); 2D geological maps; boreholes coded by lithology and interpreted stratigraphy; cross sections; contoured maps of buried surfaces; hydrogeological data; geochemical distributions; geophysical data and geotechnical
data. The modelling process, summarised by Culshaw (2005), is based around the creation of a series of intersecting user-defined cross sections (Table 2.8). The geologist producing the model must also determine the stacking order of all deposits in the study area in the generalised vertical section file (GVS). This can be complicated where deposits have limited extent. The purpose of a model should be considered prior to modelling as this will dictate the modelling scale. The procedure for producing a geological model with GSI3D is summarised in Table 2.8.

Surfaces from GSI3D models can be exported in ascii format to other software packages such as ArcGIS for more advance interrogation and spatial analysis. Culshaw (2005) goes on to state, while realistic portrayal of geological surfaces in three-dimensions is becoming easier, it remains difficult to attribute the geological volumes defined by the surfaces with geotechnical property data meaningfully.

Baynes and Rosenbaum (2004) documented the following questions raised for consideration regarding the application of 3-D geological models in engineering geology:

- What is the minimum content that constitutes a useful model?
- How can the quality of models be assured?
- What metadata should accompany the models?
- How should uncertainty associated with the model and its plausibility be described?
- How can the models be kept up to date as new information becomes available?

As the tools to create 3-D geological models become increasingly available and utilised, a mechanism is needed to capture information regarding their construction, limitations and version. Conventions for recording metadata are well established for geo-spatial digital data used in geographical information systems (GIS) e.g. the UK GEMINI Standard. It seems appropriate that these conventions should be applied to 3-D geological models.
Table 2.8 Procedure for producing a geological model with GSI3D (after Culshaw, 2005)

<table>
<thead>
<tr>
<th>Stage</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Borehole log data are stratigraphically and lithologically coded. Ideally the most reliable in terms of locational data (x,y,z coordinate) and deepest of multiple, closely space boreholes need coding.</td>
</tr>
<tr>
<td>2</td>
<td>A DTM of appropriate resolution is loaded.</td>
</tr>
<tr>
<td>3</td>
<td>The surface geological map at appropriate scale is loaded.</td>
</tr>
<tr>
<td>4</td>
<td>Boreholes to make a cross-section are selected.</td>
</tr>
<tr>
<td>5</td>
<td>Starting with the shallowest, geologically realistic correlation lines are drawn to connect the geological units (they do not need to be straight between boreholes).</td>
</tr>
<tr>
<td>6</td>
<td>A series of regularly spaced cross-sections is created. The spacing of these will depend upon the density of data and the type of 3D model being constructed e.g. overview, systematic or detailed. If possible, major cross-sections should intersect structures and valleys at approximately right angles, with minor cross sections being used to cover variations and anomalies and incorporate linear bodies not adequately included by the major cross-sections.</td>
</tr>
<tr>
<td>7</td>
<td>Once a series of sub-parallel cross sections have been constructed a second series is produced roughly at right angles to the first to produce a fence diagram. The positions of geological boundaries at cross section intersections are checked and modified as necessary.</td>
</tr>
<tr>
<td>8</td>
<td>The surfaces that define the top of each geological unit are then created from the surface geological map and the fence diagram by either working outwards from the surface outcrop to include areas buried by other units, or by taking the likely maximum extent of the unit and trimming back and editing the surface based on the cross-sections and borehole data.</td>
</tr>
<tr>
<td>9</td>
<td>The surfaces are then spatially combined to produce the 3D geological model stack. In this modelling process, an algorithm assigns elevations (z) values to each surface by reference to the DTM.</td>
</tr>
<tr>
<td>10</td>
<td>The model can be checked for mis-correlations by creating a rectangular grid across the whole area, manually viewing ‘synthetic’ cross-sections and correcting as necessary.</td>
</tr>
</tbody>
</table>

Output:
- A fully attributed Generalised Vertical Section (GVS). This forms the basis for engineering geological, hydrogeological and mineral potential classifications.
- Contoured or gridded surfaces of tops, bases, thicknesses (isopachytes of single or combined units) and volumes of a single or combined geological units (including artificial ground)
- Synthetic logs at any location, horizontal slice maps at any depth and vertical cross sections in any orientation
- Sub and supracrop maps, domain maps and maps of for tunnels or pipelines along the proposed design route.

The factors which contribute to the overall uncertainty of surfaces in a geological model can be broadly grouped into data density, data quality and geological complexity. The uncertainty associated with a modelled surface maybe represented qualitatively through the presentation of the modelling work flow using cause and effect diagrams or semi-quantitatively, for geostatistically interpolated surfaces, using resampling techniques and determining the 95% confidence limit (Cave and Wood, 2002; Lelliott et al., 2009).

2.8 Discussion

The background concepts and literature discussed in this chapter have highlighted similarities and differences in the geological evolution and the stratigraphical
systems applied to map the Chalk in each of the research catchments. Mortimore et al. (1990b) and Mortimore and Pomerol (1998) demonstrated that variation in Chalk lithology and lithological properties, and therefore also lithostratigraphy, relate to the palaeogeography of the depositional basin. The understanding of Chalk stratigraphy and lithological variation in southern England, and within the South Downs, is highly refined with the work of Mortimore (1986), Bristow et al. (1997) and Mortimore et al. (2001). Likewise, the 3-D conceptualisation of the central South Downs aquifer by Robins (2001), which also incorporates non-stratigraphical data such as water table surfaces, can be considered as a 3D ground model. There is, therefore, a significant body of research and data which covers the area of the Patcham Catchment. In contrast, the level of understanding with regard to the Chalk stratigraphy and lithology in the Hallue Catchment is more limited. The purely biostratigraphical approach currently applied to mapping the Chalk in the Hallue Catchment does not take into account the variation in Chalk lithology and lithological properties associated with variations in the depositional basin. Mortimore and Pomerol (1987), Pomerol et al. (1987), Pomerol (1988a, b; 1996) and Robaszynski et al. (2005) have demonstrated that lithological marker horizons and index fossils, used in the UK southern province Chalk lithostratigraphy, can be identified and used in some parts of the Paris Basin for correlation and mapping. There is, therefore, a requirement for a more detailed investigation of the Chalk stratigraphy and lithology within the Hallue Catchment. In light of the literature reviewed, a number of questions arise:

- Could the stratigraphy and marker horizons recognised by, Mortimore and Pomerol (1987), Pomerol et al. (1987), Pomerol (1988a, b; 1996), Robaszynski et al. (2005), Mortimore (2001b), be applied to the Hallue Catchment for mapping and correlation purposes?
- Within the context of a stratigraphical framework, what are the typical lithologies of the Chalk in the Hallue Catchment and how do they compare to other areas in the Paris Basin and southern England?
- What additional local data could be collected to enhance the conceptual understanding of the Chalk in the vicinity of the Patcham Catchment and build on the data already available for the South Downs?
• The 3-D conceptualisation of the central South Downs aquifer by Robins (2001), does not attempt to represent the weathered zone of the Chalk. This zone represents a fundamental change in the physical properties of the Chalk rock mass and aquifer (Figure 1.2). Could a method be developed to model or predict the base of the weathered zone (engineering rockhead)?

2.9 Conclusion

The literature presented and discussed in this chapter has provided the background concepts and framework for the research presented in this thesis. Key research questions have arisen from this literature regarding:

(i) The stratigraphical framework applied in the Hallue Catchment for mapping in light of other work conducted in the Paris Basin
(ii) The lithological variation of the chalk of Hallue Catchment in relation to depositional setting
(iii) Site specific data that might be required for the Patcham Catchment
(iv) A technique for predicting the position of the base of the weathered zone

The preliminary results from the field investigations, with respect to the stratigraphy and geological mapping of the research catchments, are presented and discussed in Chapter 3. The results from further field investigations and modelling are presented and discussed in Chapters 4 - 6.
Chapter 3 Stratigraphy of the Catchments

3.1 Introduction

This chapter presents the stratigraphical and lithological results from field investigations of the Chalk outcrop in the Hallue and Patcham catchments. The results were reviewed in the context of the literature presented in Chapter 2 and form the basis for the further work presented in Chapters 4-6.

Field investigations were undertaken in both the FLOOD1 research catchments to provide refined geological information in the form of lithostratigraphical logs, cross sections, correlation diagrams and maps. The research catchments were defined, for the purpose of the field investigations, as the extent of the catchment based on the groundwater divide for the water table during groundwater flooding conditions (Figure 1.4, Figure 3.1 and Figure 3.2) and were determined from the flooding potentiometric contours. Where comparative data was required, additional sites, outside of the groundwater catchments, were studied.

The focus for the field investigations varied between the research catchments due to differing data requirements. The objectives of the field investigation in the Hallue catchment were to produce a unified bedrock geological map and develop a lithostratigraphical framework based on the data collected from exposures and the FLOOD1 recharge site boreholes. The objectives of the field investigation in the Patcham Catchment were to validate current geological mapping and acquire new borehole data. The wider objective of the field investigations in both research catchments was to collate data which could be correlated and compared between the research catchments, and used to develop geological models.
Figure 3.1 Location of exposures and boreholes studied in the Hallue catchment. The north-south and east-west orientated lines represent the boundaries of the current BRGM geological maps Amiens, Albert, Doullens and Baupaume. (Mapping © IGN)
Figure 3.2 Location of fieldwork transects and boreholes in the Patcham catchment. The groundwater flooding areas and spring locations are shown for reference. (OS Mapping © Crown Copyright 2007)
3.2 Hallue Catchment

3.2.1 Background

The first geological maps which cover the Hallue Catchment were the 1:80,000 geological maps of Amiens and Arras published in 1874 (Fuchs et Clairaut, 1874; Potier, 1874). These were revised respectively by Gosselet and Cayeux et de Mercey (1894) and Gosselet (1909). Early regional geological maps which also applied to the Hallue Catchment include 1:500,000 map of France (Dufrénoy and Élie de Beaumont, 1840), 1:320,000 Lille-Dunkerque (Gosselet, 1897), the hypsometrical map of the surface of the Chalk by Dolfuss (1909) and the structural contour map of King (1921). The Hallue Catchment mapping was then re-produced between 1969 and 1977 by Bureau Recherches Géologique et Minières (BRGM), in collaboration with a number of academic institutions, and published at 1:50,000 (Dupuis et al., 1972a; Delattre et al., 1974; Mennessier et al., 1976a; Delattre and Mériaux, 1977). The chalk outcrop shown on these maps is subdivided into stage and sub-stage units based primarily on analysis of microfossil and macrofossil field samples.

There are four 1:50,000 geological maps which covered the Hallue catchment - Amiens, Albert, Doullens and Bapaume (Figure 3.1). As discussed in Chapter 2, the microfossil (foraminifera) biozones developed by Monciardini (1978, 1980) were applied on the Amiens, Albert and Bapaume sheets (Dupuis et al., 1972a; Mennessier et al., 1976a; Delattre and Mériaux, 1977). Macrofossil samples were also used on the Albert and Bapaume sheets, and were the sole source of biostratigraphical evidence used in the production of the Doullens sheet (Delattre et al., 1974). The division of mapped units in the Chalk, however, differs between these maps - as do a number of the mapped units in the Palaeogene, Neogene and Quaternary deposits (Table 3.1 and Table 3.2). Furthermore, linework for the same Chalk unit present on adjoining sheets may not always correspond on the sheet boundaries. The Hallue Catchment, therefore, required a unified geological map and lithostratigraphical framework for the Chalk for the FLOOD1 hydrogeological investigations.
<table>
<thead>
<tr>
<th>Stage</th>
<th>Amiens</th>
<th>Albert</th>
<th>Doullens</th>
<th>Baupaume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Campanian</td>
<td></td>
<td>C6b</td>
<td>C6</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Upper Campanian – biozone h)</td>
<td>(Campanian)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>C6a</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Lower Campanian – biozone g)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Santonian</td>
<td>C5d/C5e/C5d-e</td>
<td>C5c-6a</td>
<td>C4-5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Lower Santonian – biozone d/ Middle and Upper Santonian – biozone e/ Santonian undifferentiated – biozones d-e)</td>
<td>(Upper Santonian to Lower Campanian – biozone f)</td>
<td>(Coniacian-Santonian)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>C5b-c</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Middle and Upper Santonian – biozone e)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>C5a</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Lower Santonian – biozone d)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coniacian</td>
<td>C4bc</td>
<td>C4c</td>
<td>C4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Middle Coniacian to Upper Coniacian – biozones b-c)</td>
<td>(Upper Coniacian – biozone c)</td>
<td>(Coniacian – biozones a-c)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>C4b</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Middle Coniacian – biozones b)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turonian</td>
<td>C3-4a</td>
<td>C3-4a</td>
<td>C3c</td>
<td>C3c</td>
</tr>
<tr>
<td></td>
<td>(Upper Turonian to Lower Coniacian – biozone a)</td>
<td>(Upper Turonian to Lower Coniacian – biozone a)</td>
<td>(Upper Turonian)</td>
<td>(Upper Turonian – biozones Ts)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1 Chalk stratigraphical units mapped on the Amiens, Albert, Doullens and Baupaume 1:50,000 geological maps (Dupuis et al., 1972a; Delattre et al., 1974; Mennessier et al., 1976a; Delattre and Mériaux, 1977). Cells shaded in grey indicate the absence of a unit on adjoining map. The microfossil biozones of Monciardini (1978, 1980), where used in the production of the map, are indicated.
<table>
<thead>
<tr>
<th>Period</th>
<th>Amiens</th>
<th>Albert</th>
<th>Doullens</th>
<th>Baupaume</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Quaternary and Neogene</strong></td>
<td>X (Remblais)</td>
<td>X (Remblais)</td>
<td>X (Remblais)</td>
<td>C (Colluvions)</td>
</tr>
<tr>
<td>CF/C/CRs (Colluvion)</td>
<td>CV/C (Limons des vallées sèches/colluvions)</td>
<td>C/CRs (Colluvions)</td>
<td>C (Colluvions)</td>
<td></td>
</tr>
<tr>
<td>LP/LP1/LP2 (Complex des Limon des plateaux)</td>
<td>LP/LPs/CLP (Limons des plateaux)</td>
<td>LP (Complexe des « Limons des plateaux »)</td>
<td>LP (Complexe des « Limons des plateaux »)</td>
<td></td>
</tr>
<tr>
<td>Fz/Uz (Alluvion holocènes et tardiglaciaires/Tufs holocènes)</td>
<td>Fz/Uz (Alluvion recentes/Travertins)</td>
<td>Fz (Alluvions recentes)</td>
<td>Fz (Alluvions recentes)</td>
<td></td>
</tr>
<tr>
<td>Fy (Graviers de fond de vallée)</td>
<td>Fy (Alluvions anciennes)</td>
<td>Fy (Alluvions anciennes)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fx (Alluvions des niveaux de 5 m et 10 m – basses terrasse)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fw/AFw (Niveau de 30 m – moyenne terrasse/alluvions altérées, cryoturbées, souvent solifluees)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fv/AFv (Niveau de 40 a 45 m - haute terrasse/altérées)</td>
<td>Fv (Alluvions anciennes)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fu/AFu (Niveau de 55 m – tres haute terrasse/altérées)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ft/Aft (Niveau de 70 m - terrasse du bois de Montieres/altérées)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rs (Formations résiduelles à silex)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Palaeogene</strong></td>
<td>e3 (Sparnacien)</td>
<td>e2 (Thanétien)</td>
<td>e2 (Thanétien)</td>
<td>e2 (Landénien - Thanétien)</td>
</tr>
</tbody>
</table>

Table 3.2 Palaeogene, Neogene and Quaternary units mapped on the Amiens, Albert, Doullens and Baupaume 1:50,000 geological maps (Dupuis et al., 1972a; Delattre et al., 1974; Mennessier et al., 1976a; Delattre and Mériaux, 1977). Cells shaded in grey indicate the absence of a unit on adjoining map. ‘Alluvions holocènes/recentes’ are present day alluvial deposits. ‘Alluvions anciennes’ are Pleistocene river terrace deposits. ‘Colluvions’ are hill slope and valley deposits, similar to Head deposits in the UK, comprising Crayeuses (chalk fragments), Alluvion, Limon, Formations résiduelles à silex. ‘Limon des plateaux’ is a Pleistocene loessic deposit. ‘Formations résiduelles à silex’ is a remnant deposit composed of clay and flints equivalent to Clay-Where-Flints in the UK. ‘Thanétien sables’ are marine sands equivalent to the Thanet Sand and Upnor Formation in the UK.
3.2.2 Methodology

Techniques employed for mapping the Chalk differ between the UK and France (Section 2.3 and Section 2.4). In the UK, boundaries have been delineated based on field surveying using brash, exposures, geomorphology and remote sensing images. In France, in the vicinity of the Hallue Catchment, boundaries have been delineated based on field sampling of chalk and determination of age using microfossil assemblages. In this study, because of the area of the Hallue Catchment (approximately 220 km²) and the nature of the geology, a targeted field investigation was required. The catchment geology was also known to be complicated by areas of thick Quaternary deposits. These deposits limit the effectiveness of Chalk landform mapping and, where present, the agricultural land is commonly limed with chalk which complicates brash mapping. It was, therefore, decided that the most appropriate approach to the field investigation was to collect data from field exposures. These data would be correlated with the current BRGM geological maps and the new data collected from the FLOOD1 recharge site boreholes to develop a lithostratigraphical framework for the catchment.

All exposures illustrated on the BRGM 1:50,000 geological maps and the Institut Géographique National (IGN) 1:25000 maps for the catchment were identified. These exposures, typically agricultural quarries or road cuttings, were systematically logged. Qualitative and semi-quantitative data such as colour, texture, density and chalk CIRIA grade based on Lord et al. (2002), fracturing characteristics (frequency, aperture, dip and dip direction), and the presence or absence of flints, marls and fossils were recorded at each location. Macr fossil samples were collected to determine stratigraphical age and large orientated hand specimens were collected for fabric analysis (Chapter 4).

It was intended that the application of marker beds and index macrofossils, used in the UK Southern Province lithostratigraphical system and applied in the BRGM 1:50,000 maps of Bléneau (Pomerol, 1988c), Courtenay (Pomerol, 1988d), and Arcis-sur-Aube (Pomerol, 1996b), would be assessed. If feasible, a lithostratigraphical framework would be derived for the Hallue Catchment by
combining biostratigraphical evidence with lithological observations collected from the logged exposures and FLOOD1 recharge site boreholes.

### 3.2.3 Results

In total, data was collected from 63 exposures (Figure 3.1). A small number of these exposures are located outside of the Hallue Catchment but were studied because of close proximity to the catchment boundary or because they provided the nearest comparison at outcrop to strata retrieved in the recharge site boreholes. The average height of rock face exposed was approximately 4 m with the majority of the exposures studied having between 1-2 m. Typically, the exposures had been larger than this but, in many cases, were highly weathered or being backfilled. A summary of the field investigation data collected from key exposures and the FLOOD1 recharge site boreholes is presented in Table 3.3 to Table 3.6. Refer to Appendices I, II and III for complete field notes, photographs and logs.

#### 3.2.3.1 Lithology

The broad lithological characteristics of the Chalk in the Hallue Catchment were determined from logging exposures and borehole cores and are summarised in Table 3.3. At some exposures, lithological characteristics were observed which were localised and absent in strata of equivalent ages in other parts of the catchment. For example, the Middle Coniacian chalk observed at HA6 was very dense and appeared cemented. A local resident explained that the chalk from this quarry was not used for agricultural lime but for track covering. Elsewhere in the catchment, equivalent Middle Coniacian Chalk was found to be medium to high density. SEM analysis of a sample of the chalk from HA6 indicated it may have been diagenetically re-crystallised.

In addition to broad changes in lithology, a number of discrete marker horizons were identified. These comprise characteristic flint and marl horizons which were identified in exposure by lithological characteristics and fossil assemblage (Table 3.4 - Table 3.6 and Figure 3.3) and then correlated to the core from the FLOOD1 recharge site (Figure 3.4). These marker horizons were recognised by Mortimore (1983a, 1986; 1987) and are identified here as the Glynde Marls, the Southerham Marls, the Caburn Marl, the Bridgewick Marl, the Lewes Tubular Flints, the Lewes Marl, the Criel Flints, the Shoreham Tubular Flints, the Shoreham Marl 2 and the
<table>
<thead>
<tr>
<th>Stage or Substage</th>
<th>Density</th>
<th>Texture</th>
<th>Colour</th>
<th>Flint</th>
<th>Marl</th>
<th>Fractures</th>
<th>Brash/ Block Shape</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Campanian</td>
<td>Medium to High Density</td>
<td>Smooth</td>
<td>Greyish White</td>
<td>None</td>
<td>Seams (~1 mm thick)</td>
<td>Inclined (~70°) and occur in conjugates</td>
<td>Rhomboidal</td>
<td>Phosphatised lithoclasts and well preserved burrows common</td>
</tr>
<tr>
<td>Upper Santonian</td>
<td>Medium to High density</td>
<td>Smooth</td>
<td>White</td>
<td>Dispersed flint horizons</td>
<td>Seams (~1 mm thick)</td>
<td>Sub-vertical and Sub-horizontal</td>
<td>Prismatic</td>
<td></td>
</tr>
<tr>
<td>Lower and Middle</td>
<td>Medium to High Density</td>
<td>Smooth</td>
<td>White</td>
<td>No horizons and only occasional small isolated flints</td>
<td>None</td>
<td>Sub-horizontal or Random</td>
<td>Polyhedral</td>
<td>Chalk appears massive. Occasional iron pyrite or Iron (III) oxide mineralised burrows.</td>
</tr>
<tr>
<td>Middle and Upper</td>
<td>Medium to High Density</td>
<td>Smooth</td>
<td>White</td>
<td>Horizons of nodular flint</td>
<td>None</td>
<td>Sub-vertical and Sub-horizontal</td>
<td>Prismatic</td>
<td></td>
</tr>
<tr>
<td>Lower Coniacian</td>
<td>High</td>
<td>Coarse</td>
<td>White</td>
<td>Horizons of nodular flint</td>
<td>Seams (~1 mm thick)</td>
<td>Sub-vertical and Sub-horizontal</td>
<td>Prismatic</td>
<td></td>
</tr>
<tr>
<td>Upper Turonian</td>
<td>High to Very High</td>
<td>Coarse</td>
<td>Yellowish or Greyish White</td>
<td>Horizons of nodular and tubular flint</td>
<td>Seams (up to 200 mm thick)</td>
<td>Inclined (~70°) or Sub-horizontal</td>
<td>Nodular</td>
<td>Hardgrounds and phosphatised lithoclasts common</td>
</tr>
</tbody>
</table>

Table 3.3 Lithological characteristics of the major Chalk stratigraphical units in the Hallue Catchment.
Seven Sisters Flint band. The Shoreham Marl 2 was taken as the Lower Coniacian - Middle Coniacian boundary where observed in exposures. Archive well logs are tentatively correlated with the FLOOD1 recharge site boreholes based on lithological description (Figure 3.4). This correlation indicates that the Chalk unit referred to as the Dieve ‘Bleues’, which is regarded as the base of the Chalk aquifer in the Somme region (Dupuis et al., 1972b; Crampon et al., 1993), is Middle Turonian in age and equivalent to the New Pit Chalk Formation in the UK. The Upper Turonian to Upper Coniacian Chalk, therefore, forms the main aquifer in the catchment. Above the Seven Sisters flint the sequence becomes progressively homogeneous and flints are almost entirely lost by the Lower and Middle Santonian. Nodular flint horizons and marl seams return in the Upper Santonian and Lower Campanian respectively but because of the low number of exposures and lack of boreholes through this part of the sequence it is difficult to use these as marker horizons.

3.2.3.2 Stratigraphy

Macrofossils, applied in the UK Southern Province Chalk lithostratigraphical framework (Mortimore, 1986; Mortimore et al., 2001; Hopson, 2005), were used to determine the stratigraphical age of the exposures in the Hallue catchment. Prior to commencement of fieldwork it was unclear if these macrofossils could be applied effectively. Table 3.4 and Table 3.5 list the fossil assemblage determined for each of the key exposures. The inocerid bivalve fossil group, followed by the echinoid fossil group, were the most reliable stratigraphical indicators. In particular, bivalves Mytiloides striatoconcentricus, Spondylus spinosus, Volviceramus involutus, Platyceramus, Cladoceramus undulatoplicatus and Inoceramus ‘balticus pteroides’ and the echinoids Micraster turonensis and Conulus albogaleros were identified at a number of exposures and used to determine the age of the chalk exposure (Figure 3.3).

The thickness of the mapped units are estimated from the FLOOD1 recharge site boreholes and key exposures (Figure 3.4) to be approximately 40 m for C3c-4a, 22 m for C4bc and approximately 40 m for C5d-f. It is difficult to estimate the thickness of C5d-f and C6 accurately due to the lack of boreholes and limited exposure of this
Figure 3.3 Photographs of key index fossil from the Hallue Catchment. Fossils are:

A = *Inoceramus balticus pteroides* (HA27 – Lower Campanian),
B = *Conulus albogaleros* (HA51 – Middle Santonian),
C = *Cladoceramus undulatolicatus* (HA31 – Lower Santonian),
D = *Volviceramus involutus* and *Playtceramus* (HA29 – Middle Coniacian),
E = *Micraster turonensis* (HA4 – Middle/Lower Coniacian),
F = *Mytiloides striatoconcentricus* (HA57 – Upper Turonian)
<table>
<thead>
<tr>
<th>ID</th>
<th>Easting</th>
<th>Northing</th>
<th>Approximate Elevation</th>
<th>Macrofossil Assemblage</th>
<th>Stage/Substage</th>
<th>UK Lithostratigraphy</th>
<th>Marker Horizons</th>
</tr>
</thead>
<tbody>
<tr>
<td>HA1</td>
<td>610077</td>
<td>1247696</td>
<td>75</td>
<td><em>Inoceramus ‘balticus pteroides’, Echinocorys</em></td>
<td>Lower Campanian</td>
<td>Newhaven Chalk Formation - Old Nore Beds</td>
<td>-</td>
</tr>
<tr>
<td>HA4</td>
<td>617483</td>
<td>1259703</td>
<td>86</td>
<td><em>Volviceramus involutus, Micraster turonensis</em></td>
<td>Lower Coniacian/ Middle Coniacian</td>
<td>Lewes Nodular Chalk Formation - Shoreham Beds/ Seaford Chalk Formation - Belle Tout Beds</td>
<td>Shoreham Marl 2, Shoreham Tubular Flints</td>
</tr>
<tr>
<td>HA5</td>
<td>608248</td>
<td>1253529</td>
<td>45</td>
<td><em>Spondylus spinosus, Gibbithyris, Micraster deciciens</em></td>
<td>Lower Coniacian</td>
<td>Lewes Nodular Chalk Formation - Cliffe, Beeding and Hope Gap Beds</td>
<td>-</td>
</tr>
<tr>
<td>HA6</td>
<td>614598</td>
<td>1257208</td>
<td>71</td>
<td><em>Volviceramus involutus, Micraster turonensis</em></td>
<td>Middle Coniacian</td>
<td>Seaford Chalk Formation - Belle Tout Beds</td>
<td>-</td>
</tr>
<tr>
<td>HA9</td>
<td>608295</td>
<td>1256969</td>
<td>113</td>
<td><em>Playtceramus</em></td>
<td>Middle Santonian</td>
<td>Seaford Chalk Formation - Haven Brow Beds</td>
<td>-</td>
</tr>
<tr>
<td>HA11</td>
<td>613104</td>
<td>1251523</td>
<td>85</td>
<td><em>Uintacrinus socialis, Echinocorys pre-elevata</em></td>
<td>Upper Santonian</td>
<td>Newhaven Chalk Formation - Splash Point Beds</td>
<td>-</td>
</tr>
<tr>
<td>HA12</td>
<td>613762</td>
<td>1250969</td>
<td>50</td>
<td><em>Platyceramus - Sphenoceramus, Echinocorys Planodorma</em></td>
<td>Middle Santonian</td>
<td>Seaford Chalk Formation - Haven Brow Beds</td>
<td>-</td>
</tr>
<tr>
<td>HA13</td>
<td>609738</td>
<td>1258370</td>
<td>84</td>
<td><em>Cladoceramus undulatopiculatus, Orbirhynchia pisiformis, Bourgueticrinus</em></td>
<td>Lower Santonian</td>
<td>Seaford Chalk Formation - Haven Brow Beds</td>
<td>-</td>
</tr>
<tr>
<td>HA17</td>
<td>614760</td>
<td>1256306</td>
<td>82</td>
<td><em>Cladoceramus undulatopiculatus, Conulus albugalerus</em></td>
<td>Lower Santonian</td>
<td>Seaford Chalk Formation - Haven Brow Beds</td>
<td>-</td>
</tr>
<tr>
<td>HA19</td>
<td>607782</td>
<td>1250229</td>
<td>44</td>
<td><em>Cladoceramus undulatopiculatus, Micraster coranguinum, Micraster gibbus, Orbirhynchia pisiformis, Gibbithyris ellipsoidalis</em></td>
<td>Lower Santonian</td>
<td>Seaford Chalk Formation - Haven Brow Beds</td>
<td>-</td>
</tr>
<tr>
<td>HA20</td>
<td>619245</td>
<td>1266092</td>
<td>137</td>
<td><em>Volviceramus involutus, Platyceramus</em></td>
<td>Middle Coniacian</td>
<td>Seaford Chalk Formation - Belle Tout and Cuckmere Beds</td>
<td>-</td>
</tr>
<tr>
<td>HA21</td>
<td>620945</td>
<td>1265944</td>
<td>150</td>
<td><em>Cordiceramus cordiformis. Micraster</em></td>
<td>Middle Santonian</td>
<td>Seaford Chalk Formation - Haven Brow Beds</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3.4 Summary of stratigraphical data from key exposures in the Hallue Catchment. Coordinates are in France I (Lambert Zone I).
<table>
<thead>
<tr>
<th>ID</th>
<th>Easting</th>
<th>Northing</th>
<th>Approximate Elevation</th>
<th>Macrofossil Assemblage</th>
<th>Stage/Substage</th>
<th>UK Lithostratigraphy</th>
<th>Marker Horizons</th>
</tr>
</thead>
<tbody>
<tr>
<td>HA23</td>
<td>615967</td>
<td>1263080</td>
<td>129</td>
<td><em>Cladoceramus undulatoplicatus, Micraster coranginiun and Gibbithyris ellipsoidalis.</em></td>
<td>Lower Santonian</td>
<td>Seaford Chalk Formation - Haven Brow Beds</td>
<td></td>
</tr>
<tr>
<td>HA25</td>
<td>608480</td>
<td>1262326</td>
<td>100</td>
<td><em>Volviceramus involutus, Platyceramus</em></td>
<td>Middle Coniacian</td>
<td>Seaford Chalk Formation - Belle Tout and Cuckmere Beds</td>
<td>Seven Sisters flint band</td>
</tr>
<tr>
<td>HA27</td>
<td>605685</td>
<td>1260306</td>
<td>108</td>
<td><em>Inoceramus ‘balticus pteroides’, Micraster rogalae</em></td>
<td>Lower Campanian</td>
<td>Newhaven Chalk Formation - Old Nore Beds</td>
<td></td>
</tr>
<tr>
<td>HA29</td>
<td>613191</td>
<td>1260231</td>
<td>104</td>
<td><em>Volviceramus involutus</em></td>
<td>Middle Coniacian</td>
<td>Seaford Chalk formation - Belle Tout Beds</td>
<td></td>
</tr>
<tr>
<td>HA30</td>
<td>617088</td>
<td>1260617</td>
<td>98</td>
<td><em>Cremnoceramus, Volvicerceramus involutus</em></td>
<td>Lower Coniacian/ Middle Coniacian</td>
<td>Lewes Nodular Chalk Formation - Shoreham Beds/ Seaford Chalk Formation - Belle Tout Beds</td>
<td>Shoreham Marl 2, Shoreham Tubular Flints</td>
</tr>
<tr>
<td>HA31</td>
<td>607643</td>
<td>1259755</td>
<td>102</td>
<td><em>Cladoceramus undulatoplicatus, Micraster</em></td>
<td>Lower Santonian</td>
<td>Seaford Chalk Formation - Haven Brow Beds</td>
<td></td>
</tr>
<tr>
<td>HA51</td>
<td>609618</td>
<td>1252772</td>
<td>100</td>
<td><em>Conulus albogaleros</em></td>
<td>Middle Santian</td>
<td>Seaford Chalk formation - Haven Brow Beds</td>
<td></td>
</tr>
<tr>
<td>HA52</td>
<td>608157</td>
<td>1251814</td>
<td>50</td>
<td><em>Cladoceramus undulatoplicatus</em></td>
<td>Lower Santian</td>
<td>Seaford Chalk Formation - Haven Brow Beds</td>
<td></td>
</tr>
<tr>
<td>HA57</td>
<td>623375</td>
<td>1264447</td>
<td>105</td>
<td><em>Mytiloides striatoconcentricus, Cremnoceramus deformis erectus, Spondylus spinosus, Micraster pre-leskei, Micraster leskei</em></td>
<td>Upper Turonian/ Lower Coniacian</td>
<td>Lewes Nodular Chalk Formation - Kingston, South Street, Navigation and Cliffe Beds</td>
<td>Lewes Marls, Lewes Tubular Flints</td>
</tr>
<tr>
<td>HA60</td>
<td>619965</td>
<td>1261328</td>
<td>115</td>
<td><em>Volviceramus involutus, Platyceramus</em></td>
<td>Middle Coniacian</td>
<td>Seaford Chalk Formation - Belle Tout and Cuckmere Beds</td>
<td></td>
</tr>
<tr>
<td>HA61</td>
<td>625195</td>
<td>1265305</td>
<td>105</td>
<td><em>Micraster, Cremnoceramid?</em></td>
<td>Lower Coniacian</td>
<td>Lewes Nodular Chalk Formation – Beds?</td>
<td></td>
</tr>
<tr>
<td>HA62</td>
<td>594381</td>
<td>1275691</td>
<td>75</td>
<td><em>Ptychodus, Inoceramus cuvieri, Collignoniceras woollgari</em></td>
<td>Middle Turonian/ Upper Turonian</td>
<td>New Pit Chalk Formation/ Lewes Nodular Chalk Formation - Glynde Beds</td>
<td>Glynde Marls, Southerham Marls</td>
</tr>
</tbody>
</table>

Table 3.5 Summary of stratigraphical data from key exposures in the Hallue Catchment continued. Coordinates are in France I (Lambert Zone I).
<table>
<thead>
<tr>
<th>ID</th>
<th>Easting</th>
<th>Northing</th>
<th>Elevation</th>
<th>Depth</th>
<th>Macrofossil Assemblage</th>
<th>Stage/Substage</th>
<th>UK Lithostratigraphy</th>
<th>Marker Horizons</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>615242</td>
<td>1258132</td>
<td>82.94</td>
<td>50.7</td>
<td>See P2 and P3</td>
<td>See P2 and P3</td>
<td>See P2 and P3</td>
<td>See P2 and P3</td>
</tr>
<tr>
<td>P2</td>
<td>615242</td>
<td>1258190</td>
<td>84.90</td>
<td>43.5</td>
<td>N/A</td>
<td>Middle Coniacian</td>
<td>Seaford Chalk Formation</td>
<td>Seven Sisters Flint?</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N/A</td>
<td>Upper Turonian - Lower Coniacian</td>
<td>Lewes Nodular Chalk Formation</td>
<td>Shoreham Marl 2 and the Shoreham tubular flints, Lewes Marl and Lewes Tubular Flints, Bridgewick Marl</td>
</tr>
<tr>
<td>P3</td>
<td>615234</td>
<td>1258131</td>
<td>82.42</td>
<td>47.9</td>
<td><em>Volviceramus involutus, Platyceramus</em></td>
<td>Middle Coniacian</td>
<td>Seaford Chalk Formation</td>
<td>Seven Sisters Flint?</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Upper Turonian - Lower Coniacian</td>
<td>Lewes Nodular Chalk Formation</td>
<td>Shoreham Marl 2 and the Shoreham tubular flints, Lewes Marl and Lewes Tubular Flints, Bridgewick Marl</td>
</tr>
<tr>
<td>P4</td>
<td>615230</td>
<td>1258131</td>
<td>82.14</td>
<td>40.1</td>
<td>See P2 and P3</td>
<td>See P2 and P3</td>
<td>See P2 and P3</td>
<td>See P2 and P3</td>
</tr>
<tr>
<td>P4bis</td>
<td>615230</td>
<td>1258135</td>
<td>81.69</td>
<td>30</td>
<td>See P2 and P3</td>
<td>See P2 and P3</td>
<td>See P2 and P3</td>
<td>See P2 and P3</td>
</tr>
<tr>
<td>P6</td>
<td>615234</td>
<td>1258091</td>
<td>~82</td>
<td>66</td>
<td><em>Volviceramus involutus, Platyceramus</em></td>
<td>Middle Coniacian</td>
<td>Seaford Chalk Formation</td>
<td>Seven Sisters Flint?</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Middle Turonian - Lower Coniacian</td>
<td>Lewes Nodular Chalk Formation</td>
<td>Shoreham Marl 2 and the Shoreham tubular flints, Lewes Marl and Lewes Tubular Flints, Bridgewick marl, Southerham/ Caburn marl</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Middle Turonian</td>
<td>New Pit Chalk Formation</td>
<td>Glynde Marls</td>
</tr>
</tbody>
</table>

Table 3.6 Summary of stratigraphical data from the FLOOD1 recharge site boreholes in the Hallue Catchment. Coordinates and elevation are in (Lambert Zone I). Core from P3 and P6 was lithostraigraphically logged and the P2 and P6 boreholes were also geophysically logged.
part of the sequence. North – south and west – east orientated geological cross sections through key exposures and boreholes (Figure 3.5) in the catchment are presented in Figure 3.6 and Figure 3.7. These sections are drawn based on the assumption that the thickness of the Chalk units remains approximately constant within the catchment.

The mapped stratigraphical range of the Chalk, Palaeogene and Neogene deposits in the Hallue catchment are shown in Table 3.1 and Table 3.2. These tables highlight the significant variation between the current Amiens, Albert, Doullens and Baupame BRGM geological maps. The exposures listed in Table 3.4 to Table 3.5, and boreholes listed in Table 3.6, confirm the stratigraphical range of the Chalk at outcrop in the Hallue Catchment as being Upper Turonian to Lower Campanian. Borehole P6, the deepest of the FLOOD1 recharge site boreholes, also retrieved Middle Turonian Chalk at subcrop.

The Chalk stratigraphical units depicted in Figure 3.5 are derived from the Amiens and Albert maps. These units are Upper Turonian to Lower Coniacian (C3c-4a), Middle Coniacian to Upper Coniacian (C4bc), Santonian (C5d-f) to Lower Campanian (C6). They were chosen because they reflected the broad lithological changes in the Chalk, they can be delimited by macrofossils or marker horizons and they provide the information necessary for determining the structure of the Chalk in a geological map of the catchment.

In contrast to the current BRGM geological maps, Lower Santonian Chalk was identified in the area covered by the Baupame sheet north of the village of Forceville (Figure 3.5 and Figure 3.6). The Amiens sheet identifies only Lower and Middle Santonian Chalk in the Hallue Catchment but Upper Santonian to Lower Campanian Chalk was identified in a small number of exposures. Lower Santonian chalk was also identified near the village of Fréchencourt at a lower elevation than currently shown on the Amiens sheet.

The Lower Campanian Chalk was found west of the village of Toutencourt (Figure 3.7 – HA27) on the Doullens sheet and south of the village of Lahoussoye (HA1) on the Amiens sheet.
Figure 3.4 Correlation of key exposures, the FLOOD1 recharge site boreholes and archive well logs in the Hallue Catchment. Solid lines indicate direct correlation and broken lines indicate inferred correlation. Logs are positioned relative to the Lower Conianian-Middle Conianian Boundary (Shoreham Marl 2). The map units depicted in Figure 3.5 are indicated by the coloured intervals in the thickness column and the colour of the exposure and borehole logs.
Lower Campanian Chalk is mapped on the Doullens sheet but only as isolated reworked phosphatic chalk deposits (Delattre and Mériaux, 1974). The presence of macrofossils in a good state of preservation and lithological evidence for the preservation of bedding indicate that the Lower Campanian Chalk is not redeposited but in-situ at the exposures studied. Additionally, during fieldwork, the redeposited Lower Campanian phosphatic chalks exposed in quarries at Beauval were visited. The matrix texture of the Beauval chalks appeared coarse compared to the Lower Campanian chalks observed in the exposures in the Hallue Catchment. These observations in the Hallue Catchment are limited, however, to a small number of exposures (HA1, HA27) and, as such, there is insufficient density of data to map the outcrop area of this unit. Good preservation of macrofossils is also not a definitive indicator of in-situ chalk and may occur in reworked deposits. It is difficult, therefore, to dispute the interpretation of Delattre and Mériaux (1974) without additional exposures and, as result, the Lower Campanian Chalk in Figure 3.7 is depicted as lying unconformably on the Santonian Chalk.

3.2.3.3 Catchment Geomorphology

In the UK Southern Province Chalk lithostratigraphical framework, geomorphology is used to aid differentiation of the Chalk Formations (Bristow et al., 1997). A similar approach might be feasible in the Hallue Catchment and this is illustrated in Figure 3.8, which shows slope gradients for the Hallue catchment with the geological boundaries overlain.

The Upper Turonian - Lower Coniacian Chalk (C3c-4a) in the Hallue catchment tends to form slopes with lower gradients of around 0-3°. The boundary between the Upper Turonian - Lower Coniacian Chalk (C3c-4a) and Middle - Upper Coniacian Chalk (C4bc) shows no significant geomorphological expression although slope gradients of Middle - Upper Coniacian Chalk increase slightly to around 0-5°. The geomorphological expression of this boundary maybe complicated, however, by its occurrence in the base of the river valley.
Figure 3.5 Bedrock geological map of the Hallue Catchment. The boundaries illustrated are based on the Amiens and Albert BRGM geological maps and the new data from the field investigations. Sections 1-4 are illustrated in Figure 3.6 and Figure 3.7. (Mapping © IGN 2011)

The boundary between the Middle - Upper Coniacian and Santonian Chalk (C5d-f) commonly occurs around a negative break of slope with the initial Santonian slope
gradients increasing to 3-14° (Figure 3.8). This change in gradient may be the result of a change in lithological properties in the Lower – Middle Santonian Chalk - equivalent to the Haven Brow Beds of the Seaford Chalk Formation. As described earlier, the Lower – Middle Santonian Chalk is relatively homogeneous and massive - lacking regular flint horizons and marl seams. It may, therefore, be more resistive to mechanical weathering than the more heterogeneous Chalk units in the catchment. At the Middle Santonian – Upper Santonian boundary there is a return of flint horizons and marl seams in the chalk and the gradient of slope decreases to 0-3° - creating a positive break of slope. This change in lithological properties may again be responsible for the change in geomorphological characteristics.

The geomorphological expression of the boundary between the Santonian and Lower Campanian Chalk (C6) is difficult to determine due to the limited outcrop of Lower Campanian Chalk and the thick superficial deposits (Limon de Plateau) present at higher elevations in the catchment. Additionally, the dip of the strata is very gentle at around 1° which limits formation of escarpments.

3.2.3.4 Structural Geology

The geological structure of the Hallue catchment is indicated by the revised geological map in Figure 3.5, and the north - south and west – east geological sections in Figure 3.6 and Figure 3.7. These figures indicate that the regional dip of the Chalk is approximately 1° towards the southeast although this varies locally around geological structures. Due to this gentle dip, The Hallue Catchment is dominated at outcrop by Middle - Upper Coniacian (~70 km²) and Santonian Chalk (~170 km²), which are equivalent to the Seaford and Newhaven Chalk Formations in the UK. Upper Turonian – Lower Coniacian Chalk only comprises around ~1 km² at outcrop and was observed in the Hallue river valley at exposures HA5, HA50 and HA30 (Figure 3.5) near the villages of Villaincourt, Bavelincourt and Hédauville (Figure 3.1).

The geological structures present in the Hallue Catchment are the Hallue Valley fold/fault, the Ponthieu Anticline and the Forceville Syncline. The regional geological structures are described in more detail in Chapter 4. Possibly the most prominent
Figure 3.6 North–south orientated geological sections through key exposures and the FLOOD1 recharge site boreholes. Line of sections are illustrated on Figure 3.5. Key features to note are the Hallue Valley fold/fault which exposes Upper Turonian-Lower Coniacian chalk to outcrop around the village of Bavelincourt and Fréchencourt (Section 1) and the syncline which preserves Santonian chalk to the north of the village of Forceville (Section 2). Note also the slope gradients on the different Chalk units.
Figure 3.7 West–east orientated geological sections through key exposures and the FLOOD1 recharge site boreholes. Line of sections are illustrated Figure 3.5. Key features to note are the Ponthieu Anticline and the Lower Campanian Chalk observed at HA27 west of the village of Vadencourt (Section 3) which is illustrated here as a localised re-deposited chalk lying unconformably on Santonian Chalk. Note also the slope gradients on the different Chalk units.
geological structure seen in the catchment is the Hallue Valley fold/fault which is intersected by the River Hallue in the centre if the catchment between the villages of Bavelincourt and Fréchencourt (Figure 3.1, Figure 3.6 - Section 1). This structure is shown as being north east – south west trending by D'Arcy and Roux (1971) and may be responsible for bringing the Upper Turonian - Lower Coniacian Chalk to outcrop - as confirmed by exposures HA5 and HA50. Furthermore, the occurrence of Lower Santonian Chalk at exposure HA52 near the village of Fréchencourt (Figure 3.1, Figure 3.5 and Figure 3.6 - Section 1) indicates that the south eastern limb of this structure dips more steeply than previously understood. The Amiens sheet guide (Dupuis et al., 1972a) indicates this structure is responsible for thinning of the chalk sequence in the Coniacian and thickening in the Lower Santonian.

To the north of the catchment, there is a shallow syncline, referred to here as the Forceville Syncline, which leads to Santonian Chalk being present at outcrop north of the village of Forceville (Figure 3.1, Figure 3.6 - Section 2). Santonian Chalk is not recognised on the Baupaume map in this part of the catchment but was found at exposure HA23. Upper Santonian and Lower Campanian Chalk may also be present in similar shallow synclines in the central eastern and western edges of the catchment.

To the east of the catchment, the Ponthieu Anticline occurs. This structure is north west – south east trending and D'Arcy and Roux (1971) indicated its axis is continuous over tens of kilometres. This structure, however, appears to be disrupted in the vicinity of the Hallue Valley fold/fault.

To the north west of the catchment, south of the village of Puchevillers and west from the village of Toutencourt, Lower Campanian chalk is exposed in the base of the valley, Vallée d'Hérissart, at exposure HA27 (Figure 3.1 and Figure 3.5). The occurrence of Lower Campanian chalk at this elevation is contrary to what is expected from the regional dip. The main periods of formation of phosphatised chalk deposits in the Hallue Catchment were during the Middle Santonian to Lower Campanian (Mennessier et al., 1976b). Lower Campanian chalks in this area are interpreted as re-deposited chalks which lie unconformably on older chalk (Figure 3.7 - Section 3). The presence of bedding, however, indicates this Lower
Campanian Chalk (HA27) may be in-situ. If this is the case, a significant syncline or fault must exist in this area.

Figure 3.8 Slope gradients for the Hallue catchment with geological boundaries overlaid. Slope gradients for C3c-4a commonly range from 0 to 3°; slope gradients for C4bc range commonly range from 0 to 5°; slope gradients for C5d-f commonly range from 0 to 14°. Ranges depicted were determined visually to best represent the contrasts of the slopes. (Mapping © IGN 2011)
3.3 Patcham Catchment

3.3.1 Background

The first geological map of the Brighton and Worthing area, covering the Patcham Catchment, was published in 1864 at the scale of one inch to one mile (1:63,360) (Geological Survey of Great Britain, 1864). Parts of the district were re-surveyed in the period 1873 to 1890 on the six-inch scale (1:10,560), and the New Series sheets of the component areas were published in 1924 (Geological Survey of Great Britain, 1924) as well as the memoir by White (1924). The district was subsequently surveyed in full at the six-inch scale by R. A. Ellison, R. D. Lake, T. E. Lawson, D. Millward and B. Young in the period 1973-1979 and published at 1:50,000 in 1984 (British Geological Survey, 1984). The associated memoir was compiled by Young and Lake (1988). The Brighton and Worthing sheet (318/333) was then revised in a digital edition in 1999-2000 for the Environment Agency and Southern Water (British Geological Survey, 2006a). This digital map, which applied the new chalk lithostratigraphy (Mortimore, 1983a, 1986; Bristow et al., 1997; Rawson et al., 2001), was produced using a combination of remote sensing techniques, the macrofossil biozonal map of Gaster (1951), field notes of Mortimore (Mortimore, 2007) and a reconnaissance survey undertaken by the BGS over four weeks by four geologists (Aldiss, 2007; Hopson, 2009).

The 1984 Brighton and Worthing sheet (318/333) (British Geological Survey, 1984) presented the Chalk outcrop as Lower Chalk, and Middle and Upper Chalk undivided. The combining of the Middle and Upper Chalk had the effect of concealing much of the internal geological structure present. This was resolved in the current Brighton and Worthing sheet - although much of the current linework is adapted from the biozonal map of Gaster (1951). Table 3.7 lists the macrofossil biozones mapped by Gaster (1951) against the current Southern Province Chalk Lithostratigraphy.
Table 3.7 Traditional macrofossil biozones mapped by Gaster (1951) and equivalent lithostratigraphical units shown on current BGS geological maps. Where macrofossils have been renamed subsequently the newer name is indicated in brackets.

Gaster delineated the biozone boundaries by constructing structure contours between exposures with equivalent biostratigraphy. The intersection of these structural surfaces with the topography form the biozone boundaries. This approach enables boundaries to be inferred in areas of scarce data but does not take into account variation in unit thickness or dip. This approach also tends to mask or simplify geological structures. Variation in thickness is believed to occur in the Chalk due to variation in the pattern of sedimentation and the mass movement of sediments from syn-sedimentary tectonic activity. (Mortimore and Pomerol, 1991a; Mortimore and Pomerol, 1997; Mortimore, 2004, 2011).

The Brighton and Worthing 1:50,000 sheet (318/333) (British Geological Survey, 2006a), and the Patcham Catchment had, therefore, not been fully surveyed using the Chalk mapping techniques developed by Bristow et al. (1997) and the British Geological Survey. Furthermore, due to the reliance on the linework of Gaster (1951), the geological structure present in the Patcham Catchment may be oversimplified. A program of fieldwork was designed to validate the current geological map within the Patcham Catchment.
### 3.3.2 Methodology

The Southern Province Chalk lithostratigraphical framework, as developed by Mortimore (1983a, 1986), Mortimore *et al.* (2001) and ratified by Rawson *et al.* (2001), was utilised for the field investigations undertaken in the Patcham Catchment. The mapping method applied in the Patcham Catchment was based on Bristow *et al.* (1997). This method uses a combination of lithological observations from field brash, exposures and landform observations to delineate the Chalk Formations (Table 3.8 and Figure 3.9).

<table>
<thead>
<tr>
<th>Formation Boundary</th>
<th>Distinguishing features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seaford/Newhaven</td>
<td>Only a small area of the Patcham Catchment contained the Newhaven Chalk Formation at outcrop. This was poorly defined by landforms and difficult to distinguish from Seaford by brash alone. As a result, this boundary was not mapped in the field but checked using secondary data.</td>
</tr>
<tr>
<td>Lewes Nodular/Seafor d</td>
<td>Distinguished in the Patcham Catchment by a transition from nodular chalk to very dense re-cemented chalk to less dense chalk. Chalk at this boundary was often found to contain dissolution tubules. Subtle negative or positive breaks of slope were often found accompanying this transition and taken as the boundary where brash was not present. Other indicators of the transition onto Seaford Chalk Formation included the presence of thick shelled inoceramid bivalve shell debris (<em>Platyceramus</em> and <em>Volviceramus involutus</em>) in brash and the occurrence of very large nodular and semi-tabular flint fragments.</td>
</tr>
<tr>
<td>New Pit/Lewes Nodular</td>
<td>Onset of hard dense nodular chalk. A positive break of slope often occurs at this boundary as the gradient of slope decrease moving onto the Lewes Nodular Chalk Formation forming a convex slope.</td>
</tr>
<tr>
<td>Holywell/New Pit</td>
<td>Disappearance of Mytiloides inoceramid shell debris and the return of soft less dense chalk. A negative break of slope often occurs at this boundary as the gradient of the slope increases in the New Pit Chalk Formation.</td>
</tr>
<tr>
<td>Zig Zag/Holywell Nodular</td>
<td>A positive feature formed by the Melbourn rock and the onset of hard dense chalk brash. Upper Holywell Nodular Chalk Formation has abundant mytiloid inoceramid shell debris.</td>
</tr>
</tbody>
</table>

Table 3.8 Features used to delineate the Chalk Formation boundaries in the Patcham Catchment

Additional qualitative and semi-quantitative data such as colour, texture, density and chalk grade based on Lord *et al.* (2002), fracturing characteristics (frequency, aperture, dip and dip direction), and the presence or absence of flints, fossils and marls were recorded at localities along a series of transects. The information collected at these localities is detailed in Table 3.9.

These transects were typically undertaken on tracks parallel or perpendicular to the main valleys within the Patcham Catchment. Along these transects descriptions of the chalk brash were taken at roughly regular intervals of 50 – 100 m, and samples of unusual lithologies or macrofossils were collected. The location of the transects
are illustrated in Figure 3.2, and information collected at key localities is detailed in Table 3.10 to Table 3.13.

![Figure 3.9 Examples of field brash from the Patcham Catchment for the Lewes Nodular (A) and Holywell Nodular Chalk Formations (B)](image)

To supplement the field mapping, core was retrieved from the North Heath Barn 2 borehole at the FLOOD1 recharge site for lithostratigraphical logging and laboratory testing. Reference should be made to Molyneux (2012) for further information on the laboratory testing methods and results. Borehole geophysical surveys were undertaken in key Environment Agency monitoring boreholes within and close to the Patcham Catchment. Borehole core from the Southern Water Pyecombe East and Pyecombe West boreholes was also lithostratigraphically logged at the University of Brighton by the FLOOD1 team.

The borehole geophysical surveys undertaken in Environment Agency monitoring boreholes consisted of calliper, natural gamma, formation resistivity, induced conductivity, fluid conductivity, CCTV and optical televiewer. The surveys of particular use for determination of the Chalk lithostratigraphy were natural gamma, formation resistivity, induced conductivity and optical televiewer. The logs from these surveys could be correlated with published geophysical logs (Mortimore, 1986; Mortimore and Pomerol, 1987; Jones and Robins, 1999) and the core from North Heath Barn 2 borehole. The borehole geophysical surveys were conducted in collaboration with the British Geological Survey and Southern Water.
<table>
<thead>
<tr>
<th>Descriptors</th>
<th>Breaks of slope (positive, negative), shape of slope (convex, concave)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geomorphology</td>
<td></td>
</tr>
<tr>
<td>Chalk</td>
<td>Weathered colour, fresh colour, density (CIRIA), texture (coarse, smooth), structure (tabular, nodular, prismatic, polyhedral, rhombohedral), fragment size, fragment form (brash, section), fossil content, inferred formation/member/bed, sample reference, photo reference, additional notes</td>
</tr>
<tr>
<td>Flint</td>
<td>Type (nodular, finger, tubular, tabular, carious), cortex colour, core colour, cortex thickness, core diameter, length, width, condition (fragment, in-situ, not in situ), fossils present, sample reference, photo reference, additional notes</td>
</tr>
<tr>
<td>Marl</td>
<td>Marl type (seam, wispy, griotte marl zone), weathered colour, fresh colour, thickness, fossils present, sample reference, photo reference, additional notes</td>
</tr>
<tr>
<td>Fracture</td>
<td>Aperture (mm), spacing (mm), persistence (mm), dip (°), dip direction (°), chalk grade based on Lord et al. (2002), mineralisation, sample reference, photo reference, additional notes</td>
</tr>
</tbody>
</table>

Table 3.9 Qualitative and semi-quantitative data recorded at mapping locations.

### 3.3.3 Results

In total, the 21 Km² area north of the A27 was traversed during the field investigations and data were collected from 598 localities. Complementary to the field mapping data, borehole data were also acquired from cored boreholes and downhole geophysical logging of Environment Agency observation boreholes.

The stratigraphical range of the Chalk present at outcrop in the Patcham Catchment is Cenomanian to Lower Campanian with Chalk Formations ranging from West Melbury Marly Chalk to the Newhaven Chalk. The catchment also has Quaternary deposits of Clay-with-flints, Head and Brickearth.

Detailed lithostratigraphical logs were produced for the cored boreholes North Heath Barn 2, Pyecombe East and Pyecombe West by the University of Brighton FLOOD1 team (Appendix II). The geophysical formation logs, natural gamma, resistivity and induced conductivity, with the optical televiewer log, were used to identify lithostratigraphical marker horizons by comparison with published geophysical formation logs for chalk boreholes and the North Heath Barn 2 borehole core.

A summary of the data collected from key localities and the FLOOD1 recharge site borehole is presented in the following section (Table 3.10 to Table 3.15). Reference should be made to Appendices I, II and III for complete field notes, photographs and logs.
<table>
<thead>
<tr>
<th>ID</th>
<th>Easting</th>
<th>Northing</th>
<th>Approximate Elevation</th>
<th>Macrofossil Assemblage</th>
<th>Stage/Substage</th>
<th>UK Lithostratigraphy</th>
<th>Marker Horizons</th>
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<td>PA019</td>
<td>528568</td>
<td>111997</td>
<td>144</td>
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<td>PA058</td>
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<tr>
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<td></td>
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<td></td>
<td></td>
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<td>Inoceramus cuvieri?</td>
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</tr>
<tr>
<td></td>
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<td>2. Mytiloides</td>
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<td>New Pit Chalk Formation</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3.10 Summary of stratigraphical data from key localities in the Patcham Catchment. Coordinates are in British National Grid.
<table>
<thead>
<tr>
<th>ID</th>
<th>Easting</th>
<th>Northing</th>
<th>Approximate Elevation</th>
<th>Macropalaeontological Assemblage</th>
<th>Stage/Substage</th>
<th>UK Lithostratigraphy</th>
<th>Marker Horizons</th>
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<tr>
<td>PA087</td>
<td>528904</td>
<td>111652</td>
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<td>PA089</td>
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<td>106</td>
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<td>Lewes Nodular Chalk Formation</td>
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<td>111917</td>
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<td>PA106</td>
<td>528727</td>
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<td>PA115</td>
<td>529507</td>
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<td><em>Orbirhynchia dispersa, Inoceramus cuvieri</em></td>
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<td>PA116</td>
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<td>PA121</td>
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<td>Upper Turonian</td>
<td>Lewes Nodular Chalk Formation</td>
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<tr>
<td>PA122</td>
<td>529760</td>
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<td>529819</td>
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<td>PA135</td>
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<td><em>Inoceramus aff. glatiae?</em></td>
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<td>-</td>
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Table 3.11 Summary of stratigraphical data from key localities in the Patcham Catchment. Coordinates are in British National Grid.
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<th>Marker Horizons</th>
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Table 3.12 Summary of stratigraphical data from key localities in the Patcham Catchment. Coordinates are in British National Grid.
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<td>New Pit/Lewes Nodular Chalk Forma...</td>
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</table>

Table 3.13 Summary of stratigraphical data from key localities in the Patcham Catchment. Coordinates are in British National Grid.
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<th>ID</th>
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<th>Depth</th>
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<td>Lewes Nodular Chalk Formation</td>
<td>Lewes, Bridgewick, Caburn, Southerham Marls</td>
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<td></td>
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<td><em>stuemki?, Inoceramus lamarcki</em></td>
<td>Turonian</td>
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<td>-</td>
<td>Middle Turonian</td>
<td>New Pit Chalk Formation</td>
<td>Glynde, New Pit 1 &amp; 2, Iford 1 &amp; 2, Malling Street Marls</td>
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<td></td>
<td>-</td>
<td>Lower Turonian</td>
<td>Holywell Nodular Chalk Formation</td>
<td>Gun Gardens Main Marl</td>
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<td>New Pit Chalk Formations</td>
<td>Malling Street Marls</td>
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<td><em>Mytiloides, Orbitichnchia cuvieri</em></td>
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<td>Holywell Nodular Chalk Formation</td>
<td>Gun Gardens Main Marl, Meads Marls, Melburn Rock, Plenus Marls</td>
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<td>Lower - Middle</td>
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<td>Lower - Middle</td>
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Table 3.14 Summary of stratigraphical data from cored boreholes in the Patcham Catchment. Coordinates are in British National Grid. Pyecombe East and Pyecombe West were lithostratigraphically logged by R.N. Mortimore.
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<td>New Pit Chalk Fm</td>
<td>New Pit 1 &amp; 2, Iford 1 &amp; 2, Malling Street Marls</td>
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<td>Holywell Nodular Chalk Fm</td>
<td>Gun Gardens Main Marl and Plenus Marls</td>
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<td>Middle Turonian</td>
<td>New Pit Chalk Fm</td>
<td>Glynde, New Pit 1 &amp; 2, Iford 1 &amp; 2, Malling Street Marls</td>
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</table>

Table 3.15 Summary of stratigraphical data from geophysically surveyed EA observation boreholes in the Patcham Catchment. Coordinates are in British National Grid.
3.3.3.1 Lithology

The Chalk lithologies observed during the field investigation within the Patcham Catchment generally conform to the lithological characteristics of the Chalk Formations outlined by Mortimore (1986) and Bristow et al. (1997). Exceptions to this were observed on Scare Hill interfluve near the village of Pyecombe and between Pagdean and Lower Standean Farm. Very dense crystalline or saccharoidal textured chalk brash was observed. Commonly the brash is slickensided and contains dissolution tubules and shattered flints (Figure 3.10 - Photographs A-C). Dissolution tubules are a type of karst, first described by Lamont-Black and Mortimore (2000), which occurs in the chalk. The presence of brash with slickensides and shattered flint indicates this is an area of deformation and potentially groundwater dissolution. The area is located between the Pyecombe Anticline and Coldean Lane Fault (Figure 3.11 – fieldwork locations PA158, PA159 and PA487) and is discussed further in Chapter 4. These lithologies may result, therefore, from an area of flexure or deformation in the zone between these two en echelon structures. The dissolution tubules at Old Boat Corner, described by Lamont-Black and Mortimore (2000), also occur in this area between the Coldean Lane Fault and the Pyecombe Anticline.

The second area of unusual lithologies was seen at the Lewes Nodular and Seaford Chalk Formation boundary on the Scare Hill interfluve east of Pyecombe village - near Pyecombe Golf Course. At this location, there is an abundance of a calcarenite brash. This brash is composed of fragments of crinoid and inoceramid bivalve within a chalk matrix (Figure 3.10 – Photograph D). The abundance of crinoid fossil material in this calcarenite is unusual and would suggest this is a chalk sedimentary deposit rather than an accumulation of fossiliferous material weathered from the Chalk. This locality is situated on the eastern limb of the Pyecombe Anticline.
Figure 3.10 Photographs of lithological samples collected in the Patcham catchment. Photograph A is a very dense chalk sample with slickensides and shattered flint (bottom centre of sample). Photograph B is a second sample of very dense chalk with slickensides. Photograph C is a very dense chalk sample containing dissolution tubules. Photograph D is a chalk calcarenite sample. The sample in photographs A-C were collected on Scare Hill interfluve between Pagdean and Lower Standean Farm. The sample in photograph D was collected on Scare Hill interfluve east of Pyecombe village at the Lewes Nodular - Seaford Chalk Formation boundary. Grid cells in the photographs are 30 x 30 mm.
3.3.3.2 Stratigraphy

The main stratigraphical data for the Patcham Catchment are derived from a number of key localities and borehole logs. The key localities provided stratigraphical information for the Chalk at outcrop and the boreholes logs provided detailed stratigraphical information and for the Chalk at subcrop. Table 3.10 to Table 3.13 list the stratigraphical data from key localities and Figure 3.12 illustrates a correlation of marker horizons between the boreholes in the Patcham Catchment.

The new stratigraphical data from the fieldwork in the Patcham Catchment was used to validate the current linework on the Brighton and Worthing 1:50,000 sheet (318/333) (British Geological Survey, 2006a). The suggested adjustments to the linework on the published map are shown in Figure 3.11. Most of these adjustments are small and around 50 - 100 metres from the current boundary. The most significant adjustments are seen on the Scare Hill interfluve, between Pagdean and Lower Standean Farms, and on the western flank of the West Hill interfluve above Haresdean Farm. On the Scare Hill interfluve, between Pagdean and Lower Standean Farms, the Lewes Nodular and Seaford Chalk Formation boundary has been moved to a higher elevation. On the western flank of West Hill interfluve above Haresdean Farm, the Lewes Nodular and New Pit Chalk Formation boundary has been lowered.

Macrofossil samples collected in the Patcham Catchment provided a secondary stratigraphical control on the landform and lithological observations. In particular, the macrofossil group found to be the most consistent stratigraphical indicators were the inoceramid bivalves (Table 3.10 to Table 3.13). The bivalves *Mytiloides mytiloides, Inoceramus cuveri, Inoceramus larmarki, Volviceramus involutus, Platyceramus* were particularly reliable. Other bivalves, echinoids (commonly *Micraster* and *Echinocorys*), crinoids and sponges were also collected and used as stratigraphical indicators.
Figure 3.11 Bedrock geological map of the Patcham Catchment. The boundaries are based on the current Brighton and Worthing geological map (318/333) (British Geological Survey, 2006a) updated with data from the field investigation. Sections 1-4 are illustrated in Figure 3.13 and Figure 3.14. Areas of boundary modification are indicated by dashed circles.
3.3.3.3 Catchment Geomorphology

The Patcham Catchment is situated on the dip slope of the South Downs and comprises three main dry valleys, which converge in Patcham, and four interfluves. The main dry valleys from east to west are the Lower Standean Valley, the Pyecombe-Patcham Valley and the Saddlescomb-Waterhall Valley. The associated interfluves between these valleys are the Ditchling Beacon - Tegdown Hill interfluve, the Scare Hill interfluve, the West Hill interfluve and the Red Hill interfluve (Figure 3.2).

The geomorphological characteristics of the Chalk formations presented by Bristow et al. (1997) were found to be consistent on the scarp slope of the South Downs and on the spurs within the main dry valleys but less conclusive in the heads of the smaller sub-valleys. It is common for the geomorphological characteristics of the Chalk formations to be less pronounced in dip slope valleys relative to the scarp slope (Aldiss, 2007). In addition to the geomorphological characteristics of the Chalk Formations identified by Bristow et al. (1997), subtle positive and negative breaks of slope were observed at the Lewes Nodular and Seaford Chalk Formation boundaries (Table 3.8).

3.3.3.4 Structural Geology

The geological structures present in the Patcham Catchment are north - south and west – east orientated geological sections (Figure 3.13 and Figure 3.14). The regional dip of the Chalk is approximately 3° towards the south and south-west although this varies locally around geological structures. Due to a combination of the regional dip and local geological structures, the Patcham Catchment is dominated at outcrop by the Seaford (~13 km²) and Lewes (~11 km²) Chalk Formations. The Newhaven and Culver Chalk also cover large areas at outcrop, approximately 6 and 4 km², but are located south of Patcham Village and the area of groundwater flooding.

The geological structures present in the Patcham Catchment are the Pyecombe Anticline, the Henfield Syncline, the Patcham Syncline, the Hollingbury Dome and the Caburn Syncline. The regional geological structures are described in more detail in Chapter 4. The borehole logs for Pyecombe East and Casterbridge Farm, with
Figure 3.12 Correlation of key exposures, the FLOOD1 recharge site borehole and EA observation boreholes in the Patcham catchment. Solid lines indicate direct correlation and broken lines indicate inferred correlation. Logs are positioned relative to the Glynde Marl. Geophysical logs shown are resistivity (black), induced conductivity (blue) and natural gamma (grey). Axes are reversed for induced conductivity logs so signatures are comparable to resistivity logs. Resistivity and induced conductivity logs are coloured by Chalk Formation.
the map boundaries, allow the Pyecombe Anticlined to be well defined. It has an approximate amplitude of 30 m and wavelength of 2 km (Figure 3.13 – Section 1). The anticlinal inflexion indicated by extending the Lewes Nodular and Seaford Chalk boundary further up the Scare Hill interfluve, between Pagedean and Lower Standean Farm, is illustrated in Figure 3.14 – Section 3 and 4. This structure is potentially the continuation of the Pyecombe anticline to the southeast.

The Henfield syncline, which occurs to the north of the Pyecombe anticline, trends to the southeast also and crosses the Lower Standean valley just south of the North Bottom borehole (Figure 3.14 – Section 4). Evidence can be seen for this in Figure 3.12 where correlation to the North Bottom geophysical log shows expansion of the sequence between the marker marl horizons in the New Pit Chalk Formation. Expansion of the Chalk sedimentary sequence is thought to occur as a result of syn-sedimentary tectonic deformation (Mortimore, 1979; Mortimore and Pomerol, 1991a). Marl seams in this interval, such as the Glynde and New Pit marls, are known to be volcanogenic (Wray and Wood, 1998; Wray, 1999; Mortimore et al., 2001) - formed from the ash of a volcanic eruption. This means that they effectively represent time or event horizons in the Chalk and correlation can demonstrate expansion or condensation of the Chalk sedimentary sequence e.g. Mortimore and Pomerol (1991a).

3.4 Comparison and Discussion

In the following sections, the key results from the field investigations in the Hallue and Patcham catchments are compared and the similarities and differences highlighted.

3.4.1 Lithology

The Hallue and Patcham Catchment chalks have similar lithological characteristics through much of the sequence despite significant differences in the thickness of equivalent units. The Middle Turonian Chalk, equivalent to New Pit Chalk Formation, in the Hallue catchment contains a similar number of marl seams to the Patcham Catchment chalk of the same age, but the Middle Turonian Chalk in the Hallue Catchment is denser and appears more clay-rich. The Upper Turonian – Lower Coniacian Chalk, equivalent to the Lewes Nodular Chalk Formation, in the Hallue Catchment comprises coarse hard nodular chalks with well-developed hardgrounds,
Figure 3.13 North – south orientated geological sections through key boreholes. Line of sections are illustrated in Figure 3.11. Key features to note are the Pyecombe Anticline and the Henfield Syncline to the north of the catchment (Section 1) and the Hollingbury Dome to the south east of the catchment (Section 2). Note also the slope gradients on the different Chalk Formations.
Figure 3.14 West–east orientated geological sections through key boreholes. Line of sections are illustrated on Figure 3.11. Key features to note are the Patcham Syncline in the west of the catchment (Section 3 and 4), the Henfield Syncline (Section 3) and Pyecombe Anticline (Section 4). The start of the Caburn Syncline can be seen towards the east of the catchment (Section 4). Note also the slope gradients on the different Chalk Formations.
flint horizons and marl seams – which is similar to the Upper Turonian – Lower Coniacian Chalk seen in the Patcham Catchment. The Middle and Upper Coniacian Chalk, equivalent to the Belle Tout and Cuckmere Beds of the Seaford Chalk Formation, in the Hallue Catchment comprises medium density chalks with regular flint horizons similar to the Patcham Catchment. These flint horizons, however, are often less well developed in the Hallue Catchment than the Patcham Catchment. For example, the Seven Sisters Flint, which occurs at the Belle Tout Bed – Cuckmere Bed boundary, is a semi-tabular flint horizon in the Patcham Catchment but a dispersed nodular flint horizon in the Hallue Catchment. Marl seams are also less well-developed in this interval in the Hallue Catchment; the Belle Tout Marls are absent and the Shoreham Marl is reduced to a few millimetres thick. This may be due to local variations in sediment input due to sea floor currents or the distance from sediment source.

The lithological characteristics of the Lower and Middle Santonian Chalk, equivalent to Haven Brow Beds of the Seaford Chalk Formation, differ most significantly between the research catchments. The Lower and Middle Santonian Chalk in the Patcham Catchment contained regular well-developed flint horizons and sub-vertical fracturing. The Lower and Middle Santonian Chalk in the Hallue Catchment was found to be devoid of flint horizons and the chalk appeared homogeneous - although occasional small isolated flints were present. Furthermore, there was no regular fracturing pattern in the Lower Santonian although sub-horizontal fractures were common. In the Middle Santonian there was a return to regular sub-vertical fracturing. Similar occurrences in the Lower and Middle Santonian Chalk were documented by Robaszynski et al. (2005) from the Poigny Borehole in the eastern Paris Basin.

The Upper Santonian – Lower Campanian Chalk, equivalent to the Newhaven Chalk Formation, have similar lithological characteristics between the research catchments although exposure is limited in the Hallue Catchment. The Upper Santonian – Lower Campanian Chalk in the Hallue Catchment comprises medium density chalks with flint horizons, marl seams and inclined (~70°) conjugate fractures. Phosphatic chalk deposits are also common in the Lower Campanian Chalk in the Hallue Catchment. In the Patcham Catchment these chalks contain regular flint horizons, marl seams and inclined (~70°) conjugate fracturing. The flint
horizons and marl seams in the Hallue Catchment, however, are less well developed than in the Patcham Catchment, probably due to local variation in the depositional environment.

Discrete lithological marker horizons, such as marl seams and flint bands, can be correlated between the research catchments. In particular, the Glynde Marls, the Southerham Marls, the Caburn Marl, the Bridgewick Marl, the Lewes Tubular Flints, the Lewes Marl, the Shoreham Tubular Flints, the Shoreham Marl and the Seven Sisters Flint can be correlated using exposure, core and geophysical logs. There may be more lithological horizons which could be used for correlation but a lack of exposures and boreholes through the entire sequence in the Hallue Catchment makes this difficult. Figure 3.15 illustrates a correlation between the Middle Turonian – Lower Coniacian marl seams between the Hallue Catchment and the Patcham Catchment.

Figure 3.15 Correlation of the Middle Turonian – Lower Coniacian marl seams between the FLOOD1 recharge site boreholes in the Hallue, Patcham and Pang catchments. Solid lines indicate direct correlation of marl seams encountered in the boreholes. Broken lines indicate inferred correlation of marls seams which have been lost from sequence at the borehole locations due to omission on hardgrounds (e.g. EI2) or as a result of erosion (e.g. NHB2). Logs are induced conductivity (mS/m) for NHB2 and EI2, and resistivity (Ohm-m) for P6. Logs are positioned relative to the Southerham/Fogham Marl. The Patcham Catchment borehole NHB2 has the most expanded sequence and the Pang Catchment borehole EI2 has the most condensed sequence. The Hallue Catchment borehole P6 has a condensed sequence relative to NHB2 but less condensed than EI2.
The correlation shown in Figure 3.15 is between resistivity and induced conductivity logs from the FLOOD1 recharge site boreholes P6 and NHB2. Also shown in Figure 3.15 is a correlation to a third borehole EL2 from the Easy Ilsley FLOOD1 recharge site. East Ilsley was another FLOOD1 recharge site based in the Pang Catchment in Berkshire.

### 3.4.2 Stratigraphy

Although the broad lithological characteristics of the Hallue Catchment and the Patcham Catchment chalks are similar, the stratigraphical sequence present at outcrop differs significantly. Within the Patcham Catchment the stratigraphical range of chalk present at outcrop ranges from Cenomanian to Lower Campanian. This comprises the West Melbury Marly, Zig Zag, Holywell Nodular, New Pit, Lewes Nodular, Seaford and Newhaven Chalk Formations. In the Hallue Catchment, the stratigraphical range of the Chalk seen at outcrop ranges from Lower Turonian to Lower Campanian. This is equivalent to the Lewes Nodular, Seaford and Newhaven Chalk Formations.

The Upper Turonian and Lower Coniacian sequence is condensed and around 40 m thick in the Hallue Catchment whereas it is around 70 m thick in the Patcham Catchment (Figure 3.15). Although there is no borehole through the Santonian and Lower Campanian Chalk sequence in the Hallue Catchment, the relative difference in elevation of exposures indicates the entire Hallue Catchment Chalk sequence is condensed relative to the Patcham Catchment. The age range of the Chalk at outcrop in Hallue Catchment is also less than the Chalk at outcrop in the Patcham Catchment due to the relatively differences in topographic relief and regional dip of the Chalk (Sections 3.4.3 and 3.4.4).

The stratigraphical differences observed between the two catchments fits with the regional context discussed in Chapter 2. The Patcham Catchment in the South Downs, situated in the UK Southern Chalk Province, is known to be more expanded as it is closer to the depositional centre of the basin (Mortimore and Pomerol, 1987; Mortimore *et al.*, 2001). The Hallue Catchment in Northern France is situated between the Anglo-Brabant platform to the north and the Hampshire-Dieppe high to the south (Figure 2.1). The Hallue Catchment Chalk is likely to have been deposited in shallower water - further from the main depositional centre of the basin. Figure
indicates the Hallue Catchment Upper Turonian sequence is more comparable to the Upper Turonian sequence in the Pang Catchment in Berkshire (Aldiss et al., 2002; Woods and Aldiss, 2004) than the Patcham Catchment. The Pang Catchment is situated in the UK Transitional Chalk Province. In the Transitional Province in the Berkshire Downs the chalk sequence is condensed relative to the Southern Province and contains well developed hard ground units such as the Chalk Rock (Mortimore and Pomerol, 1987; Mortimore et al., 2001). The Hallue Catchment may have a similar stratigraphical sequence formed on the southern flanks of the Anglo-Brabant Platform in Northern France. The Hallue Catchment, therefore, maybe thought of as being a more marginal Chalk sequence whereas the Patcham Catchment is a more basinal Chalk sequence.

3.4.3 Catchment Geomorphology

Comparison of the revised mapping, topography and exposure logs in the Hallue Catchment indicates a similar relationship between Chalk lithology and geomorphology as seen in the UK. Similar geomorphological characteristics were observed between the Chalks of equivalent age in the research catchments. The exception to this observation is the Lower Santonian and Middle Santonian Chalk in the Hallue Catchment tends to form steeper slopes than the equivalent age chalk in the Patcham Catchment.

The Hallue Catchment is geomorphologically less mature than the Patcham Catchment. The dip of the strata in the Hallue Catchment is very gentle at around 1° which limits formation of escarpments. The regional dip of the strata in the Patcham Catchment, however, is around 3°. The Patcham Catchment is dissected by dry valleys – the Lower Standean Valley, the Pyecombe-Patcham Valley and the Saddlescomb-Waterhall Valley. In the Hallue Catchment, the Hallue River incises into the Plateau De Picardie – a plateau area similar to Salisbury Plain in the UK. The average elevation of the Hallue and the Patcham Catchment is similar at around 100 m. The relief in the Hallue catchment, however, is less variable than in the Patcham Catchment and the valleys are less incised. This is demonstrated by the range and standard deviation of elevation in the catchments. In the Hallue Catchment, the topographic minimum, maximum and standard deviation is 28 m, 155 m and 30 respectively. In the Patcham Catchment the topographic minimum, maximum and standard deviation is -2 m, 248 m and 50 respectively. The
topography is therefore more variable in the Patcham Catchment and this is reflected in the much reduced preservation of Palaeogene and Quaternary deposits in the Patcham Catchment compared to the Hallue Catchment.

The units which are equivalent between the two research catchments, and which have significant enough outcrop to allow comparison of the geomorphological characteristics, are the Lower Turonian to Lower Coniacian and the Middle Coniacian to Middle Santonian or Lewes Nodular and Seaford Chalk Formations. Bristow et al. (1997) indicated that in the UK typically there is a positive break of slope at the base of the Lewes Nodular Chalk and the slopes developed on the Lewes Nodular Chalk and the Seaford Chalk Formations are low gradient and convex. Although, the base of the Upper Turonian-Lower Coniacian or Lewes Nodular Chalk is not exposed in the Hallue catchment, the slopes gradients are low at around 0-3° consistent with this characteristic. Similarly, the characteristics of the slopes developed on the Upper and Middle Coniacian or Belle Tout and Cuckmere Beds of the Seaford Chalk Formation appear consistent between the research catchments. The slope gradients in the Patcham Catchment, due to the more developed relief, are on average higher than in the Hallue Catchment.

The Lower and Middle Santonian, equivalent to the Haven Brow Beds of the Seaford Chalk Formation, differs in characteristics between the research catchments. This unit in the Hallue Catchment appears to have a negative break of slope at the base and the slope gradients are generally steeper. A positive break of slope occurs at the top of this unit as slope gradients decrease on the Upper Santonian Chalk. This unit in the Patcham Catchment, however, is not geomorphologically distinguishable from the other beds in the Seaford Chalk Formation and Bristow et al. (1997) indicated the opposite occurs at the top of the unit. Bristow et al. (1997) described a negative break of slope around the top of the Seaford Chalk Formation and base of the Newhaven Chalk Formation – defining the base of the secondary escarpment in the South Downs.

The distinctive geomorphological characteristics of the Lower Santonian-Middle Santonian Chalk in the Hallue Catchment may relate to lithological characteristics (see Section 3.2.3.1). This unit is relatively homogeneous and lacks flint horizons and marl seams. It has no regular fracturing pattern and appears massive. These
lithological characteristics may make it more resistant to mechanical weathering than the other chalks in the catchment. Similar geomorphological and lithological characteristics occur in the New Pit Chalk Formation in the South Downs (Bristow et al., 1997) – although the New Pit Chalk Formation is more heterogeneous and contains well-developed marl seams.

3.4.4 Structural Geology

The results of the field investigations in both the Hallue and the Patcham Catchment have provided more detail on the form of the geological structures present. The revised mapping and cross sections of the Hallue Catchment have shown new structures to the north and west of the catchment. The revised map and cross sections of the Patcham Catchment have indicated that the geological structures present in the catchment are more extensive than previously understood.

The scale of the geological structures varies between the catchments. The axis length and wavelength of structures in the Hallue Catchment are of the order of tens of kilometres whereas in the Patcham Catchment the axis length and wavelength of structures is of the order of kilometres. The amplitude of the structures seen in the Patcham Catchment, however, are generally greater than those seen in the Hallue Catchment. This variation is discussed further in Chapter 4.

3.5 Conclusion

The results presented in this chapter have provided a review of the Chalk stratigraphy and geological mapping in the Hallue and Patcham catchments. The results were presented and discussed in the context of current stratigraphical systems used in both research catchments. The key outcomes from analysis of the new field data include:

(i) development of a lithostratigraphical framework for the Hallue Catchment
(ii) production of a revised geological map for the Hallue Catchment based on the lithostratigraphical framework
(iii) validation and revision of the geological map for the Patcham Catchment
(iv) identification of new geological structures in both research catchments
(v) comparative studies on lithology and sedimentation, stratigraphy, structural geology and geomorphology between the research catchments
(vi) investigation of unusual lithologies observed in the research catchments
In the context of the conceptual model of a chalk valley presented in Chapter 1, the results presented in this chapter have provided information on the lithology and stratigraphy of the Chalk aquifer in both the Hallue and Patcham Catchments. These results form the foundation for work presented in subsequent chapters. Further field data from the research catchments on Chalk structural geology, fracturing and fabric are presented and discussed in Chapter 4.
Chapter 4 Structural Geology of the Catchments

4.1 Introduction

This chapter presents the results from supplementary field and laboratory studies relating to the structural geology of the FLOOD1 research catchments. The results are reviewed in the context of the literature presented in Chapter 2 and build on the field investigation results presented in Chapter 3. The results from this chapter are complimentary to the further work presented in Chapters 5-7.

Geological structure within the Chalk is likely to influence groundwater flow (e.g. Headworth, 1972; Giles and Lowings, 1990; Mortimore, 1993; Jones and Robins, 1999). Anticlines and synclines may act as groundwater divides and sub-catchments whereas faults may act as groundwater conduits. Fracturing, which is ubiquitous in the Chalk, also influences the hydrogeological and engineering behaviour of the Chalk rock mass (Price, 1987; Lord et al., 2002). In light of this, structural data were collected in both the FLOOD1 research catchments to enhance conceptualisation of the structural geology of the catchments and characterise fracturing in the Chalk rock mass. Structural contour maps were developed from the stratigraphical data collected in the first phase of field investigation. Fracture measurements were collected in a second phase of field investigation from scanline and optical televiewer surveys.

Key exposures and boreholes were identified in each research catchment which covered the range of lithostratigraphical units present. Critical for the scanline surveys in the Hallue catchment was identifying exposures which had rock faces in a good state of preservation. Scanline surveys were conducted at seven exposures in the Hallue Catchment and optical televiewer surveys were conducted at four boreholes in the Patcham Catchment. Furthermore, fracture logs were produced from the FLOOD1 recharge site borehole cores, and, where feasible, large orientated block samples were collected from exposures in the Hallue Catchment for vein fabric analyses.
4.2 Hallue Catchment

4.2.1 Regional Structural Geology

The Hallue Catchment is situated within the Paris Basin north of the main basin axis and south of the margin of the Anglo-Brabant Massif (Chapter 2 - Figure 2.1). The regional structures within the Chalk near the Hallue Catchment are presented in Figure 4.1. The contours for the top of the Turonian “Dièves” are adapted from King (1921), D'Arcy and Roux (1971) and Dupuis et al. (1972b). The major structures in this region have a NW-SE and WNW-ESE orientation with a secondary NE-SW orientation. Dupuis et al. (1972b) considered these to relate to Variscan basement structures. The alignment of these structures is believed to have directly influenced the form of the river catchments, such as the Somme and the Authie, in Picardie (Bevan and Hancock, 1986; Mortimore and Pomerol, 1987; Crampon et al., 1993).

The major structures in the vicinity of the Hallue Catchment are labelled A-E with additional structures proposed by Dupuis et al. (1972b) labelled F-I in Figure 4.1. The two structures which directly impact the structural geology of the Hallue Catchment are the Somme Syncline (A and C) and the Ponthieu Anticline (D1 and D2). The Somme Syncline extends for over 100 km. The portion of the Somme Syncline near the Hallue Catchment is also known as the Péronne Syncline (C). Its axis is situated to the south of the Hallue Catchment and it leads to a southeast dip of strata in the lower half of the catchment. The Ponthieu Anticline extends for over 70 km. Its axis is situated in the plateaux area between the Somme and Authie valleys and it intersects the Hallue around the centre of the catchment (see Figure 4.1). Dupuis et al. (1972b) hypothesised that it continued to the southeast (D2) between Albert and Corbie until it reached the Somme Syncline. The faults present in the area of Beauquesne and Beauval and further to the west indicate that the northern limb of this structure may be fault controlled (Figure 4.1). The structure contours constructed from the new field data (Figure 4.2), indicate the axis of the Ponthieu Anticline has a WNW-ESE orientation and intersects the Hallue around the centre of the catchment – further south than D'Arcy and Roux (1971) and Dupuis et al. (1972b) placed the axis (Figure 4.1). Evidence for this as the position of the axis is further supported by the change in orientation of the course of the Hallue River at this location. The regional dip of the chalk is approximately 1° but increases to 3° due to the influence of smaller geological structures in the catchment.
4.2.2 Catchment Structural Geology

In addition to the major regional structures, a number of smaller geological structures were identified within the Hallue Catchment by Dupuis et al. (1972b). These structures are labelled in Figure 4.1 as E, H and I. These are further defined by the new field data collected in the Hallue Catchment which was used to produce the structure contours and fold axes presented in Figure 4.2. These structure contours are on the top of the Lower Coniacian. The fold axes and fault lines shown in Figure 4.1 are also shown in Figure 4.2 for reference.

Structure E is a small anticline in the north-west of the Hallue Catchment. It extends for over 5 km and its axis is shown to be orientated ENE-WSW in Figure 4.1. This structure is also proved by the new field data in the Hallue Catchment and can be seen in the structure contours shown in Figure 4.2. The structure contours in Figure 4.2 indicate, however, the orientation of this axis is closer to NE-SW and it lies further north than indicated by D’Arcy and Roux (1971) and Dupuis et al. (1972b).

Dupuis et al. (1972b) identified H as a structural or sedimentary anomaly and inferred the axis of this from the structure contours on the top of the Dièves. It has a NW-SE orientation and crosses the western edge and lower half of the Hallue Catchment. The structure is less well-defined by the top Lower Coniacian structure contours although the broadening of the Coniacian outcrop south of Querrieu indicates a structure maybe present. Little new field data were collected in this area of the Hallue Catchment to provide further evidence.

Dupuis et al. (1972b) identified structure I, referred to in Chapter 3 as the Hallue Valley Fold/Fault, as an anomaly in the structure contours on the Coniacian/Santonian boundary centred on the Hallue valley. It is noted that this structure possibly leads to a reduction in thickness of the Coniacian biozones.
Figure 4.1 Structure contours on the top of the Turonian Dièves for the Somme and Authie valleys adapted from D'Arcy and Roux (1971). The Somme and Authie valleys can be seen to follow synclines in the Chalk which themselves relate to structures in the basement. Smaller scale NW-SE, SW-NE and WSW-ENE orientated folding is observed in the vicinity of the Hallue Catchment. Labels are referenced in the main text.
(C4a-c) and an increase in thickness of the Santonian biozones (C5d-e). Monciardini (1989) indicated similar variations in thickness occurred in the Somme to the east of the Hallue Catchment. The two explanations which Dupuis et al. (1972b) presented to explain this structure is that it could either have formed as a result of syn-sedimentary faulting or a syn-sedimentary channel. In the first scenario, the faulting would be active during the Coniacian leading to local reduction in the thickness of some of the Coniacian biozones followed by a period of subsidence in the Lower Santonian which would lead to increased thickness of Santonian biozone “d”. In the second scenario, syn-sedimentary underwater currents in this area during the Coniacian would erode or reduce deposition of Coniacian chalks with this channel eventually filled during the Lower Santonian. Furthermore, Dupuis et al. (1972b) indicated that the orientation of this structure may relate to the initial uplift of the Ponthieu Anticline i.e. the channel would have developed approximately perpendicular to the axis of the Ponthieu Anticline. This is feasible when the orientation of structure I is considered relative to the orientation of D2 (Figure 4.1).

The new field data collected in the Hallue Catchment provided some evidence for the existence of structure I. The Hallue geological Section 1 presented in Chapter 3 (Figure 3.6) highlighted the dip of the strata and the Santonian sequence filling the structure. Lithological observations of the Lower Santonian Chalk provided evidence that these chalks may be re-deposited - as would be expected if they were channel fill deposits – i.e. massive, absence of bedding-related structures, such as marl seams and flint bands, with irregular conchoidal fracturing (HA52 – Appendix III). The extent of structure I as shown by Dupuis et al. (1972b), however, is difficult to validate. It is shown to cross cut the axis of the Ponthieu Anticline – which would be feasible if it were a fault but less likely if a syn-sedimentary channel related to the growth of the Ponthieu Anticline. The structure contours presented in Figure 4.2 have provided little indication of the presence of structure I north of the Ponthieu Axis. To the south of the Ponthieu Anticline axis, however, an increase in dip of the strata by approximately 2° to the southeast was observed. The orientation of the structure contours in this area were found to be parallel to the axis of structure I, as inferred by Dupuis et al. (1972b), which is more likely to occur if structure I was a fault.
Figure 4.2 Structure contours on the top of the Lower Coniacian based on interpolation from key exposures studied in the Hallue catchment. The coloured anticline and syncline axes are based on the sub-Coniacian structure contours shown. The anticline and syncline axes shown in black are from D'Arcy and Roux (1971). (Mapping © IGN 2011). Labels are referenced in the main text.
Further to the structures presented by Dupuis et al. (1972a), subtle structures are recognised from the new fieldwork data collected in the Hallue Catchment (Figure 4.2). This is particularly the case in the northern half of the catchment where the BRGM maps did not subdivide the Coniacian and Santonian chalk. For example, a synclinal inflection, structure J, is recognised north of the village of Forceville (Figure 3.1). Structure J preserves Lower Santonian chalk, seen at HA23, and lies between the Ponthieu Anticline and structure E (Figure 3.6 – Section 2).

4.2.3 Fracture Analyses

4.2.3.1 Methodology

The method used to collect fracture data from exposures in the Hallue Catchment were based on the methods employed by Priest et al. (1976), Bloomfield (1996) and Mortimore et al. (2004). In this approach, a series of parallel horizontal and vertically orientated scanlines are set out on a rock face using tape measures to create a window (Figure 4.3). The length of each scanline or tape measure was dependant on the accessibility, condition and dimensions of the rock face. The position, aperture, persistence, dip and strike of each fracture along the tape measures is then recorded. If there were multiple rock faces with different orientations at a locality, scanline surveys were conducted on each rock face to limit directional bias. The localities for scanline surveys were chosen because they covered the range of lithostratigraphical units present at outcrop in the Hallue Catchment (Table 4.1) and had rock faces in a good state of preservation.

4.2.3.2 Results and Discussion

The results from the scanline surveys are presented in Figure 4.4 to Figure 4.7 as lower hemisphere equal area stereographic projections of poles to planes and discontinuity spacing, aperture and persistence histograms respectively. A summary of the typical Chalk rock mass and fracture characteristics is also presented in Table 4.1. The Fisher concentrations displayed on the stereographic projections have been adjusted for directional bias using a Terzaghi Weighting with a minimum angle of 15° (Terzaghi, 1965; Priest, 1993; Anon, 1999b). The Terzaghi method involves application of a correction factor to each feature and subsequent stereographic projection. The results from horizontal and vertical scanlines are presented separately on the discontinuity spacing, aperture and persistence histograms. The discontinuity spacing categories are based on BSI (2003), the first
Figure 4.3 Scanline survey strategy employed at exposures in the Hallue Catchment.
five categories of which are also equivalent to suffix 1-5 of the CIRIA chalk grades (Lord et al., 1994; Lord et al., 2002) (Table 2.4). The aperture measurements are equated to the equivalent CIRIA chalk grades (Lord et al., 1994; Lord et al., 2002) (Table 2.3).

The scanline survey results for the Hallue Catchment highlighted a number of characteristics of the Chalk rock mass. The results were found to show a change in the dip angle of fractures in relation to stratigraphy. This was observed as a shift from inclined to sub-vertical and back to inclined fractures up sequence. Sub-horizontal fractures, however, were found to be consistent throughout the sequence. Results for the Upper Turonian chalk at exposure HA57B show inclined fractures. Results for the Lower Coniacian chalk at HA57A show sub-vertical fractures. Sub-vertical fractures then occur through the Middle and Upper Coniacian chalk, as shown by the stereonet for HA25, and into the Lower and Middle Santonian – as shown by the stereonets for HA13, HA23 and HA51. There is then a return to inclined fractures in the Lower Campanian chalk as shown by the stereonets for HA1 and HA27. This suggests that fracture dip varies with stratigraphy and maybe used as a characteristic for identifying and logging the Chalk in the Hallue Catchment – as has been demonstrated in England (Mortimore, 2001a, 2011, 2012).

The change in fracture dip angle with stratigraphy may be indicative of the in-situ stress state at the time of deposition or the mechanical properties of the different Chalk units and their response to post-depositional stress. The chalk units which displayed inclined fractures, the Upper Turonian and Lower Campanian, were the main units which contained marl seams (Figure 4.8). The presence of inclined fractures associated with marl seams in the Upper Turonian and Lower Campanian chalk, i.e. lower Lewes Nodular and Newhaven Chalk Formations, has been noted by Mortimore (1979, 1993, 2011), Mortimore et al. (1990b; 1996) and Lamont-Black (1995). The presence of marl seams enhances vertical heterogeneity in the Chalk sequence and may influence the mechanical behaviour of Chalk units. Mortimore (1993) described how marl seams in the Chalk may act as shear surfaces which fractures terminated against. This effect is referred to as mechanical stratigraphy and has been noted in other carbonate sequences (e.g. Cooke et al., 2006).
Figure 4.4 Stereographic projections of scanline survey fracture measurements by exposure. Also presented is the orientation of vein fabrics measured from samples—shown as a white star. Fracture and fabric measurements are plotted as poles to planes. Note no vein fabrics were measured at HA57B.
Figure 4.5 Fracture spacing histograms from scanline survey fracture measurements.
Figure 4.6 Fracture aperture histograms from scanline survey fracture measurements. Dashed lines represent the boundaries between CIRIA chalk grades A, B and C.
Figure 4.7 Fracture persistence histograms from scanline survey fracture measurements.
<table>
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<tr>
<th>ID</th>
<th>Stage/Substage</th>
<th>UK Lithostratigraphy</th>
<th>Total No Scanlines</th>
<th>Total Scanline Length (m)</th>
<th>Total No. Fractures</th>
<th>Scanline Orientation</th>
<th>Typical Chalk Rock Mass Characteristics</th>
<th>Typical Fracture Characteristics</th>
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<td>B (10 x C)</td>
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<td>Vertical</td>
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<tr>
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<td>Vertical</td>
<td>2 (M)</td>
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<td>Lewes Nodular Chalk Kingston, South Street, Navigation and Cliffe Beds</td>
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<td>36</td>
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<td>B/C</td>
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<td>Vertical</td>
<td>2 (M)</td>
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Table 4.1 Summary of typical Chalk rock mass and fracture characteristics from the scanline surveys in the Hallue Catchment. Fracture sets classified by dip range are: SH = sub-horizontal, SH-LAI = sub-horizontal to low angle inclined, I = inclined, I-SV = inclined to sub-vertical, SV = sub-vertical. BSI (2003) spacings are: C = close, M = medium, W = Wide.

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The fracture orientation measured at the majority of exposures is strongly NW-SE with a secondary, opposing and less strong NE-SW orientation. Also observed at a number of exposures was a weak N-S and E-W orientation. This is seen in the stereonets for HA57B, HA51, HA1 and HA27 or in the Upper Turonian, Middle Santonian and Lower Campanian chalks. The fracture orientations are consistent with the axes of the fold structures discussed in sections 4.2.1 and 4.2.2 and in particular the Ponthieu Anticline and the Forceville Syncline. Fractures measured at exposures HA51 and HA1 (Figure 4.9) had the strongest N-S and E-W orientation. Both exposures are located south of the axis of the Ponthieu Anticline on the east side of the Hallue Catchment. The Ponthieu Anticline appears to diminish as it reaches the Somme Syncline east of the Hallue Catchment. The change in fracturing orientation south of the Ponthieu Anticline may result from the relative decline of its influence and the increased influence of the Somme Syncline. The axis of the Somme Syncline is orientated approximately E-W in the vicinity of the Hallue Catchment.

Slickensided fractures were observed at HA57B, HA51 and HA1. The presence of slickensides in the chalk at these exposures, based on Mortimore and Pomerol (1997) and Mortimore et al. (1998), coincides with the Ilsede and Wernigerode compressional tectonics phases of Stille (1924). The dip direction of the slickensides was measured as 096° for HA57B; 323° and 333° for HA51; and 089°, 114°, 114°, 072° for HA1. The dip direction of these slickensides indicate the sense of movement on the fractures was generally NW-SE, E-W and NE-SW. The type of shear, i.e. normal or reverse, could not be established at the exposures but HA51 and HA1 are both located in the synclinal area south of the Ponthieu anticline (Figure 4.2) which would generally suggest a zone of compression. If the palaeo-stresses affecting these fractures are assumed to be related to the orientation of the folds, \( \sigma^1 \) and \( \sigma^2 \) would be orientated either NE-SW, NW-SE or E-W and \( \sigma^3 \) vertical.

The orientation of valleys on areas of Chalk outcrop are generally thought to be related to the strike of fractures or faults (Ineson, 1962; Morgan, 1971; Crampon et al., 1993; Marsh, 1993; Mortimore, 2012). Initial development of the valleys is thought to have occurred along pre-existing lines of structural weakness associated
Figure 4.8 Photographs illustrating variation in fracturing characteristics at exposures in the Hallue Catchment. A = HA57B with wide spaced fractures some of which are terminating against or parallel to the Lewes Marl (Upper Turonian – Lewes Nodular Chalk), B = HA25 with dominantly sub-vertical fractures (Middle and Upper Coniacian – Seaford Chalk), C = HA13 with anastomosing sub-horizontal fractures cross cut by sub-vertical fractures (Lower Santonian – Seaford Chalk), D = HA51 with a return to sub-vertical fracturing (Middle Santonian – Seaford Chalk), E = HA27 with rhomboidal faces from inclined conjugate fractures (Lower Campanian – Newhaven Chalk), F = HA27 with close up of inclined fractures with clay smearing, due to the presence of thin marl seams, and iron and manganese oxide mineralisation.

with the fractures or faults in the Chalk. With continued development of the valleys, stress-relief parallel to the valley sides and bottom is thought to have caused fractures, which strike in the same orientation, to have opened preferentially, leading
to enhanced development of the fractures which strike parallel to the valley axes (Ineson, 1962; Price, 1987; Price et al., 1993; Mortimore et al., 1996; Lord et al., 2002)(Figure 1.2). To evaluate whether the orientation of the valleys in the Hallue Catchment demonstrated these characteristics, rose diagrams of the fracture strikes from the surveyed exposures are shown in Figure 4.9 with lines marking the valley axis azimuth. Visually the strikes of the fractures measured at the scanline exposures and the valley axes in the Hallue Catchment do seem to have similar orientations (Figure 4.9). The dominant NW-SE and opposing NE-SW trends seen in the fracture strikes are also clearly present in the valley axes orientations. There also seems to be a slight change in orientation of the main valley axis, south of the axis of the Ponthieu Anticline, to a more N-S orientation in a similar manner to that seen in the fracture strikes for HA51 and HA1. The implications of this relationship between valley orientation and fracturing is considered further, with regard to geological structure and hydrogeology, in Section 4.4.4 and Chapter 7 – Section 7.7.

The typical facture spacing measured at the majority of exposures was found to be medium spaced or CIRIA grade suffix 2 (Table 4.1). The boundary of CIRIA grade suffix 3 and 2 is approximately the boundary between weathered and unweathered chalk (Lord et al., 2002 - Figure 2.9). This indicates that the fracture spacings observed at the majority of the exposures in the Hallue Catchment were consistent with chalk being in its natural in-situ condition. There was found to be a greater variation seen in the fracture spacing measured on the horizontal scanlines compared to the vertical scanlines. The fracture spacing measured on the vertical scanlines was consistently found to be medium spaced or CIRIA grade suffix 2 (Table 4.1). The fracture spacing measured on the horizontal scanlines varied from close spaced seen at HA13 to wide spaced seen at HA57A, HA57B and HA25. This variation in the spacing of inclined and sub-vertical fracturing may be due to site-specific variation, such as faulting, or variation in rock properties such density and the presence or absence of marl seams. The fracturing at HA13 was unusual in comparison to the other exposures with sub-vertical fractures which cross cut anastomosing low angle fractures (Figure 4.8). The sub-vertical fractures were locally concentrated and may be faults – although evaluating displacement across them was difficult due to the lack of flint bands and marl seams. These zones of intense fracturing, however, were widely spaced and this creates a histogram with
Figure 4.9 IGN digital terrain model for the Hallue Catchment with valley axes, structure contours and rose diagrams of fracture strikes from the surveyed exposures. (Mapping © IGN 2011)

a double peak (Figure 4.5). The histograms for the other exposures show a distribution more closely approximating a normal distribution. Therefore, the characteristics of the sub-vertical fractures at HA13 may be considered as only
being observed at this. The most frequent fracture spacing at HA57A, HA57B and HA25 measured on the horizontal scanlines was wide spaced or CIRIA grade suffix 1 (Table 4.1). These exposures contained the oldest Chalk at outcrop in the Hallue Catchment. The Upper Turonian and Lower Coniacian Chalk, HA57A and HA57B, were found to be high to very high density and coarse textured in hand specimen. The Middle and Upper Coniacian chalk, HA25, was found to be medium to high density. This relative difference in density of the different chalks units may have had an impact on how fracturing has developed. The implications of the fracture spacing data from the Hallue Catchment is considered further, with regard to hydrogeology, in Section 4.4.4

The typical fracture aperture measured at the majority of exposures was found to be equivalent to CIRIA grade B (Table 2.3 and Table 4.1). Fractures with greater apertures were also found to be present in the Upper Turonian - Lower Coniacian chalk at HA57B and HA57A or where widened by dissolution and filled with sediment at HA13 and HA23 (Figure 4.8). The greater apertures noted in the Upper Turonian – Lower Coniacian chalk, equivalent to the Lewes Nodular Chalk Formation, may result from dilation on the fractures due to roughness associated with the chalk nodules. A similar observation was made by Miller (2000) from laboratory tests. The maximum aperture measured was 70 mm and this fracture was filled with a loess. These widened fractures, where present in exposures, had a minimum spacing of 0.5 m and a maximum spacing of 11.95 m - with an average of 3 m. The implications of the fracture aperture data from the Hallue Catchment is considered further, with regard to hydrogeology, in Section 4.4.4

The typical fracture persistent measured at the majority of exposures was found to be $1 < p <= 2$ m at HA23, HA25, HA27, followed by $5 < p <= 10$ m at HA1, HA13, HA57A, HA57B (Table 4.1). The greater values of persistence were commonly from sub-horizontal and low angle inclined fractures measured on vertical scanlines. In some cases, these fractures extended for $>10$ m. The absolute values of persistence should be treated with a degree of caution, however, as at some locations fractures had greater persistence than could be measured in the exposure. The exposures which contained fractures with generally greater persistence were typically in the Upper Turonian-Lower Coniacian and Lower Campanian chalks which also contained marl seams - equivalent to the Lewes Nodular and Newhaven Chalk
Formations in the UK. The greater persistence of sub-horizontal or ‘bedding plane’ fractures in the Chalk has been noted by other workers as being an important control, particularly where enhance by dissolution and combined with faults, on flow in the aquifer (Younger and Elliot, 1995; Bloomfield, 1996, 1999; Soley et al., 2012). The implications of the fracture persistence data from the Hallue Catchment is considered further, with regard to hydrogeology, in Section 4.4.4.

4.2.4 Vein Fabric Analysis

4.2.4.1 Methodology

The method used to determine the dip and dip direction of the chalk vein fabric was based on the Bushinsky oil technique (Bushinsky, 1947; Bromley, 1981) which was developed to enhance the appearance of trace fossils in rock. The focus of this study, however, was chalk fluid escape or injection vein fabrics formed in the chalk prior to lithification.

A large hand sample was identified at each exposure and the strike of the exposed face of the sample was measured. The measured face was marked to indicate the strike and way-up of the sample. The sample was taken back to the laboratory and set in plaster of paris to make it a uniform shape. Using the face with the known orientation, the sample was marked with vertical cut lines in N-S and E-W orientations. The sample was cut along these lines using a clipper saw. The cut faces were cleaned with water and the sub-samples placed in an oven to dry at 60° for 24 hours. Once the sub-samples had cooled, the cut faces were lightly scrapped to remove any chalk fines that were blocking the pores. A horizontal line was marked on the centre of the cut faces using a set square. The cut faces were coated with a layer of thin oil and then allowed to dry. Each cut face was scanned in the orientations of N-SifW, S-NifE, E-WifN and W-EifS where ‘f’ denotes the facing direction. The sub-samples were cut again on the horizontal line and the process of cleaning, drying, scrapping and coating with oil was repeated on the newly cut faces. The new cut faces were then scanned in the orientations of lower facing up and upper facing down. The steps of this method are summarised in Figure 4.10. The scanned images were then used to calculate the dip and dip direction of any orientated vein fabrics in the chalk sample. The vertical N-S or E-W orientated cut faces were used to measure the apparent dip of the fabric. The horizontal cut surfaces were used to measure the strike of the fabric. The true dip was calculated
using the formula shown in Figure 4.10 and the true dip direction was determined from the strike.

In the process of collecting vein fabric orientation measurements from the chalk samples it appeared the density of vein fabrics varied significantly between samples. To quantify this observation the number of vein fabrics and the spacing between them was measured on the horizontal cut surfaces of the sample along the N-S and E-W cut faces (Figure 4.10). This was undertaken on the samples which were derived from the exposures where scanline surveys were conducted. The number of vein fabrics and average spacing is presented in Table 4.2.

### 4.2.4.2 Results and Discussion

In total, 55 large hand samples were collected from the exposures in the Hallue catchment and 82 chalk fabric orientation measurements were made from these. The fabric measurements at each scanline survey site are plotted on the stereonets shown in Figure 4.4 – as indicated by a white star symbol. The complete fabric orientation measurements are presented in Figure 4.11 in a lower hemisphere equal area stereographic projection of poles to planes and tabulated in Appendix V.

The fabric measurements for the scanline sites plotted on the stereonets in Figure 4.4 show commonly a NE-SW orientation with a less common NW-SE, N-S and E-W orientation. Fabric measurements from HA13, HA23, HA25 and HA27 all have a NE-SW orientation (Figure 4.4). Fracture measurements from these exposures also show clustering in a NE-SW orientation – although typically less strong then the NW-SE. The fabric measurements for the remaining scanline exposures all show differing orientations. HA1 has an E-W fabric measurement, HA51 has an N-S fabric measurement, and HA57A has NW-SE measurement. HA1 and HA51 show clustering of fracture measurements in these orientations but the fracture measurements of HA57A are not strongly orientated NW-SE.

The fabric dips for HA13 (49°), HA23 (61°) and HA57A (69°) are comparable to the fractures dips from these exposures but the fractures tend to be clustered at slightly higher angles (Figure 4.4). The fabric dips for HA1 (88°), HA25 (68°), HA27 (88°) and HA51 (80°) are also comparable to the fracture dips from the respective exposures and they fall exactly among fracture clusters shown. No vein fabrics were
present in the hand sample from HA57B. The stereographic projection of the fabric orientation measurements in Figure 4.11 shows a strong NE-SW and NW-SE orientation and less strong E-W orientation. The dip of the fabric ranges between a minimum of 49° and maximum of 89° with an average of 76° and a standard deviation of 10°. No sub-horizontal/low angle inclined fabrics were measured. The histogram in Figure 4.11 shows that the majority of the fabric dips are between of between 80° and 90°. The dip of the fractures range between a minimum of 0° and a maximum of 89° and with an average of 62° and a standard deviation of 32°. The histogram in Figure 4.11 shows that the majority of fractures dips are also between 80° and 90°.

The spacing of vein fabrics were measured from the hand specimens collected at the same exposures where scanline surveys were conducted. The average vein fabric spacing is presented against the average fracture spacing for the scanline survey exposures in Table 4.2 and Figure 4.12. The average vein fabric spacing varies from >38.88 mm to 2.39 mm. The average vein fabric spacing decreases progressively from the Upper Turonian (HA57B), Lower Coniacian (HA57A), Middle and Upper Coniacian (HA25) to the Santonian (HA23, HA13, HA51A and HA51B). It then increases in the Lower Campanian (HA1 and HA27). The change in average vein fabric spacing between exposures appears to be partially mirrored by the change in average fracture spacing. Cross-correlation of the average vein fabric spacing data versus the average fracture spacing data produces a reasonable strong positive correlation (Figure 4.12). More data, however, would be required to investigate this relationship fully.

A stereographic projection of the complete fracture measurements from the scanline surveys is shown in Figure 4.11 for comparison with the fabric measurements. The fabric measurements plot on a similar orientation to the fracture measurements with a strong NW-SE and NE-SW orientation to the data and weaker E-W and N-S orientations. The fabric orientations, however, appeared to be less concentrated than fracture orientations. This may be partly due to the difference in the size of the dataset – there are 422 fracture measurements but only 82 fabric measurements.
Figure 4.10 Methodology used to measure fabric orientation in chalk field specimens collected from exposures in the Hallue Catchment.
The fracture and vein fabric datasets display similar angles of dip - with the majority of the measurements from both datasets having a dip in the range between 80-90°. The stereonets and histograms in Figure 4.11, however, highlight that sub-horizontal/low angle inclined dipping fractures were measured in the chalk exposures but sub-horizontal vein fabrics were not measured from the hand samples. Typically a sample was collected from the lower part of the exposure face and, although in-situ, the blocks edges were typically formed by fractures or other planes of weakness. The samples collected, therefore, could have been bounded
by, but not contain, sub-horizontal vein fabrics. This is possibly compounded by the difficulty in differentiating the sub-horizontal vein fabrics from thin marls and other bedding features in the hand sample.

![Fracture Spacing Vs Vein Fabric Spacing](image)

Figure 4.12 Correlation of average fracture spacing from horizontal scanline surveys with average vein fabric spacing from horizontal samples cuts.

Further to the equivalency of the dip and dip direction data between the vein fabric and fractures, there also appears to be a relationship between the vein fabric spacing and the fracture spacing (Figure 4.12). The presence or absence of chalk vein fabrics may have a direct impact on the formation of fractures i.e. where the chalk is more heterogeneous due to the presence of vein fabrics it may be weaker and fractures may have developed more easily than where the vein fabrics were absent. Alternatively, the chalk fabrics may not directly influence the formation of fractures, but their presence or absence may be indicative of other sedimentary processes which influence the strength of the rock. Mortimore (2011) demonstrated that vein fabrics formed as a result of deformation and fluid escape in the soft Chalk sediment prior to lithification. The Upper Turonian and Lower Campanian samples displayed the greatest spacing of chalk fabrics and these samples appeared to have a more bioturbated and reworked matrix. If sea floor processes such as bioturbation destroy the initial chalk fabric, the rock may be more homogenous and stronger as a result - thereby impairing the formation of fractures.
4.3 Patcham Catchment

4.3.1 Regional Structural Geology

The Patcham Catchment, located in the South Downs, is on the southern margin of the former Wealden Basin (Chapter 2 - Figure 2.1 and Figure 2.8). The Wealden Basin was inverted to form the present day Weald-Artois Anticline. The Weald-Artois Anticline is a large structure, underlain by a complex of inversion faults, which extends for approximately 210 km (Jones, 1999b) crossing the Channel into northern France. It dictates the regional dip of the Chalk in the South Downs and the other structures discussed here are effectively smaller scale folds and faults on the southern limb of the Weald-Artois Anticline. Its axis is located to the north of the Patcham Catchment in the central Weald.

The regional structures within the Chalk near the Patcham Catchment are presented in Figure 4.13. The structure contours for the Bridgewick Marl 1 were adapted from Mortimore (2011). The Bridgewick Marl 1 is an Upper Turonian volcanogenic marl seam which occurs in the Lewes Nodular Chalk Formation. The major structures within the region have a WNW-ESE and an ENE-WSW orientation. There is also a secondary NW-SE and NE-SW orientation to a number of the smaller structures. The major structures in the vicinity of the Patcham Catchment are labelled A-H in Figure 4.13. Of these major structures, those that directly influence the structural geology of the Patcham Catchment are the Pyecombe Anticline (A), Hollingbury Dome (D) and the Caburn Syncline (C).

The Pyecombe Anticline extends for approximately 30 km. Its axis is located to the north of the Patcham Catchment and is orientated WNW-ESE. It is a periclinal structure which starts in the Weald and enters the Chalk at Pyecombe. The northern limb of the Pyecombe Anticline is also folded into a syncline – the Henfield syncline (Gallois, 1965). The axis of the Pyecombe Anticline is arcuate and its orientation is approximately NW-SE within the Patcham Catchment. The amplitude of the fold diminishes within the Patcham Catchment but it leads to a northeast and southeast dip of strata on its northern and southern limb in the upper half of the catchment.
Figure 4.13 Structure contours on the Bridgwick Marl 1 adapted from Mortimore (1991a; 2011). The geological structures in the vicinity of the Patcham Catchment are the Pyecombe Anticline (A), the Henfield Syncline (B), the Caburn Syncline (C), the Hollinbury Dome (D), the Patcham Syncline (E), the Coldean Lane Fault (F), the Lewes Road Fault (G), the Iford Dome (H) and the Patcham Court Farm Fracture Zone/Fault (I).
The Caburn Syncline extends for approximately 11 km. Its axis is located to the east of the Patcham Catchment and is orientated WSW-ENE. It starts in north east Brighton and continues to Lewes. Although the axis of this structure does not cross into the Patcham Catchment, it leads to south-east dip of strata on the north-west edge of the catchment.

4.3.2 Catchment Structural Geology

The Hollingbury Dome extends for approximately 3 km. The Brighton and Worthing sheet (318/333) (British Geological Survey, 2006a) shows the axis to be located at the Lewes Nodular Chalk Formation inlier and be WSW-ENE orientated (Figure 4.13 and Figure 4.14). The structure contours produced from the new data collected, however, indicate the axis is slightly further south and is NW-SE orientated. Despite its relative short axis length, it has an amplitude of 76 m (Mortimore, 2011). Mortimore and Pomerol (1991a) indicated that this structure lies on top of a basement horst structure. It is bounded on the northeast flank by the Coldean Lane Fault and on the south-east flank by the Lewes Road Fault. The structure contours presented in Figure 4.13 and Figure 4.14 indicate that the Hollingbury Dome leads to a radial dip of the strata – from north-west to west to south-west – on the central western edge of the Patcham Catchment.

The Patcham Syncline extends for 3 km (Figure 4.13 and Figure 4.14). The Brighton and Worthing sheet (318/333) (British Geological Survey, 2006a), shows the axis to be located in Patcham and orientated ENE-WSW. The structure contours produced from the data collected, however, indicate the axis is orientated NE-SW. It has formed between the Pyecombe Anticline, located to the north and north-east, and the Hollingbury Dome, located to the east and south-east.

The Patcham Court Farm Fracture Zone/Fault was observed at the Patcham Court Farm road cutting during construction of the A27 Brighton Bypass by Mortimore (1993) and Lamont-Black (1995) (Figure 4.15). Mortimore (1993) interpreted the zone of intense fracturing as having been formed by high water pressure along a fault which would have subsequently developed dissolution cavities and been infilled with residual Palaeogene and Quaternary sediments. Mustchin (1974), while describing the older system of headings at Waterhall, highlighted that the greater part of the yield was from a fissure in the east heading which is located about 750
Figure 4.14 Structure contours on the New Pit and Lewes Chalk Formation boundary based on interpolation from key boreholes and locations in the Patcham Catchment. For presentation purposes, fissures intersected in the Patcham Waterhall Pumping Station adits are given a nominal extent of 100 m orthogonal to the adit alignment. Geological map adapted from British Geological Survey (2006a). (OS Mapping © Crown Copyright 2007). Labels as for Figure 4.13.
Figure 4.15 Centre-line long section through Patcham Court Farm A27 Brighton Bypass road cutting showing fracture zones and the distribution of CIRIA chalk grades from Lamont-Black (1995). The fracture zone/fault and collapsed cave system observed at the Patcham Court Farm cutting by Mortimore (1993) and Lamont-Black (1995) is situated above a significant fissure in the east heading adit from the Patcham Waterhall Pumping Station (Mustchin, 1974).

yards (685.8 m) east of the winding shaft and almost immediately under the ridge running south, parallel to and east of the London Road valley. This fissure is located almost directly below the fracture zone/fault observed in the Patcham Court Farm cutting (Figure 4.14 - label l). Although the lateral extent of this fracture zone/fault is unknown, the elevation of the east heading adit is approximately 5 m OD and the elevation of the ground surface at the Patcham Court Farm cutting is approximately 80 m OD indicating that the vertical extent of the fracture zone/fault is approximately 75 m.

The Coldean Lane Fault extends for 2.5 km (Figure 4.13 and Figure 4.14). The Brighton and Worthing sheet (318/333) (British Geological Survey, 2006a) shows this fault to be orientated NW-SE. The fault lies just outside of the Patcham Catchment but follows the same azimuth as the Pyecombe Anticline – indicating there may be some connectivity between these structures (Figure 4.13 and Figure 4.14).
4.3.3 Fracture Analyses

4.3.3.1 Methodology

Fracture data were derived from optical televviewer surveys of key boreholes in the Patcham Catchment. The optical televviewer sonde records the borehole azimuth, dip and a continuous 360° orientated high resolution image of the borehole walls (Figure 4.16). A gyroscope, contained within the sonde, is used to record orientation data for the sonde and image. The optical televviewer can be run in both air-filled and clear water-filled boreholes. Four boreholes in the Patcham Catchment were logged using this equipment for the FLOOD1 project. These boreholes were North Heath Barn, Casterbridge Farm, North Bottom and Lower Standean. These surveys were undertaken by European Geophysical Services and the BGS in collaboration with the University of Brighton. Fracture orientation data (dip and dip direction) were determined from the optical televviewer images using specialist geophysical software such as WellCAD produced by Advanced Logic Technology. Within this software a sinusoidal curve was fitted to a dipping feature in the borehole wall such as a bedding plane or a fracture (Figure 4.16). The software, knowing the orientation of the image, then calculates the dip and dip direction for the curve fitted to the feature.

4.3.3.2 Results and Discussion

The results from the optical televviewer surveys are presented in Figure 4.17 and Figure 4.18 as lower hemisphere equal area stereographic projections of poles to planes and discontinuity spacing histograms respectively. A summary of the typical Chalk rock mass and fracture characteristics is also presented in Table 4.3. The Fisher concentrations displayed on the stereographic projections have been adjusted for directional bias using a Terzaghi Weighting with a minimum angle of 15° (Terzaghi, 1965; Priest, 1993; Anon, 1999b). The discontinuity spacing are presented separately on histograms. The discontinuity spacing categories are based on BSI (2003), the first five categories of which are also equivalent to suffix 1-5 of the CIRIA chalk grades (Lord et al., 2002) (Table 2.4).

The fracture results for the Patcham Catchment highlighted a number of characteristics of the chalk rock mass. The results show a change in the angle of fracturing in relation to stratigraphy. The formations which were surveyed were the
West Melbury Marly, Zig Zag, Holywell Nodular, New Pit and the Lewes Nodular Chalk Formations.

Figure 4.16 Illustrates an example of the optical televiewer image for the Casterbridge Farm borehole. Sinusoidal curves fitted to fractures are shown in red.

1. Borehole wall scanned by optical televiewer sonde. Image orientation is recorded by gyroscope in sonde.
2. Software is used to fit a sinusoidal curve wave to discontinuities observed in the image.
3. Dip angle and direction are then derived from the sinusoidal curve.
Only the entire vertical extent of the Holywell Nodular and New Pit Chalk Formations were surveyed in any one borehole.

The optical televiewer fracture data highlighted that low angle inclined fractures (~0-40°) may be dominant in some formations whereas in other formations both low and inclined fractures (~60-80°) were present. In particular, West Melbury, Zig Zag, and the lower Lewes Nodular Chalk Formation showed a dominance of low angle inclined fractures. The New Pit and Holywell Chalk Formations, however, were found to contain both low and high angle inclined fractures. The difference in fracturing styles between the Chalk Formations can be seen in Figure 4.18 and Figure 4.19. In Figure 4.19, the inclined fracture of the New Pit Chalk Formation can be clearly differentiated from the lower Lewes Nodular Chalk Formation. This change can be observed in both the borehole core fracture log and the optical televiewer fracture log. There was, however, a difference observed between the borehole core fracture log and the optical televiewer fracture log above the Bridgewick Marl. The borehole core fracture log shows an increase in inclined fractures above this marker horizon whereas the majority of these fractures have not been identified in the optical televiewer fracture log. This demonstrates that the Lewes Chalk could be mis-characterised as being dominated by sub-horizontal fractures when using televiewer data alone.

The fracture strikes were not found to display a strongly preferred orientation but commonly NW-SE, with less strong NE-SW, E-W and N-S, orientations were observed. A NW-SE orientation is consistent with the orientation of the axis of the Pyecombe Anticline, the Henfield Syncline and the Coldean Lane Fault within the Patcham Catchment. Outside of the Patcham Catchment, within the South Downs, there are many large structures which have a stronger E-W component to their orientation (Figure 4.13). It is interesting to note that the borehole which displayed perhaps the strongest NW-SE orientation to the fractures was Lower Standean which is located directly on the same azimuth as the axis of Pyecombe Anticline and the strike of the Coldean Lane Fault (Figure 4.14 and Figure 4.16). The fractures observed in the Lower Standean borehole during the survey were also well developed and many appeared to have been widened by dissolution - see Molyneux (2012) for further details.
Figure 4.17 Stereographic projections and fracture spacing histograms of fracture measurements from borehole optical televiewer surveys of Casterbridge Farm, North Heath Barn, North Bottom and Lower Standean.
Figure 4.18 Stereographic projections of borehole optical televiewer fracture measurements by borehole and formation. Fracture measurements are plotted as poles to planes. Note: West Melbury Marly Chalk in North Bottom is not shown due to limited data.
<table>
<thead>
<tr>
<th>ID</th>
<th>Total No. Scanslines</th>
<th>Total Scansline Length (m)</th>
<th>Total No. Fractures</th>
<th>Scansline Orientation</th>
<th>B/C No.</th>
<th>Typical Chalk Rock Mass Characteristics Per BH</th>
<th>Typical Fracture Characteristics Per BH</th>
<th>Stage/Substage</th>
<th>UK Lithostratigraphy</th>
<th>No. Fractures Per Fm</th>
<th>Typical Chalk Rock Mass Characteristics Per BH</th>
<th>Typical Fracture Characteristics Per Survey Per Fm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Casterbridge Farm</td>
<td>1</td>
<td>56.81</td>
<td>44</td>
<td>Vertical</td>
<td>B/C 1</td>
<td>I (~60 - 80°)</td>
<td>Main: NE-SW, E-W Weak: NW-SE</td>
<td>Middle - Upper Turonian</td>
<td>Lewes Nodular Chalk Fm</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Middle Turonian</td>
<td>New Pit Chalk Fm</td>
<td>11</td>
<td>B/C (2) (M) As per BH</td>
<td>E-W, NW-SE more common</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SH-LAI (~10 - 40°)</td>
<td></td>
<td>Upper Cenomanian - Lower Turonian</td>
<td>Holywell Nodular Chalk Fm</td>
<td>22</td>
<td>B/C 1 (W) As per BH</td>
<td>E-W, NW-SE more common</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Middle - Upper Turonian</td>
<td>Zig Zag Chalk Fm</td>
<td>11</td>
<td>B/C 1 (W) As per BH</td>
<td>As per BH</td>
</tr>
<tr>
<td>North Heath Barn 2</td>
<td>1</td>
<td>65.69</td>
<td>18</td>
<td>Vertical</td>
<td>B/C 1 (VW)</td>
<td>I (~60-80°)</td>
<td>Main: NW-SE Weak: N-S, E-W, NE-SW</td>
<td>Middle - Upper Turonian</td>
<td>Lewes Nodular Chalk Fm</td>
<td>3</td>
<td>B/C 1 (VW) SH-LAI only</td>
<td>As per BH</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SH-LAI (~15-40°)</td>
<td></td>
<td>Middle Turonian</td>
<td>New Pit Chalk Fm</td>
<td>15</td>
<td>B/C 1 (VW) As per BH</td>
<td>NW-SE, N-S Weak: NE-SW</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lower Turonian</td>
<td>Holywell Nodular Chalk Fm</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>North Bottom</td>
<td>1</td>
<td>129.52</td>
<td>82</td>
<td>Vertical</td>
<td>B/C 2 (M)</td>
<td>I (~60-80°)</td>
<td>Main: NW-SE, E-W, N-S</td>
<td>Middle - Upper Turonian</td>
<td>Lewes Nodular Chalk Fm</td>
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<td>NW-SE, E-W only</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td>SH-LAI (~6-40°)</td>
<td></td>
<td>Middle Turonian</td>
<td>New Pit Chalk Fm</td>
<td>40</td>
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<td>As per BH, also NE-SE</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Upper Cenomanian - Lower Turonian</td>
<td>Holywell Nodular Chalk Fm</td>
<td>17</td>
<td>B/C 2 (M) As per BH</td>
<td>As per BH</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Middle - Upper Turonian</td>
<td>Zig Zag Chalk Fm</td>
<td>20</td>
<td>B/C 1 (VW) As per BH</td>
<td>As per BH</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lower - Middle Cenomanian</td>
<td>West Melbury Chalk Fm</td>
<td>1</td>
<td>B/C - I NE-SW</td>
<td></td>
</tr>
<tr>
<td>Lower Standean</td>
<td>1</td>
<td>54.63</td>
<td>26</td>
<td>Vertical</td>
<td>B/C 1</td>
<td>I (~60-80°)</td>
<td>Main: NW-SE Weak: NE-SW</td>
<td>Middle - Upper Turonian</td>
<td>Lewes Nodular Chalk Fm</td>
<td>6</td>
<td>B/C 1 (VW) As per BH</td>
<td>As per BH</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Middle Turonian</td>
<td>New Pit Chalk Fm</td>
<td>18</td>
<td>B/C 1 (W) As per BH</td>
<td>As per BH, also N-S, E-W</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lower Turonian</td>
<td>Holywell Nodular Chalk Fm</td>
<td>2</td>
<td>B/C 1 (W) As per BH</td>
<td>As per BH</td>
</tr>
</tbody>
</table>

Table 4.3 Summary of typical Chalk rock mass and fracture characteristics from the borehole televiewer surveys in the Patcham Catchment. Fracture sets classified by dip range are: SH-LAI = sub-horizontal to low angle inclined, I = inclined. BSI (2003) spacings are: M = medium, W = Wide, VW = Very Wide.
These observations provided evidence to support the idea that the Pyecombe Anticline and the Coldean Lane fault may be structurally connected. In addition, although the methods of investigation meant it was not possible to inspect the fractures for displacement, the presence of hardened slickensided chalk brash (Figure 3.10) and well-developed NW-SE orientated fractures on the axis of this anticlinal structure would generally suggest a zone of extension. If the palaeo-stresses affecting these fractures are assumed to be related to the orientation of the folds, \( \sigma_1 \) and \( \sigma_2 \) would be orientated either NE-SW or NW-SE and \( \sigma_3 \) vertical.

The stereonets for Casterbridge Farm, North Heath Barn and North Bottom show a high proportion of low angle inclined fractures. Optical televiewer surveys, however, inherently induce directional bias. They may be considered as equivalent to vertical scanline surveys and are most likely to sample fractures which are orthogonal to the survey direction and least likely to sample fractures which are parallel to the survey direction. They, therefore, have a higher probability of intersecting sub-horizontal or low angle fractures than high angle fractures. The data collected from these boreholes are therefore likely to have a high proportion of low angle inclined fractures due to this sampling bias. The Fisher concentrations displayed on the stereographic projections have been adjusted for this bias as described previously. The results from optical televiewer fracture survey and associated limitations are discussed further in Section 4.4.4.

The most common fracture spacing measured in the boreholes was wide spaced or CIRIA grade suffix 1 (Table 4.3). There was, however, variation between boreholes and between formations within boreholes. The fracture spacing of medium spaced or CIRIA grade suffix 2 and very wide spaced, also equivalent to CIRIA grade suffix 1, were both common. The most commonly observed fracture spacing in the Zig Zag Chalk Formation (Table 4.3), measured in Casterbridge Farm and North Bottom, was wide spaced (CIRIA grade suffix 1) and very wide spaced (CIRIA grade suffix 1). The most commonly observed fracture spacing in the Holywell Chalk Formation (Table 4.3), measured in Casterbridge Farm and North Bottom, was medium spaced (CIRIA grade suffix 2) and wide spaced (CIRIA grade suffix 1). The most commonly observed fracture spacing in the New Pit Chalk Formation, measured in Casterbridge Farm, North Heath Barn, North Bottom and Lower
Standean, was medium spaced (CIRIA grade suffix 2), wide spaced and very wide spaced (CIRIA grade suffix 1).

Figure 4.19 Lithostratigraphical and fracture logs for North Heath Barn 2. Note the disparity in the number of fractures identified in the core fracture log in comparison to the optical televiewer log.
Figure 4.20 OS Landform Profile digital terrain model for the Patcham Catchment with valley axes, structure contours and rose diagrams of fracture strikes from the surveyed boreholes. (OS Mapping © Crown Copyright 2007)
The most commonly observed fracture spacing in the Lewes Nodular Chalk Formation, measured in North Heath Barn and Lower Standean, was very wide spaced (CIRIA grade suffix 1). These fracture measurements indicated that the Holywell and New Pit Chalk Formations represent more densely fractured units between the less densely fractured Zig Zag and lower Lewes Nodular Chalk Formations. The implications of the fracture spacing data from the Patcham Catchment is considered further, with regard to hydrogeology, in Section 4.4.4.

For comparison with the Hallue Catchment, and to build on data presented by Lamont-Black (1995) and Mortimore (2012), rose diagrams of the fracture strikes from the optical televiewer surveys are shown in Figure 4.20 with lines marking the valley axis azimuth. Visually the strikes of the fractures measured in the boreholes and the valley axes in the Patcham Catchment do seem to have similar orientations (Figure 4.20). The NW-SE and opposing NE-SW trends seen in the fracture strikes are also present in the valley orientations despite the scatter seen in the fracture orientations from the low angle inclined fractures. There also seems to be a slight change in the dominant orientation of the fracture strikes to NE-SW and E-W in the Casterbridge Farm and, to a lesser extent, North Heath Barn boreholes. This may be due to their position on the southern limb of the Pyecombe Anticline, relative to the positions of Lower Standean and North Bottom which are on or north of the axis.

Further to the fracture data measured from optical televiewer surveys, a detailed fracture log was made of the borehole core for North Heath Barn. Although it was not possible to measure the dip direction of fractures from the borehole core, the dip of the fractures could be measured and these are plotted against the lithological log and the fracture dips from the optical televiewer in Figure 4.19. It was clear from this figure that there is a significant difference in the number of fractures measured in the optical televiewer from that observed in the borehole core. This may be considered a result of how the two datasets were acquired; the optical televiewer images the in-situ rock in the borehole wall whereas the borehole core is a drilled sample. The optical televiewer, which requires some contrast to imagine a fracture, is likely to only image fractures which have an aperture greater than a pixel in size thereby missing closed fractures. The drilling process, however, may cause the core to break along these pre-existing closed discontinuities. The optical televiewer
image quality may also be impeded by the clarity of the medium the sonde is in. If the water is cloudy, the image quality may not be good enough to differentiate some fractures in the image.

4.4 Comparison and Discussion

4.4.1 Statistical Tests

A series of statistical hypothesis tests were undertaken to evaluate the relationship between the structural data collected at different scales within the two research catchments and to compare the structural data between the research catchments. It was thought that this comparison would aid conceptualisation of the relationship of structures within the Chalk at a local and regional scale. The tests chosen were used to evaluate the equivalency of two datasets in terms of orientation and indicate whether the data was likely to have originated from the same population. Datasets which were tested comprised vein fabric, fracture, structure (fold and fault) and valley orientation measurements. The tests, which were derived from Davis (1986) and Mardia (1972) and are based on Watson-Williams' tests, involved calculating the vector resultant length ($R$) (Figure 4.21 B-D) and mean vector resultant length ($\bar{R}$) for each of two datasets being compared and then the combined data from both datasets. These values were then used to derive a set of statistics for comparison and hypothesis testing. The type of hypothesis test and test statistic calculated was dependant on the mean vector resultant length. The data and tests were separated into the circular tests and spherical tests. Circular tests are used to test the equivalency of 1 dimensional data such as azimuth, strike or dip direction. Spherical tests are used to test the equivalency of 2 dimensional data such as dip and strike or dip and dip direction. The vector resultant length ($R$) and mean vector resultant length ($\bar{R}$) were calculated for circular tests as follows:

$$R = \left( \frac{\sum_{i=1}^{n} \cos \theta_i}{\sqrt{\sum_{i=1}^{n} \sin \theta_i}} \right)^{0.5}$$

$$\bar{R} = \frac{R}{n}$$

Where $n$ is the number of observations and $\theta$ is the directional angle. For the circular tests conducted, the directional angle was strike.
Figure 4.21 Vector resultant length \( R \) used in statistical hypothesis testing. A illustrates three unit vectors and B the vector resultant (red arrow) obtained by combing the three unit vectors. C and D illustrate the effect of low dispersion and high dispersion respectively on the vector resultant length. E-G illustrated the effect of doubling the angular direction from a bimodal dataset to obtain the mean direction. E shows the vector resultant is short due to dispersion and the mean direction unrepresentative. F shows the orientation measurements plotted as vector directions after angles are doubled. G shows orientations re-plotted at original angles with true resultant direction.
The vector resultant length \((R)\) and mean vector resultant length \((\bar{R})\) were calculated for spherical tests as follows:

\[
R = \left\{ \left( \sum_{i=1}^{n} \sin \theta_i \cos \phi_i \right)^2 + \left( \sum_{i=1}^{n} \sin \theta_i \sin \phi_i \right)^2 + \left( \sum_{i=1}^{n} \cos \theta_i \right)^2 \right\}^{0.5}
\]

\[
\theta = 90° + D, \quad \phi = 360° - A
\]

\[
\bar{R} = \frac{R}{n}
\]

Where \(n\) is the number of observations, \(D\) is inclination and \(A\) is the directional angle. For the spherical tests conducted, the inclination was dip and the directional angle was dip direction.

For both the circular and spherical tests, if \(\bar{R}\) for the combined data of the two samples was less than 0.7 the test statistic calculated was \(\bar{R}'\) and if it was greater than 0.7 the test statistic calculated was \(F\). These test statistics \(\bar{R}'\) and \(F\) are calculated as follows:

**Circular**

\[
\bar{R}' = \frac{(R_1 + R_2)}{n}
\]

\[
F_{1,n-2} = \left( 1 + \frac{3}{8\kappa} \right) \frac{(n-2)(R_1 + R_2 - R_p)}{(n-R_1-R_2)}
\]

**Spherical**

\[
\bar{R}' = \frac{(R_1 + R_2)}{n}
\]

\[
F_{2,2n-2} = \frac{(n-1)(R_1 + R_2 - R_p)}{(n-R_p)}
\]

where \(R_1\) is the resultant length calculated for the first dataset which is smaller or equal to \(R_2\); \(R_2\) is the resultant length calculated for the second dataset; \(R_p\) is the resultant length calculated for the combined or pooled data from \(R_1\) and \(R_2\); \(n\) is the number of observations for the pooled data and \(\kappa\) is a concentration parameter which is estimated from \(\bar{R}\) for the pooled data using a table provided in Davis (1986).
The critical values of $R'$ and $F$, which the calculated values are compared against, are provided in tables and appendices in Davis (1986) and Mardia (1972). The level of significance for all test was taken at 5% ($\alpha = 0.05$), which was the most conservative value, the one most likely to reject the null hypothesis, based on the tables and appendices provide in Davis (1986) and Mardia (1972). For all tests performed, the null hypothesis was that the mean directions of the two sample datasets were equal ($H_0: \theta_1 = \theta_2$) and the alternative hypothesis was that the mean directions of the two sample datasets were unequal ($H_1: \theta_1 \neq \theta_2$). The results of these tests provided an indication as to whether the data from the two datasets being compared belonged to the same population or were derived from different populations. As the tests were used to compare various structural data, the assumption can be made that if the null hypothesis was not rejected then the datasets may have formed as a result of the same tectonic processes and stress regimes or that the datasets have influenced the formation of each other. The results from these tests are summarised in Table 4.5.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Vector Resultant Length ($R$)</th>
<th>Mean Vector Resultant Length ($\bar{R}$)</th>
<th>Mean Direction ($\theta$)</th>
<th>Concentration Parameter ($\kappa$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>Hallue vein fabric</td>
<td>25.35</td>
<td>31.57</td>
<td>0.67</td>
<td>0.72</td>
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<td></td>
<td>78.37</td>
<td>0.96</td>
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<td>12.7661</td>
</tr>
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<td>Hallue fractures</td>
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<td>186.98</td>
<td>0.67</td>
<td>0.77</td>
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<td></td>
<td>320.90</td>
<td>0.79</td>
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</tr>
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<td>14.91</td>
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<td>0.88</td>
</tr>
<tr>
<td>Hallue valley axes</td>
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<td>64.76</td>
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<td>0.63</td>
</tr>
<tr>
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<td>132.46</td>
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<td>Patcham valley axes</td>
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<td>97.84</td>
<td>0.68</td>
<td>0.64</td>
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</table>

Table 4.4 Parameters calculated for statistical hypothesis tests. Values in columns A and B were calculated for circular tests where A is the subset of data which falls in the quadrants 0-89°/180-269° and B is the subset which falls in the quadrants 90-179°/270-359°. Values in italics were calculated for spherical tests. The greater the value of $R$ and $\kappa$ the smaller the dispersion of the dataset.
For each of the circular tests, two test statistics were calculated - Table 4.4 and Table 4.5 columns A and B. This was because the circular test requires a von Mises distribution, equivalent to a normal distribution for directional data, which is unimodal. Orientation data, however, typically has a bimodal distribution because an orientated feature can be expressed as either of two opposite directions. Krumbein (1939) and Davis (1986) present a simple method for converting bimodal orientation data to unimodal by doubling the angle e.g. two orientations measurements of 45° and 225° become 45° x 2 = 90° and 225° x 2 = 450°, 450° - 360° = 90°. The effect of this method is illustrated graphically in Figure 4.21 E-G.

The stereographic projections of the fracture and fabric data highlighted four areas of pole concentration which represent the two dominant orientations of the data - NW-SE and NE-SW. These two dominant orientations may be considered as two separate bimodal distributions and in order to test them the orientation data for the circular tests were separated into two subsets. These subsets consisted of the data present in the opposing quadrants 0-89°/180-269° and 90-179°/270-359°.

<table>
<thead>
<tr>
<th>Test No</th>
<th>Comparison</th>
<th>Test Type</th>
<th>Test Statistic Calculated</th>
<th>Critical Value</th>
<th>Null Hypothesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hallue Fabr vs Frac</td>
<td>Circular</td>
<td>$R' = 0.67, F = 0.1$</td>
<td>$R' = 0.68, F = 3.87$</td>
<td>FTR, FTR</td>
</tr>
<tr>
<td>2</td>
<td>Hallue Struc vs Frac</td>
<td>Circular</td>
<td>$R' = 0.68 (R' = 0.67), F = 6.44 (F = 2.99)$</td>
<td>$R' = 0.68 (R' = 0.67), F = 3.88 (F = 3.88)$</td>
<td>FTR (FTR), R (FTR)</td>
</tr>
<tr>
<td>3</td>
<td>Patcham Struc vs Fract</td>
<td>Circular</td>
<td>$R' = 0.65, R' = 0.67$</td>
<td>$R' = 0.66, R' = 0.68$</td>
<td>FTR, FTR</td>
</tr>
<tr>
<td>4</td>
<td>Hallue Vall vs Frac</td>
<td>Circular</td>
<td>$R' = 0.67, F = 0.67$</td>
<td>$R' = 0.67, F = 3.87$</td>
<td>FTR, FTR</td>
</tr>
<tr>
<td>5</td>
<td>Patcham Vall vs Frac</td>
<td>Circular</td>
<td>$R' = 0.67, R' = 0.66$</td>
<td>$R' = 0.68, R' = 0.65$</td>
<td>FTR, R</td>
</tr>
<tr>
<td>6</td>
<td>Patcham vs Hallue Struc</td>
<td>Circular</td>
<td>$R' = 0.69, F = 2.06$</td>
<td>$R' = 0.71, F = 4.20$</td>
<td>FTR, FTR</td>
</tr>
<tr>
<td>7</td>
<td>Patcham vs Hallue Frac</td>
<td>Circular</td>
<td>$R' = 0.67, F = 0.96$</td>
<td>$R' = 0.67, F = 3.87$</td>
<td>FTR, R</td>
</tr>
<tr>
<td>8</td>
<td>Hallue Fabr Vs Frac</td>
<td>Spheric</td>
<td>$F = 1.08$</td>
<td>$F = 3.00$</td>
<td>FTR</td>
</tr>
<tr>
<td>9</td>
<td>Patcham vs Hallue Frac</td>
<td>Spheric</td>
<td>$F = 4.76$</td>
<td>$F = 3.00$</td>
<td>R</td>
</tr>
</tbody>
</table>

Table 4.5 Results from statistical hypothesis tests on structural data from the Hallue and Patcham catchments. Abbreviations are as follows: Fabr = fabric data, Frac = fracture data, Struc = fold or fault axis data, Vall = valley axis data, FTR = failed to reject null hypothesis, R = reject null hypothesis

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4.4.2 Folding

The stratigraphical data collected from the research catchments was used to produce structure contours (Figure 4.2 and Figure 4.14). These structure contours showed that the research catchments were intersected by both large-scale regional fold structures and contained smaller local fold structures. The orientation of the axes of these structures were found to be similar in both the research catchments – typically NW-SE, NE-SW and E-W. These fold structures have the form of en echelon periclines. The orientation of the axes of these fold structures are believed to relate to Variscan basement structures which were reactivated and inverted as result of the Subhercynian, Laramide and Alpine phases of compression (Figure 2.2 and Figure 2.3) beginning in the Upper Cretaceous and continuing into the Cenozoic. (Mortimore and Pomerol, 1991a; Mortimore and Pomerol, 1997; Mortimore et al., 1998).

The larger scale folds, of the Pyecombe Anticline, Henfield Syncline and Caburn Syncline, which intersect the Patcham Catchment are WNW-ESE and ENE-WSW orientated whereas the smaller scale folds, of the Hollingbury Dome and Patcham Syncline, are NW-SE and NE-SW orientated. A similar relationship exists in the Hallue Catchment where the large scale folds, of the Ponthieu Anticline and Somme Syncline, are WNW-ESE or E-W orientated and the smaller scale folds, of structures E and H, are NW-SE and NE-SW orientated. This difference in orientation of folds of different scales is likely to related to faults of different scales within the basement (Mortimore and Pomerol, 1991a). Statistical tests (Table 4.5 test 6A-B) were undertaken to compare the orientation of fold and fault axes between the research catchments. These tests failed to reject the null hypothesis, that the mean directions of the two sample datasets were equal, which supports the observation that the structures showed similar trends in both research catchments.

The length of the axes of the small scale folds is similar between the research catchments but the large folds tend to have shorter axes in the South Downs than in the Somme. The ratio of the amplitudes to axis length of the folds in the South Downs and the Patcham Catchment, however, tends to be greater than that of the Somme and the Hallue Catchment. For example, the Pyecombe Anticline is 300 m/30 km and the Caburn Syncline is 110 m/11 km whereas the Ponthieu Anticline
is 130 m/75 km and the Somme Syncline is 80 m/110 km. This difference may be due to the Patcham Catchment being located in the South Downs on the flanks of the Weald-Artois Anticline – a large inversion structure.

These fold structures affect the entire Chalk sequence in both research catchments. The elevation of the base of the Chalk aquifer is controlled by these structures. The changes in elevation of the base of the aquifer caused by these structures will influence the direction of groundwater flow – with anticlines potentially acting as groundwater drainage divides and synclines acting as sub-catchments. The occurrence of ground water in both research catchments is further influenced by the inter-relationship between the fold structures and the geomorphology of the research catchments. In the Hallue Catchment, where the Hallue river crosses the Ponthieu Anticline axis the active aquifer thins. The consequence of this is the occurrence of groundwater at the surface in the form of springs and wetland. In the Patcham Catchment, with the exception of the Pyecombe Anticline which has eroded inwards from the escarpment, much of the geomorphology mirrors or is concordant with the geological structures. For example, Hollingbury is on an interfluve and Patcham in a dry valley which mirrors the Hollingbury Dome and Patcham Syncline. This influence of structure on geomorphology means that based on the typical form of the water table, Patcham is relatively the lowest elevation in the landscape and first intercepted at high groundwater levels - leading to groundwater emergence or flooding. This relationship is discussed further in Chapter 7 – Section 7.7

### 4.4.3 Faulting

Within the research catchments, faulting is only confirmed to exist in the Patcham Catchment although structure I in the Hallue Catchment may be a fault or related to faulting as indicated by Dupuis et al. (1972a). If Structure I is regarded as a fault, the length of the fault traces would be similar between the two research catchments. The maximum displacements due to faults in the Patcham Catchment, however, are greater than the amplitude of Structure I in the Hallue Catchment. The Coldean Lane Fault on the edge of the Patcham juxtaposes the Newhaven against the Lewes Chalk Formation – which is a displacement equivalent to the full thickness of the Seaford Chalk Formation and approximately 70 m (Mortimore and Pomerol, 1991a).
4.4.4 Fracturing

Data collected in the research catchments from exposures and boreholes was used to evaluate whether there were changes in the characteristics of fracturing through the Chalk sequence. It was observed from these data that some characteristics vary between stratigraphical units - such as dip and fracture spacing. To a lesser extent aperture and persistence also display a relationship to stratigraphy. These observations agreed with Mortimore (2001a; 2004; 2011) and are thought to be associated with changes in the lithological properties of a unit which, in turn, relates to syn-sedimentary processes.

The orientations of fractures from both research catchments, similarly to the fold axes, had a NW-SE, NE-SW and E-W orientation. The similarity of orientations between the fold axes and the fractures indicate they formed from the same tectonic stresses. Statistical tests (Table 4.5 tests 2A-B and 3A-B) were undertaken to compare the orientations of the fractures and the fold axes in both the Hallue and Patcham Catchment. With the exception of test 2B, these tests failed to reject the null hypothesis, that the mean directions of the two sample datasets were equal, which supports the observation that the fractures show similar trends to the large scale folds in the catchments. These tests incorporated structure axis orientation data from the wider region, outside of the research catchments, as shown in Figure 4.1 and Figure 4.13. To evaluate the effect of the region data on test 2B, the test was repeated but only incorporating the structure axis orientation data from inside the Hallue Catchment. The results of the repeated test are presented in parenthesis in Table 4.5. In the repeated test, the null hypothesis was not rejected which indicates that the fractures with a NW-SE orientation in the Hallue Catchment have a stronger relationship to the local fold structures than the regional fold structures.

In addition to fracturing data, large field samples were collected in the Hallue Catchment to measure the orientation of vein fabrics. The vein fabric data was plotted on the fracture stereographic projections for each exposure where both were measured (Figure 4.4) and the complete vein fabric data and fracture data were plotted on stereographic projections and histograms for comparison (Figure 4.11). Both the vein fabric and fracture datasets displayed similar NW-SE, NE-SW and E-W orientations. The dip or inclination of the vein fabrics and fractures were also
found to be similar – with the exception that no sub-horizontal vein fabrics were measured. Statistical tests (Table 4.5 tests 1A-B and 8) were undertaken to compare the orientations of the vein fabric and fracture datasets. Test 1A-B were circular tests and test 8 was a spherical test. The tests failed to reject the null hypothesis, that the mean directions of the two sample datasets were equal, which supports the observation that the vein fabric showed similar trends and inclinations to the fractures. Mortimore (2011) demonstrated that vein fabrics formed as a result of deformation and fluid escape in the soft Chalk sediment prior to lithification. This suggests that similar stress fields affected the Chalk during deposition which continued to affect the Chalk after lithification. It also supports the ideas of Mortimore (1979; 1991a; 1996; 2001a) that some fractures and/or faults are syn-sedimentary. Chalk vein fabrics, therefore, maybe considered as indicators of the larger scale fracture characteristics.

The dominant fracture orientations, NW-SE and NE-SW with components of N-S and E-W, measured in the Hallue Catchment and Patcham Catchment are consistent with those recognised in the Chalk of northern France and southern England by other workers e.g. Bevan and Hancock (1986), Hibsch et al. (1993; 1995; 2003), Bergerat and Vandycke (1994), Vandycke and Bergerat (2001), Vandycke (2002), Mortimore (1979, 1993, 2001a, 2011, 2012). While these authors generally recognised similar fracture and fault trends within the Chalk, their interpretations of the palaeo-stress history affecting the Chalk differ. Bevan and Hancock (1986) associated the E-W trends with Oligocene to Early Miocene deformation and the NW-SE trends with later NE-SW oriented extension in response to late Neogene to recent NW-SE Alpine convergence. They did not recognise tectonic activity during the deposition of the Chalk. Vandycke (2002), Hibsch et al. (1993; 1995; 2003), Mortimore and Pomerol (1991a; 1997) and Mortimore et al. (1998), however, did recognise an early stage and penecontemporaneous genesis to fractures and faults in the Chalk. Vandycke (2002) concluded that most trends related to regional extension with periodic episodes of compression. They separated the region into geographical areas with varying palaeo-stress histories. These can be generalised as N-S extension in the Lower Cretaceous, NW-SE and E-W extension in the Campanian, NW-SE and NE-SW dextral strike-slip associated with the Laramide (Figure 2.2) phase of compression in the Lower Maastrichtian and E-W,
N-S, NW-SE and NE-SW extension from the Palaeogene to Recent with a period of strike-slip in Sussex during the Palaeogene. Hibsch et al. (1993; 1995; 2003) emphasised the radial nature of faults in the Chalk and attribute them to non-tectonic extension related to compaction of the early stage sediments. They indicated these structures were then exploited by subsequent phases of Middle Paleocene/Early Eocene Laramide NW-SE oriented and Middle Eocene/Early Miocene N-S oriented transpressional strike-slip. Mortimore (1979, 1993, 2001a, 2011, 2012) also recognised the radial nature of the fracture and faults in the Chalk but, using detailed lithostratigraphy, demonstrated changes in the Chalk sediments and fracturing are closely associated with periclinal folds - indicating an early stage penecontemporaneous development of folds and fractures. Mortimore and Pomerol (1997) and Mortimore et al. (1998) dated the occurrences of these features through the Chalk sequence and related them to Subhercynian tectonic compression phases (Figure 2.3), recognised by Stille (1924), Voigt (1963) and Ziegler (1975a; 1975b; 1987, 1990), which led to the initiation of transpressional strike-slip and inversion along Variscan basement structures. In general terms, these basement structures have a NW-SE orientation in northern France and a WNW-ESE orientation in southern England (Figure 2.1 and Figure 2.8). The episodic growth of these periclinal folds is likely to have led to winnowing of sediments and extension over the crests, slumping and compression in the troughs and a radial fracture pattern (Mortimore, 2011). This is generally consistent with observations in the research catchments. Slickensided fractures were observed in synclinal areas in the Hallue Catchment, and hardened slickensided chalk brash (Figure 3.10) and enlarged fractures were observed on the crest of anticlinal areas in the Patcham Catchment. In both research catchments, the generalised palaeo-stress orientations were interpreted as varying between NE-SW, NW-SE and E-W for $\sigma^1$ and $\sigma^2$ and vertical for $\sigma^3$. The age of the chalks which contained these features are Upper Turonian, Middle Santonian and Lower Campanian in the Hallue Catchment and Middle Turonian, Lower and Middle Coniacian in the Patcham Catchment. The age of the features observed in the Hallue Catchment correspond to the Ilsede and Wernigerode compressional tectonic phases (Mortimore and Pomerol, 1997; Mortimore et al., 1998).
The fractures measured in the Patcham Catchment displayed greater dispersion and lower average dip than the fractures measured in the Hallue Catchment (Figure 4.22). Statistical tests (Table 4.5 tests 7A-B and 9) were undertaken to compare the fracture datasets from the Hallue and the Patcham Catchment. Test 7A-B were circular tests and test 9 was a spherical test. With the exception of test 7A, the tests rejected the null hypothesis, that the mean directions of the two sample datasets were equal, which indicates that the fracture datasets are not from the same population. Test 7A, which compared NE-SW striking fractures, only just failed to reject the null hypothesis as the test statistic and critical value were equal. This difference may be due to regional differences in tectonic stresses during formation or the difference in methods used to collect the fracture data in the two research catchments.

![Figure 4.22 Stereographic projections of all fracture data from the Hallue and Patcham catchments.](image)

Scanline surveys were conducted at exposures in the Hallue Catchment whereas optical televiewer surveys were conducted in boreholes in the Patcham Catchment. At each exposure in the Hallue Catchment several scanlines surveys were undertaken in different orientations to reduce directional bias in the data. The orientations of the scanlines were also used to applying a Terzaghi weighting to the fracture data when plotted in stereographic projections (Terzaghi, 1965; Priest, 1993; Anon, 1999b). The locations for the scanlines surveys were selected carefully to avoid exposures which were significantly weathered. In the Patcham Catchment, the optical televiewer surveys allowed fracture data to be collected from a considerable vertical extent of the Chalk sequence which was not possible from exposures in the catchment. A further advantage of the optical televiewer was that
Fracture data could be obtained from pre-existing boreholes, in this case the Environment Agency monitoring boreholes of Casterbridge Farm, Lower Standean and North Bottom. The main limitations of the optical televiewer surveys, however, were that fracture persistence could not be measured, fracture data were collected only in one orientation thereby introducing directional bias into the dataset, and the resolution of the optical televiewer image was limited such that the majority of small aperture or closed fractures could not be distinguished.

Fracture persistence could only have been evaluated from exposure and although a small number of fracture dip and dip direction measurements were made during the field investigations in the Patcham Catchment, the only exposure suitable for scanline surveys, and close to the catchment boundary, was Newtimber Chalkpit which was not accessible during this study. The directional bias, as previously described, was compensated for when plotting the data in stereographic projections by using the orientation of the borehole to apply a Terzaghi weighting (Terzaghi, 1965; Priest, 1993; Anon, 1999b). Perhaps the most significant limitation of the optical televiewer surveys, for the purpose of this study, was the inability to resolve small aperture or closed fractures. Although the quality of the optical televiewer surveys may have varied, as a result of differences in the clarity of the water in the boreholes, the contrast in the numbers of fractures observed in the core and in the optical televiewer survey for the North Heath Barn borehole (Figure 4.19) suggest that as much as 88% of the fractures within the Chalk sequence were missed by the optical televiewer survey. The typical fracture spacing derived from the optical televiewer survey for North Heath Barn was very wide spaced (CIRIA grade suffix 1). The typical fracture spacing based on the core log, however, would be medium to wide spaced (CIRIA grade suffix 2-1). It is possible that disturbance due to the drilling process may have induced additional fracturing into the core, however, care was taken to log only the naturally occurring fractures. This comparison suggests that the typical fracture spacing in the unweathered Chalk in the Patcham Catchment has been over estimated from the optical televiewer surveys and a spacing of medium to wide (CIRIA grade suffix 2-1) would be more appropriate. Corroboratory evidence for this conclusion, from the Patcham Catchment, may be provided by the A27 road cutting geological sections produced by Lamont-Black (1995) during construction of the A27 Brighton Bypass. These geological sections commonly show
that the Chalk grade, below the weathered zone, is CIRIA grade B2 (Figure 4.15). The typical fracture spacing observed in the Hallue Catchment was medium spaced or CIRIA grade suffix 2 also (Table 4.1). This would suggest that the natural or unweathered fracture spacing within the Chalk generally approximates to medium to wide spaced (or CIRIA grade suffix 2-1).

In spite of the image limitation, the optical televiewers surveys probably allowed the dissolution enhanced fractures, which would be significant for flow in the aquifer, to be resolved. The aperture of these fractures would equate to a CIRIA grade of B or C. Similarly, in the Hallue Catchment the typical aperture of fractures from the scanline surveys was found to be equivalent to CIRIA grade B with some fractures also being significantly widened by dissolution. These fractures, in the Hallue Catchment, had apertures of between a minimum of 1 mm and a maximum 70 mm and were sometimes filled with sediment (Figure 4.8 - C). These fractures, where present in exposures, had an average spacing of 3 m, a minimum spacing of 0.5 m and a maximum spacing of 11.95 m. In the Patcham Catchment, these fractures had an average spacing of 4 m, a minimum spacing of 0.02 m and a maximum spacing of 31.03 m. The orientation of the dissolution enhanced fractures for both catchments were found to be similar to the orientations seen in the complete fracture datasets with NW-SE striking dissolution enhanced fractures being the most common (Figure 4.23).

The fracture datasets were also compared with the valley axis azimuths in the research catchments. In particular, this was to evaluate if the Hallue Catchment displayed a similar valley orientation relationship to fracture and fault strikes as has been observed on the Chalk outcrop in England (Ineson, 1962; Morgan, 1971; Crampon et al., 1993; Marsh, 1993; Mortimore, 2012). Fracture data from both the Hallue Catchment scanline surveys and Patcham Catchment optical televiewer
surveys were found to display similar strikes to the valley axis orientations (Figure 4.9 and Figure 4.20). Statistical tests (Table 4.5 tests 4A-B and 5A-B) were undertaken to compare the orientations of the fracture strikes and the valley axis azimuths in both the Hallue and Patcham Catchment. With the exception of test 5B, the tests failed to reject the null hypothesis, that the mean directions of the two sample datasets were equal, which supports the observation that the fractures showed similar trends to the valley axes. Test 5B, which compared NW-SE striking fractures and valleys from the Patcham Catchment, may have been impacted by the optical televiewer surveys over sampling sub-horizontal fractures which typically display more scatter in strike.

In areas of Chalk outcrop, valleys are generally regarded as locations of higher transmissivity (Jones and Robins, 1999) and have been represented as such in regional flow models (e.g. Soley et al., 2012). This is considered to be due to a combination of a number of factors which are summarised in Table 2.7. In the Hallue and Patcham catchments, dry valleys were the focus for groundwater emergence during the winter of 2000/2001. The generally location of groundwater emergence in these valleys was probably related to the interplay between the form of the water table and topography rather than specific characteristics of the fracture network, however, the specific location of springs maybe be intrinsically related to localised dissolution enlargement of parts of the fracture network. Dissolution enhanced fractures, as described above, were observed in both catchments.
Present-day recharge is considered as being essentially fully saturated by the time it passes through the soil zone (Edmunds et al., 1992). It has been suggested, however, that much of the dissolution enlargement of fractures occurred during periglacial episodes when recharge waters were relatively cool and more chemically aggressive (Younger, 1989). Dissolution enlarged fractures have also been observed below Quaternary and Palaeogene cover (Lamont-Black, 1995; Macdonald et al., 1998), such as at HA13 in the Hallue Catchment (Figure 4.8), probably due to acidic runoff/recharge entering the aquifer from these materials. Fractures in the zone of water table fluctuation (e.g. van Rooijen, 1993), or where flow is concentrated are also considered as being commonly dissolution enhanced (Price, 1987; van Rooijen, 1993). A conceptual model for the development of dissolution enhanced fractures due to the concentration of flow towards discharge points in a valley, or due to thinning of the aquifer, was presented by Price (1987) based on Rhoades and Sinacori (1941) (Figure 4.24). This model may be applicable to the locations of springs in the Hallue and Patcham where, due to ephemeral flow over a longer period of time, dissolution enhancement of parts of the fracture network have occurred at the points of discharge into the valley. An indication of this is perhaps demonstrated in the Patcham Catchment by the adit system of the Patcham Waterhall Pumping Station (Figure 4.14 and Figure 4.20), which intersects a number of fissures directly below the area of flooding groundwater emergence of winter 2000/2001 and historical spring locations in Patcham village (Carder, 1990; Collis, 2010).
Figure 4.24 Topographic control of the development of enhanced permeability in a carbonate aquifer; (a) flow pattern to a river in a homogeneous isotropic aquifer; (b) concentration of flow near the river leads to preferential solution at shallow depths along the valley, which enhances permeability and leads to further concentrations of flow; (c) eventually a highly permeable zone (or a single enlarged fissure) develops, and the water table is constrained to within this zone - from Rhoades and Sinacori (1941) and Price (1987).

The conceptual model presented in Figure 4.24 suggests that a zone of enhanced permeability would develop horizontally and laterally from the point of discharge. This would likely favour enhancement of fractures which are predominantly equal in elevation to the point of discharge, such as sub-horizontal or low angle inclined fractures. Sub-horizontal or low angle inclined fractures were observed in the Hallue Catchment to be the most persistent fractures - sometimes extending for > 10 m or the entire length of an exposure. These fractures tended to be more persistent in the Upper Turonian and Lower Campanian Chalk (Figure 4.8 - HA57B and HA27), or Lewes and Newhaven Formations, where bedding features such as marl seams were also present. Low angle inclined or sub-horizontal fractures were common in the data from both research catchments and the field data from the Hallue
Catchment would suggest that the greater persistence of these fractures is typical of the Chalk rock mass and particularly where the Chalk has distinct lithological heterogeneity due to presence of marl seams or continuous flints horizons. Where there is a compartmentalised Chalk sequence, due to the mechanical limitation of inclined or sub-vertical fractures between lithological features, sub-horizontal and low angle inclined fractures would probably provide the lateral hydraulic conductivity. In the Patcham Catchment, such heterogeneity may occur in the Zig Zag, Holywell, New Pit, Lewes, Belle Tout Beds of Seaford and Newhaven Chalk Formations. The greater persistence of sub-horizontal or ‘bedding plane’ fractures was also observed by Bloomfield (1996) who inferred that they would control, in combination with faults, flow in the aquifer fracture system and presented a conceptual model to illustrate the distribution of these hydrogeologically significant fractures in the Chalk (Figure 4.25).

Figure 4.25 Conceptual model of fracture systems in the Chalk from Bloomfield (1996). The model illustrates the Chalk as consisting of scale-invariant fault-bounded segments. Within each fault-bounded segment there are two types of scale-dependent structures: laterally continuous bedding planar fractures with heterogeneous apertures, and a pervasive array of orthogonal interconnected joints. Shaded areas are segments, bounded laterally by faults and vertically by bedding planar fractures that may act as hydraulically discrete units. The dashed line indicates the position of the potentiometric surface.
The complexity of this conceptual model is apparent and, if the effects of weathering and stratigraphy on fracturing were incorporated, the model would be substantially more complex. This, in effect, highlights a limitation of the practical application of field based fracture surveys i.e. fracturing in the Chalk can be characterised but how can this data be meaningfully used. By equating the data from the scanline and optical televiewer surveys in this study to the CIRIA engineering chalk classification scheme (Lord et al., 2002), it was felt that useful generalisations could be made, which would be comparable to other sources of fracture data, such as arising from engineering ground investigations, and be applicable generally to other areas of Chalk outcrop. The CIRIA classification scheme may also allow the general hydrogeological characteristics to be inferred. For example, Roberts and Preene (1990) related permeabilities from pumping tests to Munford Grades (Ward et al., 1968) which Mortimore (1996) then equated to the CIRIA classification scheme (Table 2.5).

CIRIA grades of C have also been generally regarded as being equivalent to permeabilities of, or greater than, $1 \times 10^{-4}$ m/s for tunnelling purposes (Warren, 2008). The fracture survey data, in terms of CIRIA chalk grades, may also aid hydrogeological conceptualisation of the unsaturated zone – a key focus of the FLOOD1 research project in the Hallue and Patcham catchments. For example, if the mechanism of water storage on fracture surfaces in the unsaturated zone presented by Price et al. (2000) is considered, the typical CIRIA grades of unweathered chalk determined from the fracture surveys, grades B2 – B1, would equate to an available surface area for storage of 30 - 6 m$^2$ in a 1 m$^3$ volume of Chalk with 3 sets of orthogonal fractures. If the total volume of unsaturated Chalk in a catchment is determined, and the typical depth or thickness of water held on the fracture surfaces estimated, then the total volume of water held in this format could be calculated for a catchment. Although simplistic, this would permit observations from field surveys of complex fracture systems (e.g. Figure 1.2, Figure 4.8 and Figure 4.25) to be hydrogeologically conceptualised at a catchment scale.
4.5 Conclusion

The results presented in this chapter have outlined the structural geology of the Hallue and Patcham Catchments. The results were presented and discussed in the context of the regional structural setting. By combining data from hand specimens, fracture surveys and field mapping an understanding has been gained of:

(i) the form and character of known geological structures in the catchments
(ii) the orientation, spacing, aperture and persistence of fractures - and their relationship to lithology and stratigraphy
(iii) the origin of vein fabrics and fracturing - and their relationship to lithology and stratigraphy
(iv) structural similarities and differences between the two catchments and their causes
(v) the relationship at different scales between various structural features such as vein fabrics, fracturing and folding
(vi) the relationship between geomorphology and structural features in the catchments
(vii) the implications, strengths and weaknesses of different methods of collecting structural data

In the context of the conceptual model of a chalk valley presented in Chapter 1, the results presented in this chapter have provided information on the structural geology of the Chalk aquifer, in terms of folding and faulting, and the rock mass character of the Chalk units, in terms of fracturing, for both the Patcham and Hallue catchments. Further field data on the Quaternary geology, geomorphology and soils at a local scale are presented and discussed in Chapter 5.
Chapter 5 Quaternary Geology, Geomorphology and Soils

5.1 Introduction

This chapter presents the results from a series of reconnaissance surveys conducted in the area of the Patcham Catchment recharge site. The results provide information on soil field saturated hydraulic conductivity, soil mineralogy and soil distribution at the site. The results are reviewed in the context of soil evolution and the literature presented in Chapter 2. The results build on those presented in Chapters 3 and 4 by providing detail on the typical variation in Quaternary geology and geomorphology encountered in a Chalk valley in relation to the conceptual model presented on Chapter 1. The results from this chapter form the basis for further work presented in Chapters 6.

Recharge sites were installed in both the Hallue and the Patcham catchments to monitor the process of groundwater recharge through the unsaturated zone to the saturated zone of the Chalk aquifer - and the resulting evolution of the water table (Section 1.1.1 and Figure 1.5). The Patcham Catchment recharge site was planned to contain purgeable tensiometers installed at 0.2 m intervals from 0.2 to 1.2 m BGL and 0.3 m intervals from 1.2 to 3.0 m BGL, equitensiometers installed at 1 m intervals from 1 to 5 m BGL and 16 EnviroSMART probes installed at depths of 0.1 to 3.6 m BGL. In light of the shallow depths of these instruments, and after the locations of the deep recharge site boreholes had been identified (Figure 5.1), surveys were undertaken to investigate the proposed area of the shallow instruments for the presence of near-surface karst and for variation in soil properties. The surveys consisted of ground conductivity using a Geonics EM31, field saturated hydraulic conductivity using a Guelph Permeameter and topography using a Leica differential GPS. In addition to these field surveys, soil samples were collected from the Guelph Permeameter locations for particle size analysis of the soil fines and determination of the soil mineralogy.
Figure 5.1 Illustrates the location of the deep recharge site boreholes and the area considered for the shallow recharge site instrumentation. (Aerial photographic image © Getmapping)
5.2 Patcham Catchment

5.2.1 Field techniques

5.2.1.1 EM31

The EM31, produced by Geonics Limited, measures ground conductivity by generating a primary electromagnetic field from a transmitter coil, which propagates above and below the ground, and a receiver coil detecting eddy currents produced if a conductive medium is present (Reynolds, 1997). The first or primary magnetic field produced stimulates horizontal current loops in the ground which then result in a secondary magnetic field (Zalasiewicz et al., 1985). The overall measured response in the receiver is the combined effect of the primary and secondary fields (Reynolds, 1997), and the primary field effect on the receiver coil is removed by the instrument. EM instruments typically record the signal strength out of phase with the source signal, which is called the quadrature and is directly related to the apparent conductivity of the ground, and in phase with the source signal, where the signal strength only responds to very strong conductors notably buried metallic materials. The EM31 has a fixed inter-coil spacing of 3.66 m with observation depths between 3 m and 6 m in the horizontal and vertical dipole orientations respectively (Doolittle and Collins, 1998).

Variation in apparent ground conductivity occurs where the underlying sediments are heterogeneous. Factors that are likely to influence ground conductivity in the study area are clay content, clay type, moisture profile with depth, moisture salinity and moisture temperature (McNeill, 1980). Fine grained sediments such as clay and silt, due to their ability to retain moisture, will typically produce higher ground conductivity readings than coarser sediments such as sand and gravel. The contrasting properties of chalk and various sediment fills have allowed karst features in areas of chalk outcrop to be successfully identified from ground resistivity and conductivity surveys (McDowell, 1975; Zalasiewicz et al., 1985; Mortimore et al., 1990a; Rigby-Jones et al., 1997; Matthews et al., 2000). Topography, ground compaction, vegetation, utility structures and season, however, may all have an influence on ground conductivity (McNeill, 1980).
The EM31 equipment used for the main survey comprised two coils (transmitter and receiver), a battery pack, data logger, Allegro CX field computer and a Silva Multi-Navigator GPS (Figure 5.2). Prior to the main survey a trial survey was conducted with an older EM31 which did not have a data logger (Figure 5.2). With the addition of the data logger and GPS data could be collected by setting a regular recording interval e.g. every 5 seconds and the survey could be conducted at a slow walking pace. The survey consisted of 30 survey lines in a NW-SW orientation and 21 survey lines in a NE-SW orientation which were spaced approximately 5 metres apart. The area covered by the survey was 98,781 m². All measurements were taken over 2 consecutive days to minimise the impact of weather variation.

Once the EM31 survey was complete, the data were downloaded from the data logger, converted into comma separated text files containing easting, northing and conductivity. The text file was imported in ArcGIS ArcMap to create a XY Event Layer and then converted to a point shapefile. The shapefile was used to create a raster grid of ground conductivity for the survey area. The interpolation method used to create the raster was the inverse distance weighted method in the Spatial Analyst Tools for ArcGIS. This interpolation is a weighted distance average method where the cell values are determined using a linearly weighted combination of a set of sample points. The weight is a function of inverse distance and the cell value calculated cannot be greater than the highest or less than the lowest input value. This method is suitable where the data is sufficiently dense with regard to the local variation which is being simulated (Watson and Philip, 1985). The raster created was used to identify zones of approximately equal ground conductivity. These ground conductivity zones were then targeted in the subsequent surveys and sampling carried out at the site to identify any variation in soil and Quaternary geology which may have caused the response.
Figure 5.2 EM31 instrument used for the recharge site ground conductivity survey. The instrument shown in this photograph was used for a trial survey. For the full survey, the EM31 instrument was connected to a GPS and field computer and the measurements were data logged at 5 second intervals.
5.2.1.2 Guelph Permeameter

The Guelph Permeameter, produced by SoilMoisture Equipment Corp, is a field constant head permeameter and is designed for quickly measuring in-situ hydraulic conductivity. The equipment comprises four basic sections: tripod assembly; support tube and lower air tube fittings; reservoir assembly; and well head scale and upper air tube fittings (Figure 5.3). Measurements can be made with the Guelph Permeameter in the depth range of 0.15 to 0.75 m below the soil surface. A measurement takes between 1/2 to 2 hours, depending on soil type, and requires approximately 2.5 litres of water. The Guelph Permeameter works on the Mariotte siphon principle, whereby water discharges under constant flow from a closed reservoir.

At a chosen test location, a hole is augured and the Guelph Permeameter equipment is positioned in the hole. The air inlet tube and tip are raised to a predetermined level (Figure 5.3) indicated on the reservoir. Water to flows from the tip into the augured hole to the equivalent level. The air-inlet tube maintains a vacuum above the water in the permeameter reservoir so that the water flows out of the device at the rate required to maintain the water level in the hole (Reynolds and Elrick, 1986). The water level in the reservoir is then monitored and recorded at a regular interval until a constant rate of decrease is reached and the water infiltrating the unsaturated soil has reached a steady state. It is usually assumed to be constant when the rate of decrease is the same for three consecutive readings. Once constant, the air inlet tip is raised again and a second water level is created in the hole. The water level is monitored again until a constant rate is reached.

The rate of outflow from the reservoir at the two water levels is used to calculate the field saturated hydraulic conductivity, matric flux potential and sorptivity. The field saturated hydraulic conductivity is the saturated hydraulic conductivity of soil containing trapped air (Reynolds and Elrick, 1986) and is considered more appropriate to unsaturated zone investigations (Anon, 1991). Matric flux potential is a measure of a soil’s ability to pull water by capillary force through a cross sectional area per unit time and sorptivity is a measure of the ability of a soil to absorb a wetting liquid (Anon, 1991). For this study, the main parameter of interest was the...
field saturated hydraulic conductivity – which was assumed to be a proxy for hydraulic conductivity and infiltration rate.

From the EM31 and ground conductivity surveys, seven locations were identified within the contrasting ground conductivity zones for Guelph Permeameter measurements. A further two measurements were undertaken outside of the EM31 survey area to evaluate the hydraulic conductivity of the lower gradient slopes in the dry valley below the recharge site area. The depth of Guelph Permeameter measurements undertaken in the area considered for the shallow recharge site instrumentation was around 0.20 m BGL. The water levels applied during the survey were typically 0.05 and 0.10 m. All measurements were taken over 3 consecutive days to minimise the impact of weather variation.

Figure 5.3 Guelph Permeameter equipment used for field saturated hydraulic conductivity measurements. Adapted from Anon (1991)
5.2.1.3 Differential GPS

The differential GPS system used was a Leica GPS1200. The Leica GPS1200 equipment components are illustrated in Figure 5.4. The horizontal and vertical accuracy of the Leica GPS1200 system used was ±10 mm and ±30 mm respectively. The Leica GPS1200 system measures easting and northing from satellite triangulation and elevation by one of two methods. The first method for measuring elevations involves using two GPS units whereby one unit is a base station and the second unit is a rover. The base station is set-up at a location of known easting, northing and elevation. The first unit then calculates elevation relative to the base station. The second method for measuring elevation uses a Leica subscription service called Smartnet. When using Smartnet only one GPS unit is required and elevation is calculated using the mobile telephone network for triangulation. Both methods for measuring elevation were used during this survey. The Smartnet method was used to establish a point of known easting, northing and elevation which could then be used to establish a base station for the full survey.

The differential GPS survey was undertaken to produce topographical profiles through the area considered for the shallow recharge site instrumentation. It was intended that the profiles would cross the EM31 ground conductivity zones and Guelph Permeameter locations to aid evaluation of the spatial relationship between geomorphology and soil characteristics. In total, eight differential GPS profiles were undertaken across the site – four orientated approximately Southwest – Northeast and four orientated approximately Southeast – Northwest (Figure 5.5). The data were collected by walking the profile and taking a measurement of the elevation of the ground surface approximately every five metres. The raw differential GPS data were converted to a comma separated text file using the Leica Geo Office software and imported into ArcGIS ArcMap and Excel for plotting and analysis.
Figure 5.4 Leica GPS1200 equipment used for the topographic transects. Adapted from Anon (2008).
5.2.2 Laboratory techniques

Soil samples were collected at each of the Guelph Permeameter locations for particle size and X-ray diffraction analysis. The objective of these analyses was to obtain data on the composition of the soils to aid interpretation of the field saturated hydraulic conductivity results and to provide an indication of the spatial distribution of soil composition.

5.2.2.1 Laser Particle Size Analysis

The main objective for this analysis was to determine the ratio of clay, silt and sand size particles in the soil. It was thought these fractions of the soil, especially the clay and sand proportions, would indicate the parent material of the soil i.e. Chalk, Palaeogene deposits or Quaternary deposits – the latter two being present as either remnant deposits or karst infilling. It was also thought the proportion of clay in the soil would affect the field saturated hydraulic conductivity measured by the Guelph Permeameter and the response of the shallow instrumentation proposed for the recharge site. As the main focus for this analysis was the soil fines, a laser particle size analyzer was used to measure particle size. The laser particle size analyser used for this work was the Mastersize 2000 produced by Malvern Instruments Limited.

The samples were taken from depths of between 0.10 – 0.20 m (Table 5.1). Each sample was sieved through a 2.0 mm sieve. If aggregated blocks of sediment were present in the sample they were gently broken up by hand to pass through the sieve. Organic matter, such as plant roots, was removed prior to sieving. The sample was then sieved by hand for approximately 2 minutes. Once sieved, three sub-samples of approximately 10 ml of the soil were added to three 50 ml beakers. The sub-samples were then mixed into a slurry with approximately 1.5 to 2 ml of water. The volume of water added to the samples to obtain the correct consistency for analysis was dependant on clay content. If the sample had high clay content and became congealed during the initial mixing a few drops of a Calgon water solution mix was added. The solution was made of 50 g of sodium hexametaphosphate plus 5.724 g of sodium carbonate in 1 l of water. A record was made of the sample number and amount of Calgon solution added. When the desired consistency was attained, a small portion of the soil sample was added to the Mastersizer 2000.
The Mastersize 2000 determines particle size by measuring the volume of the particle and expressing this result in terms of an equivalent spheres (Anon, 1999a). The potential problem of this method, however, is that the size of an angular particle may be underestimated.

### 5.2.2.2 X-Ray Diffraction Analysis

The main objective for this analysis was to determine the mineralogical content of the soils at the Guelph Permeameter locations to aid interpretation of the field saturated hydraulic conductivity results. It was thought the mineralogy would also be indicative of the soil parent materials.

Each soil sample was dried at 60 °C for 24 hours. Once dried, each sample was ground using a pestle and mortar until it formed a fine powder. An XRD powdered sample holder was used to contain the sample for analysis. Small quantities of the powder were added to the central hole in the mount until it was full. The powder was then compacted with a hand press to give a flat surface and the excess powder was cleared away from the holder. The programme used for analysis of the powdered samples was the same for all samples. After the sample was analysed, the powder was disposed of and the holder cleaned using distilled water and acetone.

The XRD technique is used to determine the crystalline compounds present in powdered and solid samples (Anon, 2007). A crystal lattice has a three dimensional distribution which produces a series of planes. Each of these planes is separated by a distance which is characteristic of that material. Furthermore, for any crystal plane there are a number of different associated orientations with individual spacing. Thus, when a ray hits the lattice, diffraction occurs only when the distance travelled by the rays reflected from successive planes differ by a certain number of wavelengths (Anon, 2007). A plot of angular positions and intensities of the diffraction peaks produces a pattern that is characteristic of the sample (Anon, 2007). In the absence of all other effects, the peak intensities are related to the mass percentage of the phase in the sample. Peak broadening effects that influence this relationship may occur either as a result of grain size and crystallinity or lattice strain. In the absence of lattice strain, peak broadening relative to a standard material also
gives an indication of the average crystal size with large crystals showing sharp peaks.

The diffraction patterns measured were compared to the Powder Diffraction Data File (PDF) 2006, to identify the mineral components in the samples, using the software program HighScore Plus. A simulation was then conducted on the pattern to calculate the proportions of the minerals present in each sample. The Rietveld simulation was used to calculate the quantitative proportions of different phases in the sample, using atomic co-ordinates for each of the phases identified from the diffraction pattern. Atomic co-ordinates for each phase were obtained from the International Crystallographic Database (Appendix VI). Rietveld simulation can take into account effects from grain size, lattice strain and the form of the background to produce more accurate phase proportions than procedures involving only peak intensities relative to a standard.

5.2.3 Results

5.2.3.1 EM31

The EM31 survey covered an area of 98,781 m². The results from the EM31 survey are presented as a colour graded raster grid (Figure 5.6 and Figure 5.7) with low values in blue and high values in red. The data represent apparent ground conductivity in millisiemens per metre (mS/m). From Figure 5.6 and Figure 5.7, it is clear that there are three areas of relatively high ground conductivity. These areas are located along the dry valley axis, on the hilltop to the southeast of the survey area and on the hilltop to the southwest of the survey area. Areas of relatively low and intermediate conductivity are located along the dry valley slopes. The values of conductivity for the survey area ranged from 4.5 to 49.7 mS/m.

5.2.3.2 Guelph Permeameter

The Guelph Permeameter field saturated hydraulic conductivity results are presented in Figure 5.6 and Figure 5.7 and soil descriptions in . The values range between $2.86 \times 10^{-5}$ and $4.55 \times 10^{-8}$ m/s. The majority of the values fall between $1.08 \times 10^{-5}$ and $2.86 \times 10^{-5}$ m/s - although three locations have values an order of magnitude lower at around $1 \times 10^{-6}$ m/s. The location with the lowest field saturated
hydraulic conductivity is location 4 at $4.55 \times 10^{-8}$ m/s and the location with the highest is location 6 at $2.86 \times 10^{-5}$ m/s.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Sample Depth (cm)</th>
<th>Sample Description</th>
<th>Soil Colour</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.11 – 0.19</td>
<td>Roots; flint fragments (angular, weathered); some white-chalk pebbles; silty, clayey soil</td>
<td>Brown; 10YR 4/3</td>
</tr>
<tr>
<td>2</td>
<td>0.10 – 0.19</td>
<td>Roots; small chalk fragments; large flints (&lt; 10 mm to 50 mm)</td>
<td>Dark yellowish brown; 10YR 4/4</td>
</tr>
<tr>
<td>3</td>
<td>0.12 – 0.20</td>
<td>Roots; broken/angular flints (10 – 30 mm)</td>
<td>Dark yellowish brown; 10YR 4/4</td>
</tr>
<tr>
<td>4</td>
<td>0.10 – 0.19</td>
<td>Roots; flints (subrounded to angular); white chalk fragments (&lt; 20 mm)</td>
<td>Dark yellowish brown; 10YR 4/6</td>
</tr>
<tr>
<td>5</td>
<td>0.13 – 0.18</td>
<td>Roots; white chalk fragments; flint clasts; clayey silty soil</td>
<td>Brown</td>
</tr>
<tr>
<td>6</td>
<td>0.10 – 0.18</td>
<td>Roots; chalk clasts; flint clasts; clayey silty soil</td>
<td>Light brown</td>
</tr>
<tr>
<td>7</td>
<td>0.10 – 0.18</td>
<td>Clayey silt; chalk fragments (&lt; 5 mm)</td>
<td>Dark brown; 10YR 3/4</td>
</tr>
<tr>
<td>8</td>
<td>0.15 – 0.20</td>
<td>Some roots; chalk fragments; flint clasts (20 mm), subangular</td>
<td>Dark brown</td>
</tr>
<tr>
<td>9</td>
<td>0.15 – 0.20</td>
<td>Some roots; chalk fragments; clayey silty soil</td>
<td>Dark brown</td>
</tr>
</tbody>
</table>

Table 5.1 Depths and descriptions of soil samples from Guelph Permeameter measurement locations
Figure 5.5 EM31 (A), differential GPS (B) and Guelph Permeameter (C) survey locations. (OS Mapping © Crown Copyright 2007)
Figure 5.6 Ground conductivity from EM31 survey with soil particle size fractions. Field permeability measurements from the Guelph Permeameter are also indicated. Black lines indicate the boundaries of the superficial deposits shown on the Brighton and Worthing (318/333) 1:50,000 sheet 318/333 (British Geological Survey, 2006a). (Aerial photographic image © Getmapping)
Figure 5.7 Ground conductivity from EM31 survey with soil mineralogy. Field permeability measurements from the Guelph Permeameter are also indicated. Black lines indicate the boundaries of the superficial deposits shown on the Brighton and Worthing (318/333) 1:50,000 sheet (British Geological Survey, 2006a). (Aerial photographic image © Getmapping)
5.2.3.3 Differential GPS

The topographical profiles from differential GPS survey are presented in Figure 5.8 and Figure 5.9. The minimum elevation measured from all profiles was 83 mOD and the maximum elevation measured was 134 mOD. The slopes shown in the topographical profiles are predominantly north, northeast, northwest, south and southeast facing. Above the topographical profiles the gradient of the slope and the interpolated ground conductivity from the EM31 survey are shown. The gradient profile emphasises the changes in the topographical profile - a curved line indicates a convex or concave slope and a flat line indicates a slope of constant gradient. The interpolated ground conductivity is included to highlight any potential relationship between gradient and the EM31 readings. Also, shown are the lateral extents of mapped Quaternary deposits and the bedrock geology.

Southwest – Northeast profiles 1 and 2 show a convex slope with the gradient ranging from a minimum of 0° and maximum of 15°. Profile 1 is interpreted as having a break of slope at around 177 m after which the gradient increases. Profile 2 is interpreted as having five breaks of slope whereby the overall convex slope is divided by a series of lower gradient benches. The average gradients of the slopes between each break range from a minimum of 1° and a maximum of 7°.
Figure 5.8 Southwest – Northeast orientated topographic profiles through the proposed recharge site area. Gradient as a two point moving average (grey line) and interpolated ground conductivity (red line) are shown above the topographic profiles. Breaks of slopes are indicated by arrows and the average gradient is given between the arrows. The bars labelled CWF and HD indicate mapped locations of Clay-With-Flints and Head deposits. The profiles are coloured by Chalk formation and the position of marker marls are indicated with dotted lines: N = Navigation, L = Lewes, B = Bridgewick C = Caburn.
Southwest – Northeast profile 3 is interpreted as having six breaks of slope. The slope becomes concave between 111 m and 251 m. The gradient of profile 3 ranges from a minimum of 0° and maximum of 17°. The average gradients of the slopes between each break ranges from a minimum of 5° to a maximum of 12°.

Southwest – Northeast profile 4 shows that the hill slope is an overall convex slope but has a bench or concave inflexion between 48 m and 176 m. The gradient ranges from a minimum of 0° and maximum of 20°. The profile is interpreted as having five breaks of slope. The average gradients of the slopes between each break ranges from a minimum of 2° and maximum of 9°.

Southeast – Northwest profile 5 is parallel to the crest of the interfluve and has a maximum gradient of 3° dipping towards the southeast.

Southeast – Northwest profile 6 shows two small valleys from 88 m to 230 m and 250 to 350 m. The slopes of these valleys are convex but with a subtle asymmetry. The northwest facing slopes have average gradients of around 9-7° whereas the southeast facing slope have average gradients of around 6°. The overall gradient ranges from a minimum of 0° and maximum of 11°. The profile is interpreted as having eight breaks of slope. The average gradients of the slopes between each break ranges from a minimum of 1° and a maximum of 9°.

Southeast – Northwest profile 7 crosses the valley which represents the convergence, at a lower elevation, of the small valleys seen in profile 6. As in profile 6, the slopes are convex but with a subtle asymmetry. The northwest facing slope has an average gradient of 15° whereas the southeast facing slope has average gradients of 10°, 11° and 7°. The overall gradient ranges from a minimum of 1° and maximum of 19°. The profile is interpreted as having six breaks of slope. The average gradients of the slopes between each break ranges from a minimum of 4° and a maximum of 15°.

Southeast – Northwest profile 8 is similar to profile 7 but intersects the valley at a lower elevation. As in profiles 6 and 7, the slopes are convex but with a subtle asymmetry. The northwest facing slope has an average gradient of 13° whereas the
Figure 5.9 Southeast – Northwest orientated topographic profiles through the proposed recharge site area. Gradient as a two point moving average (grey line) and interpolated ground conductivity (red line) are shown above the topographic profiles. Breaks of slopes are indicated by arrows and the average slope gradient is given between the arrows. The bars labelled CWF and HD indicate mapped locations of Clay-With-Flints and Head deposits. The profiles are coloured by Chalk formation and the position of marker marls are indicated with dotted lines: N = Navigation, L = Lewes, B = Bridgewick C = Caburn.
southeast facing slope has average gradients of 10°-13°. The overall gradient ranges from a minimum of 0° and maximum of 19°. The profile is interpreted as having five breaks of slope. The average gradients of the slopes between each break ranges from a minimum of 1° and a maximum of 13°.

5.2.3.4 Laser Particle Size Analysis

The results from the laser particle size analysis are presented in Figure 5.10 and Figure 5.6. The soil samples analysed were found to have a particle size distribution consisting of between 2.5 - 17.6% clay, 29 - 83.9% silt and 8.5 - 68.3% sand. The two samples with the highest clay content are from locations 6 and 7 which comprise 17.6%, 58.5%, 23.8% and 7.6%, 83.9% and 8.5% clay, silt and sand respectively. Silt is the principal particle size fraction for the soil samples from locations 1-3 and 6-7. Sand is the principal particle size fraction for the samples from locations 4-5 and 8-9. The change in soil particle size distribution over the survey area displays a subtle spatial variation (Figure 5.6) with silt-dominant soils occurring in the centre of the survey area and sand-dominant soils occurring on the north-east, south-east and west of the survey area. The clay fraction is also seen to be generally greater in the centre and south-east of the survey area.

Figure 5.10 Particle size distribution curves for soil samples at Guelph Permeameter measurement locations. Sample depths and descriptions are provided in Error! Reference source not found.
5.2.3.5 X-Ray Diffraction Analysis

The results from the X-ray diffraction analysis are shown in Figure 5.7 and in Table 5.2. The primary mineral component in the majority of the soil samples from locations 1, 2, 3, 4, 5 and 7 was found to be silica – which ranges from 22.7% to 83.2%. Soil samples from locations 6, 8 and 9, however, were an exception to this and were found to have a primary mineral component of calcite. Most of the soil samples also have minor constituents. All soil samples, with the exception of the samples from locations 6 and 4, were found to have a small proportion of feldspar which ranged from a total of 3.6% to 16.2%. All soil samples, with the exception of the sample from location 6, were found to have a small proportion of clay minerals which ranged from a total of 0.7% to 9.2%. These clay minerals can be broadly divided into those belonging to the smectite, illite and kaolin groups. Soil samples from locations 1, 2, 8 and 9 all contained smectite clay minerals which ranged from a total of 1.1% to 9.2%. Soil samples from locations 3-7 all contained illite clay minerals which ranged from a total of 0.8% to 8%. The soil sample from location 3 contained kaolin clay minerals at 2.4%. In addition to a clay mineral fraction, the soil sample from location 4 contained a minor component of metal oxides at a total of 11.2% - comprising 4.6% goethite and 6.6 % rutile.

<table>
<thead>
<tr>
<th>Location</th>
<th>Silica</th>
<th>Calcite</th>
<th>Feldspar</th>
<th>Smectite</th>
<th>Illite</th>
<th>Kaolin</th>
<th>Metal Oxides</th>
<th>Other</th>
</tr>
</thead>
<tbody>
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<td>1</td>
<td>79.9</td>
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<td>12.4</td>
<td>7.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
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<td>2</td>
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<td>11</td>
<td>6.2</td>
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<td>83.2</td>
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<td>4</td>
<td>67.8</td>
<td>13</td>
<td>-</td>
<td>8</td>
<td>-</td>
<td>4.6 (Goethite), 6.6 (Rutile)</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>72.5</td>
<td>14.9</td>
<td>8.1</td>
<td>-</td>
<td>4.5</td>
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</tr>
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<td>24.8</td>
<td>74.4</td>
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<td>16.2</td>
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<td>50.5</td>
<td>3.6</td>
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<td>-</td>
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<td>-</td>
</tr>
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<td>31.9</td>
<td>61.3</td>
<td>5.7</td>
<td>1.1</td>
<td>-</td>
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</tr>
</tbody>
</table>

Table 5.2 Mineral composition of soil at Guelph Permeameter measurement locations. Minerals identified using X-ray diffraction powder analysis. Proportions of minerals determined by Rietveld simulation – mineral patterns are provided in Appendix VI.
5.3 Hallue Catchment

In the Hallue Catchment, identification and characterisation of the recharge site was undertaken by BRGM (Machard de Gramont, 2007; Baltassat et al., 2008). The location chosen was north-east of the village of Warloy-Baillon in an area of arable farm land (Figure 5.11 and Figure 5.12) and north-west of the ephemeral tributary to the Hallue - Le Ravin. In contrast to the recharge site installed in the Patcham Catchment at North Heath Barn, the shallow instrumentation for the Warloy-Baillon recharge was installed directly adjacent to the deep boreholes P1-P6 (Figure 1.5). These boreholes provided a full profile of the soil and Chalk bedrock prior to installation of both the shallow and deep instrumentation.

![Figure 5.11 Location of FLOOD1 recharge site in the Hallue Catchment relative to the village of Warloy-Baillon](image)

The soil was found to be less than 1 m thick at the Warloy-Baillon recharge (0.67 m deep in borehole P2) and was interpreted as being a cultivated soil with centimetre size granules of chalk and flint fragments. The soil directly overlaid the Chalk with no Quaternary deposits identified at the site (Robelin, 2008).
Quaternary and remnant Palaeogene deposits were observed, however, to be widely preserved overlying the Chalk, or infilling karst, at the exposures logged in the Hallue Catchment (Figure 5.13). The deposits observed consisted of Colluvion (Head) in valley areas and remnant Thanétien (Thanet Sand/Upnor Formation), Formations résiduelles à silex (Clay-with-flints) and Limon des plateaux (loess) at higher elevations on interfluves or plateau areas. A selection of the material from the latter three deposits was collected for X-ray diffraction mineralogical analysis and the results are presented in Table 5.3.

5.3.1 Results

5.3.1.1 X-Ray Diffraction Analysis

The primary mineral component in the Limon des plateaux was found to be either silica, with five samples having 52.8% - 83%, or calcite with one sample having 81.5%. The secondary mineral component was found to be variable in proportion and composition (Table 5.3). For example, HA49-1 was found to have a secondary
Figure 5.13 Photographs of Quaternary and remnant Palaeogene deposits overlying the Chalk and infilling karst at exposures in the Hallue Catchment. A = HA15 with Colluvion (Head) overlying the Chalk, B = HA43 with Limon des plateaux (loess) overlying the Chalk, C = HA57A with cross-laminated reworked Limon des plateaux within a karst feature, D = HA14 with remnant Thanétien (Thanet Sand/Upnor Formation) and Formations résiduelles à silex (Clay-with-flints) overlying and infilling the Chalk, E = HA23 with remnant Thanétien infilling dissolution pipe karst, F = HA39 with remnant Thanétien and Formations résiduelles à silex infilling dissolution pipe karst component of 34.9% calcite whereas HA13-1 was found to have a secondary component of 6.3% illite clays.
The secondary component of samples, in order of frequency and proportion, comprised smectite clays (8 - 11.2%), calcite (34.9%), silica (16%), feldspar (11.7%) and illite clays (6.3%). Minor mineral components also consisted of illite and smectite clays, metal oxides and, at one location, the carbonate mineral Ankerite. The metal oxides identified were goethite, rutile and jacobsite.

<table>
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<th>Location</th>
<th>Strata</th>
<th>Silica</th>
<th>Calcite</th>
<th>Feldspar</th>
<th>Smectite</th>
<th>Illite</th>
<th>Kaolinite</th>
<th>Metal Oxides</th>
<th>Other</th>
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<td>3.6 (Rutile)</td>
<td>6.8 (Ankerite)</td>
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Table 5.3 Mineral composition of Quaternary and remnant Palaeogene deposits at exposures in the Hallue Catchment. Minerals identified using X-ray diffraction powder analysis. Proportions of minerals determined by Rietveld simulation – mineral patterns are provided in Appendix VI. LP = L Limon des plateaux, Rs = Formations résiduelles à silex and e2 = remnant Thanétien

The primary mineral component in the Formations résiduelles à silex was found to be either silica, with six samples having 50% - 80.9%, or smectite clays with one sample having 53.2%. The secondary mineral component was found to be either smectite or illite clays, with three samples having 12.1% – 22.7% smectite clays and two samples having 18.3% - 19.1% illite clays, or calcite with one sample having 22.3%. The iron carbonate mineral siderite was also found at one location at 22.5%. Minor mineral components consisted of goethite with one sample also having a small proportion of the phosphate mineral hydroxylapatite.

The primary mineral component in the remnant Thanétien was found to be silica with 69.4 – 93.2%. The secondary mineral component was found to be variable in composition (Table 5.3) but, in order of frequency, was found to be feldspar (6.7 -
14.3%), illite (6.8 - 8.6%), smectite (5.1 – 5.8%) and calcite (10.4%). Minor mineral components consisted of rutile, ankerite and hydroxylapatite.

5.4 Discussion

The results from the EM31 survey highlighted three main areas of relatively high ground conductivity. When these results were compared to the Quaternary deposits shown on the Brighton and Worthing (318/333) sheet (British Geological Survey, 2006a), the areas of relatively higher ground conductivity correlated well with the locations of Clay-with-flints and Head deposits (Figure 5.6 and Figure 5.7).

The area of relative higher ground conductivity in the centre of the surveyed area was found to occur where Head deposits are mapped in the dry valley. The area of higher conductivity to the south-west of the survey area was found to occur where Clay-with-flints are mapped on the crest of the hill. A third area of higher ground conductivity was found to occur to the south-east of the survey area but no mapped Quaternary deposits are shown in this location. Ground conductivity values of up to ~14 mS/m were observed at the location of the Head deposits and up to ~19 mS/m were observed at the location of the Clay-with-flints deposits. The mean ground conductivity from all readings was 8.9 mS/m. The third area of high ground conductivity was interpreted as being an area of unmapped Clay-with-flints based on the geomorphological location and the mineralogy of soil. The ground conductivity progressively decrease away from the high areas possibly indicating the thinning out of the Quaternary deposits. Towards the edge of the EM31 surveyed area, there are areas of high conductivity which may have resulted from the close proximity of vegetation or metallic objects. For example, small trees are present in the high conductivity area to the north-west of the site near location 5 (Figure 5.6 and Figure 5.7).

The EM31 survey results do not appear to relate specifically to any particular elevation or slope gradient. The relatively higher values of ground conductivity are observed at both the lowest and highest elevations seen at the proposed site and on some of the high and low gradients slopes. It appears, however, the EM31 survey results do relate the distribution of the Quaternary deposits within the survey area, which are associated with geomorphology. That is, high ground conductivities were
recorded in the dry valleys due to the occurrence of Head deposits and on the crests of hills due to the occurrence of Clay-with-flints.

The results from the EM31 survey were used to identify locations for the Guelph Permeameter measurements and soil sampling - thereby linking ground conductivity observations with data on the hydraulic nature and composition of the underlying soils. The Guelph Permeameter readings were found to vary over the site by four orders of magnitude from $2.86 \times 10^{-5}$ m/s to $4.55 \times 10^{-8}$ m/s. The variation in the field saturated hydraulic conductivity can be partially correlated with variation in the EM31 ground conductivity results and the location of Quaternary deposits. For example, the field saturated hydraulic conductivities measured for locations 2 and 4 are $4.03 \times 10^{-6}$ m/s and $4.55 \times 10^{-8}$ m/s respectively. Locations 2 and 4 are in areas of higher ground conductivities where Clay-with-flints deposits are mapped or suspected to occur. Compare these values with $2.86 \times 10^{-5}$ m/s measured at location 6 where ground conductivity is lower and no Quaternary deposits are mapped. The results obtained from the Guelph Permeameter for the Clay-with-flints deposits are also consistent with published values from Harrington et al. (1994) and Klinck et al. (1998) (Table 5.4).

<table>
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<th>Location</th>
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<th>Comments</th>
</tr>
</thead>
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<td>Kent</td>
<td>$1.91 \times 10^{-5}$</td>
<td>Geometric mean hydraulic conductivity from field infiltrometer measurements</td>
</tr>
<tr>
<td>Dorset</td>
<td>$1.33 \times 10^{-5}$</td>
<td>Geometric mean hydraulic conductivity from field infiltrometer measurements</td>
</tr>
<tr>
<td>Rothamsted and Soberton</td>
<td>$1.7 \times 10^{-6}$ to $2.4 \times 10^{-8}$</td>
<td>Hydraulic conductivities calculated from triaxial constant flow rate tests</td>
</tr>
</tbody>
</table>
| Rothamsted        | $3.5 \times 10^{-5}$ (mean)  
$8.8 \times 10^{-9}$ (0.82 m BGL)  
$1.5 \times 10^{-7}$ (4.25 m BGL) | Field infiltrometer depth profile in a trial pit |

Table 5.4 Hydraulic conductivity values for Clay-with-flints. Values derived from Harrington et al. (1994) and Klinck et al. (1998).

The field saturated hydraulic conductivity measured in the higher ground conductivity areas associated with the Head deposits ranges from $6.48 \times 10^{-6}$ m/s to $1.49 \times 10^{-5}$ m/s. These values are higher than those measured for the Clay-with-flints, and may relate to differences in soil particle size, mineralogy and structure between the two deposits. Location 1 also demonstrated a relatively lower ground conductivity and field saturated hydraulic conductivity at $6.50 \times 10^{-6}$ m/s - although located outside the mapped area of Clay-with-flints and Head deposits. It is inferred
that the soil at this location may be developed over a pocket of soliflucted Clay-with-flints derived from the suspected Clay-with-flints to the south on the crest of the hill. Qualitative evidence for this was the observation of subtle ridges on this slope while conducting the surveys. These ridges may be seen in Figure 5.1 as subtle lineations in vegetation and ground colour. Soliflucted slope Clay-with-flints have been recognised by Laignel et al. (2003) in the Paris Basin as having similar properties to the pure Clay-with-flints but with higher degrees of weathering and fragmentation.

The differential GPS profiles highlighted the dry valley and hill-slope characteristics at the site. This geomorphology is typical of the South Downs as shown in the conceptual geological model of a chalk valley (Figure 1.2). The dry valleys at the site, although minor subsidiary dry valleys, have a form typical of the larger valleys seen in the Patcham Catchment and may be considered as small-scale examples. Within the survey area, two minor dry valleys orientated NW-SE and NE-SW converge to form a larger dry valley orientated NE-SW (Profiles 6 and 7 - Figure 5.9). This valley then converges with another dry valley orientated NW-SE further down slope from the deep recharge site boreholes - which in turn converges with the main Patcham valley.

Generally, the surveyed hill-slopes were found to be convex with gradients ranging from a minimum of 1° to a maximum of 15°. Breaks of slope do not appear to be strongly related to the bedrock geology although generally higher slope gradients are observed with the transition from the Seaford to Lewes Nodular Chalk Formation. Profiles 3 and 4 (Figure 5.8) highlighted a subtle bowl shaped inflexion observed in the overall convex slope. Similar features are inferred by French (1972, 1996) as relating to periglacial wash processes where snow patches accumulated. The dry valley slopes were found to be typically asymmetrical with the north-west facing slopes (Profiles 6, 7 and 8 - Figure 5.9) having a higher gradient, by between 1° and 5°, than the southeast facing slopes. This asymmetry is in agreement with the observations made by Ollier and Thomasson (1957), Clark (1965), French (1972) and Williams (1986), and is thought to relate to differences in the intensity of periglacial erosion on slopes of different aspect.
The distribution of Quaternary deposits over the survey area was found to be related to geomorphology (Figure 5.6 and Figure 5.7). Clay-with-flints corresponded with higher elevations and low slope gradients on the crests of hills, whereas Head deposits corresponded with lower elevations in the axis of the dry valleys. The occurrence of Clay-with-flints in the South Downs has been demonstrated to be related to the sub-Palaeogene surface (Hodgson et al., 1967; Hodgson et al., 1974; Catt and Hodgson, 1976; Catt, 1986; Quesnel et al., 2003). Clay-with-flints, therefore, tend to occur at higher elevations, capping interflues, closer to where the sub-Palaeogene surface would have occurred. The presence and development of Head deposits in the axes of dry valleys is predominately related to the mass movement of frost shattered material into the valleys via solifluction processes and meltwater during the Pleistocene (French, 1996) - see Chapter 2. In the present day, hill slope processes continue to transport sediments into the dry valleys via creep and hill wash as highlighted by Williams (1986).

The variation in particle size over the survey area does not appear to correlate obviously with the ground conductivity or the field saturated hydraulic conductivity (Figure 5.6 and Figure 5.14). Locations 1-3 and 6-7 located approximately in the centre of the survey area were found to have a principal composition of silt and an overall greater fines content. Locations 4-5 and 8-9 located approximately on the north-east, south-east and west edge of the survey area were found to have a principal composition of sand. This distribution does not display a strong correlation to the underlying geology but some characteristics may be related. For example, Location 6, comprised around 58.5% silt and 17.6% clay, and was found to have a relatively higher proportion of calcite, based on the XRD analysis, indicating the particle size distribution of the soil at this location was less influenced by Quaternary deposits and more influenced by the Chalk bedrock. This location also had the highest measured field saturated hydraulic conductivity of $2.86 \times 10^{-5}$ m/s. The soil structure in the base of the hole at location 6 was noted as being approximately equivalent to chalk CIRIA grade Dc. The presence of voids and discontinuities associated with the fragment chalk, therefore, may account for the higher field saturated hydraulic conductivity. Similarly, the principal and relatively higher sand fraction found at locations 2, 4 and 5 is consistent with the underlying geology being Clay-with-flints and commonly containing pockets of sand.
The majority of the soil samples analysed by XRD, locations 1, 2, 3, 4, 5 and 7, have a mineralogical composition with silica as the primary constituent. These soil samples come from locations which are in the south of the survey area (Figure 5.7). Silica as a primary constituent indicates the soil at these locations has a high input from a silica rich parent material such as the Lambeth Group, Clay-with-flints or brick earth. The Chalk also contains silica in the form of flint. Flint, however, is resistant to weathering, as demonstrated by the experiments of Lautridou et al. (1986a), and tends to form angular gravel size clasts when weathered from the Chalk. It thus is an unlikely contributor to the silica fraction of the fines in these soils. The soil samples from locations 6, 8 and 9 had a mineralogical composition with calcite as the primary constituent. These soil samples come from locations which are situated in the north of the survey area and were furthest from the Clay-with-flints. Calcite as a primary constituent indicates the soils at these locations have a high input from a calcite rich parent material. In the South Downs, calcite in soils maybe derived from the Chalk, from shelly layers within the Lambeth Group or from Quaternary calcretes and loess. The soil samples from locations 6, 8 and 9 were observed to contain chalk clasts. The Chalk, therefore, is interpreted as the primary parent material for these soils.

The minor mineralogical constituents identified in the soil samples analysed by XRD also show spatial variation. The soil samples from all locations have a minor proportion of smectite, illite or kaolinite and, with the exception of locations 4 and 6, a proportion of feldspar. Calcite is also present as a minor constituent in the soil samples from locations 4 and 5. Chalk clasts, however, were observed in the soil at these locations so again it is likely this calcite was originally derived from the Chalk bedrock (Table 5.1). The source of smectite, illite, kaolinite and feldspar in the soil samples, however, maybe mixed. These minerals are known to exist in the Chalk in small proportions from studies on insoluble residues (Perrin, 1964; Weir and Catt, 1965; Young, 1965; Perrin, 1971; Morgan-Jones, 1977; Spears, 1979; Kimblin, 1992; Jeans, 2006). From these studies, smectite is commonly the most abundant mineral in the clay particle size fraction of the insoluble residues and is discussed by many authors as arising from alteration of volcanic ash which was incorporated in the chalk sediments during deposition. Kaolinite in these studies was found to be
significantly less common or absent in the White Chalk Subgroup - which includes the Lewes and Seaford Chalk Formations. Mineralogical analysis by Hodgson et al. (1967) of Lambeth Group – Reading Formation clay and the Winchester Series soils, however, identified these minerals and, in particular kaolinite, at around 20% of the clay particle size fraction of the sample mass. The Winchester Series soils, as demonstrated by Hodgson et al. (1967) and Avery et al. (1959), have typically developed over Clay-with-flints. The model for the genesis of Clay-with-flints, presented by Avery et al. (1959), Loveday (1962), Hodgson et al. (1967), Catt and Hodgson (1976) and Quesnel et al. (2003) (Chapter 2 – Section 2.2), would support a mixed origin for the minerals in the soil samples. That is, Clay-with-flints are thought to have formed from clay which was illuviated from the Palaeogene veneer, and mixed with flints and other insoluble residue released by sub-surface dissolution of the Chalk. The soils samples derived from locations 2, 4 and 5, which overlay the mapped and suspected areas of Clay-with-flints, may be considered as being derived from equivalent horizons to A and Eb in the Winchester Series soils of Hodgson et al. (1967). A progressive decrease in the mineralogical influence of the Clay-with-flints and an increase in the influence of the Chalk bedrock may occur, therefore, at lower elevations and towards the north-east of the survey area – as indicated by locations 6, 8 and 9 (Figure 5.6 and Figure 5.7).

At location 4, the minor constituents differ slightly from the other locations. The minor constituents consist of 13% calcite, 8% illite and 11.2% metal oxides – comprising 6.6% rutile (TiO₂) and 4.6% goethite (FeO(OH)). Rutile is a mineral composed of primarily titanium dioxide and may contain up to 10% iron. Its identification in the sample seems unusual because it is typically associated with metamorphic and igneous rocks. Rutile, however, is weathering resistant and is common in detrital deposits. It has also been identified in studies on the insoluble residues of the Chalk (e.g. Perrin, 1964; Weir and Catt, 1965; Spears, 1979). Goethite is an iron oxide mineral which commonly occurs as a weathering product of iron-bearing minerals in soil and low-temperature environments (Deer et al., 1992). It has a yellow, red to dark brown rust colour. Due to the presence of goethite, the soil colour at location 4 was dark yellowish brown (Table 5.1). This area also has the lowest field saturated hydraulic conductivity of all the locations in the proposed area for the recharge site. The presence of both illite and goethite may have reduced the permeability of the
soil significantly - illite being a clay mineral and goethite forming a cement between soil particles. These mineralogical findings plus the high ground conductivity in this area provide strong evidence to support the idea that the soil at location 4 is likely to overlie an area of unmapped Clay-with-flints (Figure 5.6 and Figure 5.7).

The soil at location 6 has less mineralogical variation than the other soil samples analysed. It is composed of 74.4% calcite, 24.8% silica and 0.8% illite. The very low proportion of illite and high proportion of calcite indicates the soil at this location may represent a soil developed over the Chalk with little influence from the Clay-with-flints. In terms of the preferred geological conditions for the recharge site outlined in Chapter 1, this location is the most suitable compared to the other locations reviewed. That is, it is a site where there is little or no detectable evidence of karst, Palaeogene or Quaternary deposits and the shallow recharge site instrumentation would be installed directly into the Chalk. As demonstrated, however, this is perhaps not entirely representative of the ground profile in the survey area or wider Patcham Catchment.

The XRD analyses from the Hallue Catchment exposures provide a useful comparison to the results from the Patcham Catchment, North Heath Barn survey area. The mineralogical composition of Quaternary and remnant Palaeogene deposits sampled from the Hallue Catchment may be considered as being equivalent to the parent materials that the soils at the North Heath Barn have formed from. Comparison of the mineral constituents supports this (Table 5.2 and Table 5.3). In both sets of samples, the primary mineral components typically consist of silica and calcite, with secondary or minor components of feldspar, smectite, illite and metal oxides – particularly goethite and rutile. The sampled deposits from the Hallue Catchment have a generally purer composition. For example, the remnant Thanétien (Thanet Sand/Upnor Formation) was found to commonly have a silica content of >80% and Formations résiduelles à silex (Clay-with-flints) was commonly found to absent in feldspar. The general proportions of minerals are comparable between the Hallue samples and the Patcham soil samples, with the exception of the samples of Formations résiduelles à silex. These samples from the Hallue Catchment have a much higher smectite and illite clay content (12.1% - 53.2%) than any of the soils analysed from the Patcham North Heath Barn survey (8% - 9.2%).
This perhaps gives an indication of what the composition maybe like of the Clay-with-flints underlying the soil at locations 2, 4 and 5 in the North Heath Barn survey area, and is comparable to samples of Clay-with-flints collected from the wider Patcham Catchment (Table 5.5) by Ullyott (2008). The hydraulic conductivity of Formations résiduelles à silex / Clay-with-flints, with such high proportions of clay minerals, maybe partly inferred from the field saturated hydraulic conductivity measurements collected at the North Heath Barn survey area.

<table>
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<th>Mineral Composition (%)</th>
<th>Location</th>
<th>Mineral Composition (%)</th>
</tr>
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</tr>
<tr>
<td>B1-81-04</td>
<td>71.3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B1-81-06</td>
<td>92.9</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B1-97-23</td>
<td>76.2</td>
<td>-</td>
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<tr>
<td>B1-97-24</td>
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<td>-</td>
<td>-</td>
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<td>B1-97-25</td>
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<td>B1-97-31</td>
<td>87.4</td>
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<td>-</td>
</tr>
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<td>B1-97-39</td>
<td>66.8</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B1-130-08b</td>
<td>80.9</td>
<td>-</td>
<td>6</td>
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<tr>
<td>B1-130-16</td>
<td>63.8</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>B2-08-09</td>
<td>69.3</td>
<td>2.2</td>
<td>-</td>
</tr>
<tr>
<td>B2-09-04</td>
<td>53.1</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 5.5 Mineral composition of Clay-with-flints samples collected in the Patcham Catchment from Ullyott (2008). Minerals identified using X-ray diffraction powder analysis. Proportions of minerals determined by Rietveld simulation – mineral patterns are provided in Appendix VI.
The field saturated hydraulic conductivity measurements from the North Heath Barn survey area were found to display little or no relationship to the fines (clay and silt) content of the soils (Figure 5.14). Similar observations were made by MacDonald et al. (2012) with regard to the principal particle size and field saturated hydraulic conductivity of superficial deposits in Northern Scotland. A clearer correlation was demonstrated by the clay content alone, however, this may be complicated by the presence of clay size particles derived from the Chalk. Perhaps the strongest correlation was displayed by comparing the field saturated hydraulic conductivity with the minor mineral constituents of clay and metal oxide minerals in the soil determined from the XRD analysis. Generally, the field saturated hydraulic conductivity for locations where the soil samples contained smectite clays (locations 1, 2, and 8) was found to be lower than where the soil samples contained illite clays (locations 3, 5, 6 and 7) - with the exception of the soil at locations 4 and 9. One of the characteristics of smectite clays is their ability to take up water between their structural layers and expand (Deer et al., 1992). The presence of smectite clays in soils may, therefore, alter the structure of soils under wet conditions by expanding and reducing the size of voids in the soil, thereby also reducing the hydraulic
conductivity. The correlation of the combined total clay and metal oxides mineral component with field saturated hydraulic conductivity (Figure 5.14), however, suggests that the combined effect of the clay and metal oxide minerals has a more significant impact on hydraulic conductivity than smectite alone.

The lowest field saturated hydraulic conductivity measured in the North Heath Barn survey area was observed at location 4 which is interpreted as being an area of Clay-with-flints. The soil at this location had a total clay and metal oxides mineral component of 19.2% and field saturated hydraulic conductivity of $4.55 \times 10^{-8}$. Klinck et al. (1998) stated that where the hydraulic conductivity of Clay-with-flints is less than $1 \times 10^{-7}$ m/s surface runoff will occur for most rainfall events, leading to point or focused recharge on the margins of the deposits or through voids. For hydraulic conductivities of greater than $1 \times 10^{-7}$ m/s most effective rainfall will infiltrate the Chalk. The data collected from the North Heath Barn survey area, indicates this threshold would be exceeded when the mineralogical component of clays and metal oxides exceed approximately 20-30% in the soil (Figure 5.14). The XRD analyses of samples from the Hallue and wider Patcham Catchment (Table 5.3 and Table 5.4), have demonstrated that the clays and metal oxides in Formations résiduelles à silex / Clay-with-flints deposits commonly equate to or exceeded 20-30%. If these deposits are relatively continuous, this would suggest that surface runoff and point recharge on the margins and through voids in the deposits would be a significant process. Klinck et al. (1998) presented a conceptual model of the potential recharge pathways associated with Clay-with-flints (Figure 5.15).

![Conceptual model of the recharge pathways associated with Clay-with-flints](image)

Figure 5.15 Conceptual model of the recharge pathways associated with Clay-with-flints. The diagram illustrates runoff and recharge processes to the Chalk overlain by and adjacent to Clay-with-flints deposits from Klinck et al. (1998).
The resemblance of features depicted in Figure 5.15 to the Quaternary and remnant Palaeogene materials and karst features photographed in Hallue Catchment is clear (Figure 5.13). This suggests that runoff and point recharge processes may be significant in the Hallue Catchment. Similar infilled karst was also observed in road cuttings on interfluves within the Patcham Catchment during the A27 Brighton bypass construction (Lamont-Black, 1995; Mortimore, 2012).

The results from North Heath Barn survey suggest that the combination of EM31 ground conductivity, field permeameter and mineralogical assessment using XRD analysis may aid rapid assessment and prediction of the susceptibility of soils and Quaternary deposits to runoff recharge processes and focused recharge. This has application for identification of sites of potentially localised rapid groundwater level response – and, due to the potential for focused recharge, also identification of sites of aquifer vulnerability from contamination. At a catchment scale, extensive cover of low permeability deposits, such as Clay-with-flints observed in the Patcham and Hallue catchments, may have a significant effect on recharge and water level response by altering the pattern of recharge across the catchment (Adams et al., 2008).

5.5 Conclusion

The data presented in this chapter have clarified the shallow depth ground conditions at the Patcham Catchment recharge site and surrounding area. By combining data from the EM31 ground conductivity survey with topographical, field saturated hydraulic conductivity, soil particle size and mineralogical data a better understanding has been gained about:

(i) the distribution of Quaternary deposits and soil materials at the Patcham Catchment North Heath Barn recharge site
(ii) the relationship between geomorphology and the distribution of Quaternary deposits and soil materials
(iii) the relationship between geomorphology and the underlying Chalk bedrock stratigraphy
(iv) the processes forming the various soil types
(v) the soil parent materials with respect to the mineralogy of the Chalk, Palaeogene and Quaternary deposits
(vi) probable field saturated hydraulic conductivity rates for different soil materials in the South Downs
(vii) the relationship between soil mineralogy, hydraulic conductivity and recharge processes

Although the data presented in this chapter was derived from reconnaissance surveys and a relatively limited number of samples, it may be considered as a small-scale study of deposits which are present in both the wider Patcham and Hallue catchments. In the context of the conceptual model of a chalk valley presented in Chapter 1, the results presented in this chapter have provided additional information on the Quaternary geology, geomorphology and soil in the Patcham and Hallue catchments. In Chapter 6, the field data from Chapters 3, 4 and 5 are synthesised to form 3D digital ground models based on the conceptual model of a chalk valley present in Chapter 1.
Chapter 6 Geological Modelling of the Catchments

6.1 Introduction

This chapter presents the results from geological modelling of the field data collected in the research catchments. The results and techniques presented in this chapter build on the results presented in Chapters 3-5 and are reviewed in the context of the literature presented in Chapter 2.

A geological model may be considered as anything ranging from a sketch to a parameterised 3D digital representation. It can comprise a mixture of conceptual understanding, factual data and interpolation. The proportion of these components vary dependant on a number of factors such as levels of pre-existing data, time available for modelling and requirements of the model. In essence, however, the purpose of a geological model is to communicate a concept of the geology appropriate to the study.

The original geological modelling requirement for FLOOD1 project was to produce a series of cross sections through the research catchments (Figure 3.6, Figure 3.7, Figure 3.13 and Figure 3.14). To develop this work further, 3D digital ground models were developed for the Hallue and Patcham research catchments. This was made possible by using GIS software available through the University of Brighton and specialist geological modelling software made available through the British Geological Survey. The key objectives for this work were that the models would allow 3D visualisation of the geology within the research catchments and they could be distributed in a format that would not require specialist software.

Stratigraphical data collected from the exposures and boreholes combined with the revised geological maps of the research catchments were used as the primary data for the geological models. Additional data, derived from a number of ground investigations conducted on areas of Chalk outcrop, were also used in the development of the models. The data were derived from ground investigations located in the South Downs, the North Downs, London and Salisbury Plain. Union Rail, the Highways Agency and Southern Water provided these datasets to the University of Brighton as support for the FLOOD1 project.
6.2 Modelling Methodology

6.2.1 Modelling Software

The two main software programmes used for the geological modelling were Esri ArcGIS Desktop 9.0 and GSI3D 1.5.2 (Geological Surveying and Investigation in 3D). Additionally, the geotechnical database software gINT was used for storage and interrogation of AGS format data (AGS, 2004) provided to the FLOOD1 project.

6.2.1.1 ArcGIS Desktop 9.0

ArcGIS is a GIS (geographical information system) software package developed by Esri. ArcGIS can be used for creating, editing and analysing digital spatial data. Digital spatial data takes two main forms: raster and vector. Raster data comprises matrix or grid based spatial data. Raster data can be as simple as a scanned image which has been georeferenced or as sophisticated as a multi-band satellite survey. Vector data comprises points, lines and polygons - where geographical features are expressed as geometric shapes. Most digital mapping data is available in a vector format.

ArcGIS was used in the geological modelling process for digitising, editing and conversion of spatial data for use in GSI3D. This included both raster data such as the OS landform DTM (digital terrain model) data and vector data such as the geological maps of the research catchments. ArcGIS was also used for visualisation of the results of the geological modelling. The main components of ArcGIS which were used for this work were ArcMap, ArcScene, Spatial Analyst and 3D Analyst.

6.2.1.2 GSI3D 1.5.2

Geological Surveying and Investigation in 3-D (GSI3D) is a specialist geological modelling software tool. The initial software tool and methodology was developed during the 1990s by Dr. Hans-Georg Sobisch for use in Quaternary sequences in northern Germany in collaboration with Dr Carsten Hinze and Heinrich Mengeling of the Soil and Geological Survey of Lower Saxony, based in Hanover. From 2000-2004 the British Geological Survey acted as a test bed for the accelerated development of the software and methodology. In 2004 BGS bought a perpetual unrestricted licence for use of GSI3D version 1.5 (Benham et al., 2003; Kessler et
al., 2008). Through the collaboration with the BGS on the FLOOD1 project, it was made possible for the University of Brighton to licence GSI3D 1.5.2.

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Data files loaded into GSI3D These consist of: DTM in Esri ascii grid format (<em>.asc), geological map as Esri shape file (</em>.shp), borehole data in as GSI3D *.bid and *.blg tab separated ascii text files, and cross sections (as well as horizontal sections) as a GSI3D *.gxml text file.</td>
</tr>
<tr>
<td>2</td>
<td>Format files loaded into GSI3D These consist of GSI3D generalised vertical section file (<em>.gvs) and legend file (</em>.gleg) as tab separated ascii text files. These files dictate the vertical stacking, and assign colours and/or textures to the strata.</td>
</tr>
<tr>
<td>3</td>
<td>Construct or edit cross sections A GSI3D geological model is built from a series of intersecting cross section. The cross sections are constructed by manually correlating boundaries between the outcrop map and subsurface data from boreholes logs. Elevation profile is derived from the DTM. Correlation lines comprise a series of nodes which each have a XYZ value and are created as the user constructs the correlation line. Once complete the correlation line is assigned to a particular geological boundary.</td>
</tr>
<tr>
<td>4</td>
<td>Definition of envelopes To define the lateral extent of a geological unit an “envelope” is constructed. This is different to the outcrop area of a geological unit. It must take into account the full lateral extent of the geological unit in plan and therefore must also include its lateral extent in subcrop. This is may become complicated at unconformable contacts.</td>
</tr>
<tr>
<td>5</td>
<td>Calculation of TINs TINs (Triangulated Irregular Networks) are generated from the envelopes, cross sections and DTM. The triangulation method in GSI3D takes into account the structure of the superseding geological units when triangulating and adjusts the new lower TIN surface accordingly.</td>
</tr>
<tr>
<td>6</td>
<td>Calculation of volume model The TINS, which represent the base of each unit, can then be used by GSI3D to produce a solid volume model of the geological units. This can be displayed and interrogated in various ways. The volume model is most easily viewed in the GSI3D 3D window or viewer. The volume model can be interrogated to produce synthetic borehole sticks, cross sections and horizontal slices.</td>
</tr>
<tr>
<td>7</td>
<td>Export model to GSI3D viewer/ export to other software The volume model can be exported to the GSI3D viewer which is a stand-alone tool which does not require the GSI3D software. Once in the GSI3D viewer the model can be easily distributed. In addition, the TIN surfaces modelled in the GSI3D can also be exported as ascii grids for use in other applications such as ArcGIS.</td>
</tr>
</tbody>
</table>

Table 6.1 GIS3D geological modelling steps.

The method of geological modelling in GSI3D replicates the method geologists use to construct cross sections. The data required also is essentially the same but in digital formats i.e. geological maps as shapefiles, topographical maps as digital elevation or terrain models and borehole logs as coded text files. There is also the option of incorporating specialist data such as geophysical, geochemical, hydrogeological or geotechnical data. The GSI3D modelling process (detailed in Table 6.1) involves creating a series of intersecting cross sections; geological boundaries from these cross sections are then triangulated to create geological surfaces and the geological surfaces are used to create a geological volume model.
The modelling process, however, may vary depending on data availability and requirements.

GSI3D 1.5.2 was originally designed for modelling near-surface Quaternary deposits. For the geological modelling of the FLOOD1 research catchments, GSI3D was used primarily for modelling Chalk bedrock geology. The data available for inclusion in the geological models differed between the research catchments. As a result, the standard GSI3D geological modelling workflow required modification. The differences from the standard GSI3D geological modelling methodology are outlined in the following sections.

6.2.2 Stage 1: GSI3D Geological Modelling

6.2.2.1 Hallue Catchment

The Hallue Catchment is the larger of the two FLOOD1 research catchments at 247 km$^2$. It is insufficiently incised to allow cross sections to be constructed from a geological map alone and borehole information is required to provide depth control on the lower stratigraphical boundaries. There were, however, only a limited number of boreholes available with detailed stratigraphical information. The boreholes which have this level of information consist of those drilled for the FLOOD1 recharge site, and logged as part of this work, and a small number of well logs that could be reinterpreted. The GSI3D geological modelling methodology for the Hallue Catchment was, therefore, adapted to model a large area with a low density of borehole information.

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topographical DTM (*.asc)</td>
<td>Institute Géographique National 50 m interval BD ALTI® DTM</td>
</tr>
<tr>
<td>Geological Maps (*.shp)</td>
<td>Bedrock geological map produced from the field work in the Hallue Catchment. Superficial geological map simplified from the BRGM 1:50,000 geological maps for Amiens, Albert Doullens and Bapaume.</td>
</tr>
<tr>
<td>Borehole Data (*.bid and *blg)</td>
<td>Borehole logs from FLOOD1 experimental site, exposure logs, Senlis-le-Sec and Rubempre well logs.</td>
</tr>
<tr>
<td>Top Lower Coniacian and Dieve DEMs (*.asc)</td>
<td>DEMs produced from the top of the Lower Coniacian structures present in Chapter 4 and contours published by D'Arcy and Roux (1971).</td>
</tr>
</tbody>
</table>

Table 6.2 Data used to produce the Hallue Catchment GIS3D geological model.
The boreholes drilled as part of the FLOOD1 project intercepted the stratigraphical range from Middle Turonian to Middle Coniacian – equivalent to the New Pit, Lewes Nodular and Seaford Chalk Formations in the UK. The well logs intercepted the stratigraphical range from Middle Turonian to Lower Campanian – equivalent to New Pit, Lewes Nodular, Seaford and Newhaven Chalk Formations in the UK. The exposures studied provided the greatest density of accurate and detailed stratigraphical information. To use the exposures in GSI3D, synthetic borehole logs were created. The borehole and well logs were used to calculate an average thicknesses for the stratigraphical units. A synthetic log was created for the exposures by calculating the depth to the lower stratigraphical boundaries from those observed in the exposure using the average thickness for the unit. This approach could only be applied where there was a clear marker horizon or boundary identified at an exposure. These synthetic logs were then used for correlation in GSI3D and provided a density of data sufficient to construct cross sections.

The cross sections for the Hallue Catchment GSI3D model were constructed in three stages. Initially, two primary cross sections with the greatest density of logs were constructed - orientated North–South and East–West respectively. Secondary cross sections were then constructed approximately parallel to and cross-cutting the primary cross sections. The secondary cross sections contained fewer logs but in the GSI3D software the levels of boundaries are shown at intersections. This meant that the level of the boundaries from the primary cross sections are shown on the secondary cross sections. This forces three-dimensional consistency and provided control levels on the secondary cross sections. Finally, tertiary cross sections were added to improve the TIN interpolation. The tertiary cross sections were constructed using solely the primary and secondary cross sections and the geological map. The network of cross sections in the Hallue catchment GSI3D model are shown in Figure 6.1.

To assist with the initial cross sections, the structure contours on the top of the Lower Coniacian were used as a guide. In ArcGIS the contours were used to create a TIN surface. The TIN was converted to a raster format and exported to an ascii grid which could be imported into GSI3D as a DEM (digital elevation model). Once
imported into GSI3D a trace of the DEM appeared on all cross sections and acted as a guide for a correlation between logs.

The main focus of the geological modelling of the research catchment was the Chalk bedrock. The majority of the new data collected during the fieldwork and used for the construction of the cross sections provided only stratigraphical information for the Chalk and not the remnant Palaeogene and Quaternary deposits. Approximately 80% percent of the Hallue Catchment is mantled with these younger deposits – although only around 1% is of Palaeogene age. It was thought, therefore, that these deposits should be represented in the model despite there being insufficient borehole data to model them accurately.

These deposits were simplified from the BRGM geological maps for inclusion in the model. Envelopes were created for the Thanétien deposits, Formations résiduelles a silex, Limons des plateaux, Colluvions and Alluvion recente/anciennes – equivalent to the Thanet Sand/Upnor Formation, Clay-with-flints, loess, colluvium, alluvium and river terrace deposits in the UK. This process was complicated for some deposits due to differences in interpretation and mapping between the BRGM geological maps. In these cases, the envelope constructed was the best approximation of the geometry feasible.

The bases of the remnant Palaeogene and Quaternary deposits were modelled simplistically - the steps undertaken in ArcGIS are outlined in Table 6.3. Logs for the catchment which penetrated these deposits were reviewed and an average depth for the deposit was derived - typically this was 5 m. The envelope for the deposit was then used to crop out a portion of the DTM for the area the deposit covered. The extracted portion of the DTM was then offset by the average depth of the deposit. The cell centres of the raster were converted to a point shapefile using ArcToolbox Conversion Tools. The points within 50 m of the envelope boundary were then selected and the depth of the points in this area were reduced to half the average depth. This was repeated again at 10 and 0 metres from the boundary and the depth of the points in this area were reduced to a quarter and zero of the
Figure 6.1 Location of GSI3D cross sections constructed through the Hallue Catchment. (Mapping © IGN 2011). Primary sections highlighted light blue.
average depth. The purpose of this was to simulate a more geologically realistic scenario whereby the thickness of the unit thins towards its boundary. The coordinates of the DTM points were then calculated and the coordinates and depth values were converted to *.dat XYZ tab separated text files. These text files were imported into GSI3D for calculation of the TIN for each respective deposit using the ‘Add scattered data points’ function. This approach was applied to modelling all the Quaternary and remnant Palaeogene deposits represented in the Hallue Catchment GSI3D model.

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Area of topographical DTM covered by deposit extracted by deposit envelope using: <em>ArcGIS Toolbox &gt; Spatial Analyst &gt; Extract by mask</em></td>
</tr>
<tr>
<td>2</td>
<td>Extracted portion of topographical DTM offset to average depth of deposit using: <em>Spatial Analyst Toolbox &gt; Raster Calculator &gt; [VALUE]-(average depth)</em></td>
</tr>
<tr>
<td>3</td>
<td>Extracted portion of DTM converted to a point feature dataset using: <em>ArcToolbox &gt; Conversion Tools &gt; From Raster &gt; Raster to Point</em></td>
</tr>
<tr>
<td>4</td>
<td>The depth value of points which lie within 50 m of the boundary are reduced to a half using: <em>Select By Location &gt; Field Calculator &gt; [VALUE]+((average depth)/2)</em></td>
</tr>
<tr>
<td>5</td>
<td>The depth value of points which lie within 10 m of the boundary are reduced to a quarter using: <em>Select By Location &gt; Field Calculator &gt; VALUE+((average depth)/4)</em></td>
</tr>
<tr>
<td>6</td>
<td>The depth value of points which lie in contact with the boundary are reduced to no depth: <em>Select By Location &gt; Field Calculator &gt; VALUE+(average depth)</em></td>
</tr>
<tr>
<td>7</td>
<td>The coordinates for the points are calculated using: <em>ArcTool Box&gt; General &gt;Add XY coordinates</em></td>
</tr>
<tr>
<td>8</td>
<td>All fields are hidden in the attribute table except Easting, Northing and Depth. The attribute table is exported as a DBF file: *Options &gt;Export... <em>.DBF</em></td>
</tr>
<tr>
<td>9</td>
<td>DBF file opened in Excel and saved as a tab separated *.dat text file for import in GSI3D</td>
</tr>
</tbody>
</table>

Table 6.3 Steps undertaken in ArcGIS for preparation of XYZ text files for modelling of remnant Palaeogene and Quaternary deposit in GSI3D.

The modelled units in the Hallue Catchment GSI3D model from the first stage of modelling are shown in Figure 6.1. These consist of Upper Turonian – Lower Coniacian Chalk (C3c-4a), Middle – Upper Coniacian Chalk (C4bc), Santonian Chalk (C5d-f), Thanetian sand (E), Formation Residuelles (Rs), Ancient and Modern Alluvium (F), Limon des Plateaux (OE) and Colluvions (C). The highest bedrock model surface is the base of unit C5d-f (Santonian). A number of exposures in the Hallue Catchment indicated that in the Upper Santonian there is a change in lithology with the return of thin marl seams and discontinuous flint horizons. There were insufficient data, however, to map out the Middle/Upper Santonian boundary from field exposures. The approximate thickness for the Lower and Middle
Santonian unit could be estimated by reviewing the difference in elevation between the Upper Coniacian/Lower Santonian boundary and the Upper Santonian exposures. Using this thickness and the base of unit C5d-f (Santonian) – the outcrop area of the Upper Santonian could be predicted using ArcGIS and the unit modelled simplistically in GSI3D.

To do this, the GSI3D TIN for the base of the Santonian (C5d-f) was exported to an Esri Ascii grid file and imported into ArcGIS. The various steps undertaken in ArcGIS are indicated in Table 6.4. A raster for the predicted base of the Upper Santonian was then produced by adding the estimated thickness in metres (35 m) of the Lower and Middle Santonian to the base of the Santonian (C5d-f) raster. The new Upper Santonian raster, however, had a lateral extent equivalent to the base of the Santonian (C5d-f) and the edges of the surfaces protruded above the topographical DTM. To resolve this, and determine the outcrop extent of the Upper Santonian raster, three further steps were required. Firstly, the protruding edges of the raster required removing. To do this, a calculation was performed with the raster calculator whereby the new raster for the base of the upper Santonian was taken away from the topographical DTM. The result raster from this calculation produced negative numbers where the raster protruded above the topographical DTM and positive numbers where the Upper Santonian raster was below the topographical DTM. The result raster was then re-classified so that all negative numbers are treated as NoData thereby removing them from the raster. The reclassified raster then represented the predicted outcrop extent of the Upper Santonian. The reclassified result raster was then converted to a polygon feature dataset. This polygon feature was imported into GSI3D and used to define the envelope for the Upper Santonian unit and also used to clip the predicted base of the Upper Santonian to its outcrop area. The predicted outcrop area of the Upper Santonian is shown in the revised bedrock geological map shown in Figure 6.2. The raster for the base of the Upper Santonian was converted to a point feature data set and used to create an XYZ table separated *.dat text file which could be imported into GSI3D to model the base of the unit.
<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>GSI3D TIN for the base of the Santonian (C5d-f) exported to Ascii Grid format and imported into ArcGIS using: <strong>ArcToolbox &gt; Raster &gt; Ascii to Raster</strong></td>
</tr>
<tr>
<td>2</td>
<td>The base of the Upper Santonian (C5f) predicted by adding the thickness in metres of the Middle and Lower Santonian (C5d-e) to the base of the Santonian raster using: <strong>Spatial Analyst Toolbar &gt; Raster Calculator… &gt; [VALUE]+(thickness of C5d-e)</strong></td>
</tr>
<tr>
<td>3</td>
<td>To identify the areas of the upper Santonian raster protruding above the topographical DTM a calculation was conducted using: <strong>Spatial Analyst Toolbar &gt; Raster Calculator… &gt; [VALUE]-[DTM]-[C5f]=[RESULT]</strong></td>
</tr>
<tr>
<td>4</td>
<td>To determine the outcrop extent of the Upper Santonian (C5f) the result from step was reclassified using: <strong>Spatial Analyst Toolbar &gt; Reclassify &gt; -[VALUE] reclassified as NoData</strong></td>
</tr>
<tr>
<td>5</td>
<td>Result from step 4 is converted to a polygon feature and imported into GSI3D to create an envelope for the Upper Santonian (C5f) unit: <strong>ArcToolbox &gt; Conversion Tools &gt; From Raster &gt; Raster to Polygon</strong></td>
</tr>
<tr>
<td>6</td>
<td>Result from step 5 is used as a mask to clip the base of the Upper Santonian (C5f) raster: <strong>ArcToolbox &gt; Spatial Analyst &gt; Extract by mask</strong></td>
</tr>
<tr>
<td>7</td>
<td>Result from step 6 is converted to a point feature class using: <strong>ArcToolbox &gt; Conversion Tools &gt; From Raster &gt; Raster to Point</strong></td>
</tr>
<tr>
<td>8</td>
<td>The coordinates for the points are calculated using: <strong>ArcTool Box&gt; General &gt; Add XY coordinates</strong></td>
</tr>
<tr>
<td>9</td>
<td>All fields are hidden in the attribute table except Easting, Northing and Depth. The attribute table is exported as a DBF file: *<em>Options &gt; Export… &gt; <em>.DBF</em></em></td>
</tr>
<tr>
<td>10</td>
<td>DBF file opened in Excel and saved as a tab separated *.dat text file for import in GSI3D</td>
</tr>
</tbody>
</table>

Table 6.4 Steps undertaken in ArcGIS for predicting and modelling the Upper Santonian (C5f) in the Hallue Catchment GSI3D geological model.

The final stage of the modelling process was capturing the GSI3D geological model of the Hallue Catchment into the GSI3D subsurface model viewer. This was undertaken by Holger Kessler and Ricky Terrington at BGS Keyworth and the model files were transferred to a BGS ftp site with accompanying opening slide and map for incorporation into the viewer. The map included showed the position of springs in the catchment.
Figure 6.2 Predicted outcrop area of Upper Santonian and Lower Campanian Chalk, equivalent to the Newhaven Chalk Formation, in the Hallue Catchment. The outcrop area was predicted by using the Hallue GSI3D model and estimating the Lower Santonian – Middle Santonian unit thickness. (Mapping © IGN 2011)
6.2.2.2 Patcham Catchment

The Patcham Catchment is the smaller of the two FLOOD1 research catchments at 38 km². It is more incised then the Hallue Catchment which allows cross sections to be partially constructed from the geology map - although borehole information is required to provide depth control on the lower stratigraphical boundaries. The Patcham Catchment had been geologically modelled previously as part of the 3D conceptualisation of the central South Downs aquifer by the BGS (Robins, 2001). The GSI3D geological modelling methodology for the Patcham Catchment was, therefore, adapted to refine an existing geological model with new borehole data – with the overall model covering a smaller area than the Hallue Catchment model.

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topographical DTM (*asc)</td>
<td>Ordnance Survey Landform Profile 10 m DTM</td>
</tr>
<tr>
<td>Geological Maps (*shp)</td>
<td>Bedrock geological map adapted from the digital bedrock Brighton and Worthing 1:50,000 sheet (318/333) based on the field work in the Patcham Catchment. Superficial geological map adapted from the digital superficial Brighton and Worthing 1:50,000 sheet (318/333) based on the field work in the Patcham Catchment.</td>
</tr>
<tr>
<td>Borehole Data (*bid and *blg)</td>
<td>Borehole logs from FLOOD1 experimental site, geophysical borehole logs from EA observation boreholes, Southern Water borehole from Pyecombe East and West, A27 Brighton Bypass boreholes</td>
</tr>
<tr>
<td>Base of Lewes Nodular Chalk Formation DEM (*asc)</td>
<td>DEM from the contours presented in Figure 4.14 in Chapter 4.</td>
</tr>
<tr>
<td>Base West Melbury Chalk Formation DEM (*asc)</td>
<td>DEM from the Vulcan model of the central South Downs aquifer produced by BGS.</td>
</tr>
</tbody>
</table>

Table 6.5 Data used to produce the Patcham Catchment GSI3D geological model.

The extent of the Patcham GSI3D geological model is shown in Figure 6.3 by the limits of the geological map shown. This extent is larger than the Patcham Catchment itself but was chosen because it encompassed the area which was covered by the hydrogeological model for the Patcham Catchment developed by the BGS FLOOD1 team. The cross sections for the Patcham Catchment GSI3D model were constructed in three stages – similarly to the Hallue Catchment GSI3D model. Initially, four primary cross sections with the greatest density of logs were constructed - orientated North–South and East–West respectively. Secondary cross sections were then constructed approximately parallel to and cross cutting the primary cross sections. The secondary cross sections contained fewer logs but
Figure 6.3 Location of GSI3D cross sections constructed through the Patcham Catchment. The extent of the geological map shown indicates the extent of the Patcham Catchment GSI3D geological model. Geological map adapted from British Geological Survey (2006a). Primary sections highlighted light blue.
in the GSI3D software the position of boundaries are shown at the intersections between the primary and secondary cross sections. This facilitated correlation by providing control levels on the secondary cross-sections. It also forced three-dimensional consistency between the primary and secondary cross sections. Surfaces from the Vulcan model of the central South Downs were provided by Helen Rutter from the BGS FLOOD1 team. The Vulcan surfaces were used as a guide on the cross sections where there was little or no borehole information available. Finally, tertiary cross sections were added to improve the TIN interpolation. The tertiary cross sections were constructed using only the primary and secondary cross sections, Vulcan surfaces and the geological map.

The network of cross sections in the Patcham catchment GSI3D model are shown in Figure 6.3. Many of the sections constructed for the Patcham Catchment geological model were extended outside of the model boundary to correlate with borehole information available in the wider Brighton area. The purpose of this was to get a wider understanding of the geological structures outside of the model area. This can be seen in Figure 6.3 – with higher density sections constructed in the model area shown in Figure 6.3 and Figure 6.4. As with the Hallue Catchment, the density of boreholes was too low for modelling the Quaternary deposits accurately. The Quaternary deposits were, therefore, modelled using the same simplistic methods as in the Hallue Catchment - the various steps undertaken in ArcGIS are defined in Table 6.3. Logs for the catchment which penetrated these deposits were reviewed and an average depth for the deposit was derived - typically this was 3 m. This approach was applied to modelling all the Quaternary deposits represented in the Patcham Catchment GSI3D model.

The modelled units in the Patcham Catchment GSI3D geological model from the first stage of modelling are shown in Figure 6.3. As with the Hallue Catchment, the final stage of the modelling process was capturing the GSI3D geological model of the Patcham Catchment into the GSI3D subsurface model viewer. This was undertaken by Holger Kessler and Ricky Terrington at BGS Keyworth and the model files were transferred to a BGS ftp site with accompanying opening slide and maps for incorporation into the viewer. The maps included comprised a map of the known
spring positions and groundwater flooding extent and a map of the location of known karst in the catchment.

Figure 6.4 Location of GSI3D cross sections constructed through the Patcham Catchment. Primary sections highlighted light blue. Geological map adapted from British Geological Survey (2006a). (OS mapping © Crown Copyright 2007)
6.2.3 Stage 2: Modelling Discrete Horizons

6.2.3.1 Engineering Rockhead

The geological unit that represents potentially the greatest physical change in the Chalk rock mass, after the variation in primary lithology and fracturing, is the weathered zone – the base of which is commonly regarded as engineering rockhead, the base of the engineering soil, in areas of Chalk outcrop. The weathered zone is also located predominantly in the unsaturated zone of the aquifer – which was the focus for FLOOD1 research project. Chalk has been subjected to both chemical and mechanical weathering in a variety of climates since its uplift and exposure in the Early Palaeogene (Lord et al., 2002) – see Chapter 2 Section 2.2. The majority of weathering of chalk is in the form of chemical dissolution as a result of acidic meteoric waters and mechanical weathering by plant roots and frost on exposure (Lord et al., 2002). In particular, freeze-thaw cycles in periglacial conditions at the end of the Devensian glaciation 14,000 years ago, and during the Loch Lomond readvance some 13,000-11,500 years ago, reduced exposed chalks to metastable silts (Lord et al., 2002) or ‘putty chalk’ which is commonly found as chalk Head and valley-fill deposits (e.g. Fookes and Best, 1969).

Culshaw (2005) stated that models of geological rockhead, i.e. the base of superficial deposits, need to be complemented by a model that can predict the depth to engineering rockhead - and that the transition to engineering rockhead is unpredictable because of weathering effects. Jones (1999b) indicated that the North and South Downs have experienced relatively low rates of denudation - particularly since exhumation from below the Palaeogene deposits in the Pleistocene (Figure 2.6). This suggests the geomorphology of the Chalk downland in the research areas has been relatively stable and changed little since the end of periglacial conditions in southern England. The weathered zone therefore, which Lord et al. (2002) stated is closely related to geomorphological setting, may also have remained relatively stable. Williams (1987), Mortimore et al. (1996) and Lord et al. (2002) presented conceptual models (Figure 1.2 and Figure 2.12) of the weathered zone and engineering rockhead which illustrate this relationship. The base of the weathered zone or engineering rockhead on areas of Chalk outcrop is seen to vary in response to ground relief, slope aspect and slope gradient.
The methodology presented here was developed to predict the base of the weathered zone, or engineering rockhead, based on this observed relationship between geomorphology and weathering on areas of Chalk outcrop. To develop a method for predicting the base of the weathered zone borehole data from a number of ground investigations on areas of Chalk outcrop were studied. The borehole data were derived from the FLOOD1 recharge sites boreholes in the South Downs and the Somme; the A27 Brighton Bypass and Lewes CSO Scheme ground investigations in the South Downs; the Channel Tunnel Rail Link ground investigation in the North Downs; and the A303 Stonehenge Bypass ground investigation on Salisbury Plain.

A fracture discontinuity profile was produced for the exploratory holes in each of the datasets. Due to the ground investigations being of different ages, the fracture data in each dataset required standardisation into one format. To this end, the fracture data was reclassified to be consistent with BSI (2003) and CIRIA chalk grade suffixes 1-5 (Lord et al., 2002). For some data, this required conversion from Munford Grades or the average/typical fracture interval. The Munford Grades were converted using Table 2 in Spink (2002). Discontinuity spacing was considered to be a reasonably consistent measurement irrespective of the age of data or type of exploratory hole e.g. trial pit or borehole. In-situ discontinuity aperture, however, cannot be measured from borehole core and fractures are assumed to be closed if discontinuities are clean and free from infill (Spink, 2002). This assumption, however, is complicated where fractures are not infilled but their surfaces are mineralised or have relief due to shearing or dissolution. Some workers assume apertures for fractures with these characterises but this assumption is subjective. Discontinuity aperture was, therefore, not included in this analysis due to the majority of data being derived from borehole core.

The discontinuity profiles for each exploratory hole were reviewed and exploratory holes that demonstrated a natural progression through the discontinuity grades from high to low with depth were used. If a discontinuity profile had a discrete fracture or fault zone, which could be identified, this profile was also retained. Exploratory holes with unusual discontinuity profiles as result of localised conditions such as karst or extensive faulting were not used. The objective of this analysis was to develop a simple model which could predict the base of the weathered zone from the
relationship between geomorphology and weathering in areas of Chalk outcrop. The ability to predict unusual, locally highly weathered Chalk, therefore, was beyond the scope of this model. Once all the discontinuity profiles had been reviewed, the depth to the base of CIRIA grade suffix 5-2 were plotted against the exploratory hole elevation.

To be able to compare the exploratory hole data from significantly different geomorphological regions (e.g. South Downs, Salisbury Plain), and evaluate the relationship between topography and discontinuity spacing, the elevations for the boreholes required converting from absolute values to a relative standardised form. This is because the focus of this study was to derive a relationship for the change in depth of the base of the weathered zone (engineering rockhead) relative to topography i.e. interfluves and valleys. The average elevation and relief may vary significantly between geomorphological regions (Table 6) and, therefore, the exploratory hole data required compensating for these factors. Other regional factors which were not compensated for but could influence the data are variation in periglacial processes and Chalk lithostratigraphy. A method for transformation of data to standard normal form is presented by Davis (1986), and is as follows:

$$Z_i = \frac{X_i - \bar{X}}{s}$$

where $X_i =$ variable, $\bar{X} =$ mean of the variable, $s =$ standard deviation of the variable, $Z_i =$ standardised variable. In this instance, the variable ($X_i$) is the elevation of the exploratory hole. The mean ($\bar{X}$) and standard deviation ($s$) of the variable is the mean and standard deviation of the elevation of the Chalk outcrop in the respective geomorphological region. The standardised variable ($Z_i$) is the standardised elevation of the exploratory hole. This is effectively the relative change in elevation of the top of the exploratory hole expressed as standard deviations from the mean elevation in a geomorphological region.

The exploratory hole discontinuity data were separated into the geomorphological regions of the North Downs, the South Downs and Salisbury Plain. For each region, the mean elevation and standard deviation were calculated. To do this the Ordnance Survey Landform Profile 50 m DTM and the BGS 1:50,000 digital bedrock geological maps were acquired for each region. In ArcGIS, the bedrock geological maps were
used to create polygons of the Chalk outcrop relevant to the location of the ground investigation exploratory holes. The boundaries of these polygons comprise either the limit of the Chalk outcrop or a dissecting valley. In the North Downs, the polygon consists of the Chalk Outcrop between the River Darent and the Great Stour. In the South Downs, the polygon consists of the Chalk Outcrop between the River Adur and the River Ouse. In Salisbury Plain, this polygon consists of the Chalk Outcrop north of the River Nadder and west of the River Bourne. These polygons were used to extract the relevant areas of the Chalk outcrop from the DTM's (Figure 6.5). The mean elevation and standard deviation for these extracted DTM's (Table 6.6) were then used to standardise the exploratory hole elevation.

![Figure 6.5](image)

Figure 6.5 Location of Ordnance Survey Landform Profile 50 m DTM extracts used to derive statistics for standardisation of exploratory hole elevation. (OS Mapping © Crown Copyright 2007)

<table>
<thead>
<tr>
<th>Geomorphological Region</th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Downs</td>
<td>0</td>
<td>235</td>
<td>88.23</td>
<td>58.33</td>
</tr>
<tr>
<td>South Downs</td>
<td>0</td>
<td>248</td>
<td>82.66</td>
<td>53.9</td>
</tr>
<tr>
<td>Salisbury Plain</td>
<td>43</td>
<td>284</td>
<td>134.06</td>
<td>37.67</td>
</tr>
</tbody>
</table>

Table 6.6 Elevation statistics for the Ordnance Survey Landform Profile 50m DTM extracts. The mean and standard deviation for each geomorphological region were used to standardise exploratory hole elevation.

The depths of CIRIA grade suffixes 5-2 were plotted against the exploratory hole standardised elevation (Figure 6.6). In Figure 6.6, the standardised elevation \( Z_i \) of zero equates to the mean elevation of all the geomorphological regions. Negative
values of standardised elevation equate to higher elevations or interfluves and positive values of standardised elevation equate to lower elevations or valleys. It can be seen in Figure 6.6 that the base of CIRIA grade suffixes 5-3 generally occur or cluster at shallower depths for negative values of standardised elevation and deeper depths for positive values of standardised elevation. The base of CIRIA grade suffix 2, however, does not display a similar relationship. This supports the observed fracturing or discontinuity relationships presented in the conceptual ground profiles of Williams (1987), Mortimore et al. (1996) and Lord et al. (2002). That is, more intense fracturing or discontinuities are seen to occur at shallower depths on interfluve areas and deeper depths in valley areas. From Figure 6.6, the base of CIRIA grade suffixes 4 and 3 commonly represent the last physical boundary at which topography impacts discontinuity spacing in the Chalk rock mass - although the base of CIRIA grade suffix 4 displays perhaps the stronger overall relationship.

![Diagram showing the relationship between standardised elevation and depth to base of CIRIA grade suffixes.](image)

Figure 6.6 CIRIA chalk grades for cored boreholes from the A27 Brighton Bypass, Channel Tunnel Rail Link and Stonehenge Bypass ground investigations plotted against standardised elevation.

To represent this relationship, two curves were modelled to the data displayed in the Figure 6.6. Curve A was modelled to represent the lowest boundary where discontinuity spacing displayed a relationship to topography and above which 90% of the data plotted. Curve B, with a slightly lower gradient, was modelled to represent the lower boundary to the highest density area above which 75% of the data plot. At
the mean elevation ($Z_i = 0$) these curves give a depth of 20 and 14 m below ground level respectively. These depths are consistent with those noted for weathered Chalk in the South Downs by Williams (1986). Lawrence (2007), from interpretation of seismic sections on the south coast of England and northern France recognised a change in seismic velocity at around 20-26 m below ground level which he attributed to the depth at which stress relief or unloading occurred leading to dilation of fractures. Lawrence (2007) also indicated that this surface was not necessarily the base of the weathered zone but, in some places, weathering may have penetrated to this depth. Similarly, Molyneux (2012), from permeability tests on partially fractured chalk samples, found that around an equivalent confining pressure of 20 m depth the fractures would close and the permeability of the sample would become equivalent to that of the matrix without fractures. These two observations indicate Curve A may represent the stress relief boundary where fractures begin to open and Curve B, above which the majority of the discontinuity data fall, may be considered as representing the typical base of the weathered zone or engineering rockhead.

To test Curve B, it was used to generate a predicted profile for the base of the weathered zone in an area where the discontinuity profile was well recorded. The discontinuity profile chosen was derived from Newman et al. (2003) for the Ramsgate Harbour Approach Road. Newman et al. (2003) presented two discontinuity profiles. The first profile was based on ground investigation data prior to construction and the second profile was based on face logging in the tunnel during construction. The base of Munford grade IV/III (pre-construction) and CIRIA grade suffix 3 (construction) from these profiles was taken as equivalent to the base of the weathered zone and plotted with the predicted profile from Curve B in Figure 6.7.

It can be seen from Figure 6.7 that the predicted base of the weathered zone profile generated from Curve B consistently follows or lies between the pre-construction and construction profiles of Newman et al. (2003). In the west, the predicted curve follows more closely the pre-construction profile whereas in the east the predicted curve more closely follows the construction profile. The pre-construction profile shows a large inflexion in the west at around 100 m, which is not in the predicted profile. Based on Newman et al. (2003), this inflexion has resulted from the logs of one or two boreholes and was not seen during construction so is regarded as a
logging anomaly. The predicted profile, therefore, generally gives reasonable agreement to the pre-construction and construction profiles considering that it only utilises topographical data to predict the base of the weathered zone and does not take into account localised factors which may affect the depth of weathering such as faulting.

Figure 6.7 Predicted base of the weathered zone for the Ramsgate Harbour Approach Road Tunnel. Elevation data for topography, tunnel crown and invert, pre-construction profile (base Munford grade IV/III) and construction profile (base CIRIA grade suffix 3) derived from Newman et al. (2003).

Curve B was then used to model a predicted surface for the base of the weathered zone for the Hallue and Patcham catchments using the OS and IGN DTMs. To do this, the DTMs required conversion into standardised elevation first. This was done in ArcGIS using Spatial Analyst Toolbar > Raster Calculator. The base of the weathering zone surface was then calculated from the standardised elevation DTM for each catchment using the formula for Curve B. The result from this calculation can be seen in Figure 6.8, where the grey surface represents the topographical DTM for an area of chalk outcrop and the red surface represents the calculated base of the weathered zone or engineering rockhead.
Figure 6.8 Illustration of the base of the weathered zone surface calculated in ArcGIS from a digital terrain model for the Patcham Catchment. View is of Hollingbury interfluve, with London Road valley to the left and Lewes Road valley to the right of the lower image. Note the relative difference in slope gradients between the topographic surface and the weathered zone surface.

The topographical DTMs used to calculate the base of the weathered zone (engineering rockhead) were bare earth DTMs i.e. they represent the ground surface with buildings removed. For predicting the base of the weathered zone, the calculation assumes that the ground surface is approximately equivalent to the top of the Chalk bedrock. This, however, does not take into account the presence of Quaternary superficial deposits. To compensate for the presence of Quaternary superficial deposits the calculated base of the weathered zone or engineering rockhead was offset by the estimated thickness of the Quaternary superficial deposits. This was done in ArcGIS by creating a raster for the base of the superficial deposits and then subtracting this raster from the base of the weathered zone surface or engineering rockhead surface using Spatial Analyst Toolbar > Raster Calculator. The steps undertaken in ArcGIS are outlined in Table 6.7.
<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
</table>
| 1 | Create a polygon feature for each superficial unit in the GSI3D models: 
  *ArcCatalog > File > New > Shapefile…* |
| 2 | Select and copy the geometry of each superficial unit from the BGS digital geological map to the respective new polygon feature: *Editor > Start Editing > Select > Copy > Paste* |
| 3 | Dissolve all parts of the new feature using: 
  *ArcToolbox > Data Management Tools > Generalization > Dissolve by FID* |
| 4 | Add a field called “VALUE” to the feature for the superficial deposits thickness. Populate field by: 
  *Attribute Table > Field Calculator > VALUE = X m* |
| 5 | Create a polygon feature for the extent of the base of the weathered zone surface using: 
  *ArcToolbox > Conversion Tools > From Raster > Raster to Polygon* |
| 6 | Dissolve all parts of the feature using: 
  *ArcToolbox > Data Management Tools > Generalization > Dissolve by FID* |
| 7 | Add a field called “VALUE” to the result from step 6. Populate field by: 
  *Attribute Table > Field Calculator > VALUE = 0* |
| 8 | Clip the result from step 4 using result from step 7 using: 
  *ArcToolbox > Analysis Tools > Extract > Clip* |
| 9 | Combine the result of step 7 and 8 using: 
  *ArcToolbox > Analysis Tools > Overlay > Union* |
| 10 | Convert result of step 9 to raster and select the VALUE field to assign the value to the raster: 
  *ArcToolbox > Conversion Tools > To Raster > Polygon to Raster* |
| 11 | Subtract the result of step 10 from the engineering rockhead surface using: 
  *Spatial Analyst Toolbar > Raster Calculator…* |

Table 6.7 Steps undertaken in ArcGIS to adjust engineering rockhead surface for superficial deposits.

### 6.2.3.2 Water Table and Marl Seams

Discrete layers are surfaces or boundaries which, at the scale of the geological model, have negligible unit thickness. These surfaces may be stratigraphical, for example marker horizons, or non-stratigraphical, for example a water table. Discrete layers were incorporated into the subsurface viewers of the Hallue and Patcham geological models to provide additional ground information. The discrete layers incorporated in the GSI3D subsurface viewer of the Hallue Catchment geological model were the base of the weathered zone and the typical water table which was provided by BRGM (Figure 6.9 and Figure 6.10). The discrete layers incorporated in the GSI3D subsurface viewer of the Patcham Catchment geological model are shown in Figure 6.9, Figure 6.10 and listed in Table 6.8.

The marl horizons were incorporated into the Patcham Catchment geological model because they were observed, at the FLOOD1 recharge site in the Patcham Catchment, to cause perched water tables in the unsaturated zone (Adams et al., 2008; Molyneux, 2012). With the exception of the Iford Marls, all the marls represented in the Patcham Catchment geological model are regarded as volcanogenic marls (Wray, 1999; Mortimore et al., 2001). Due to the small thickness
of the marls (~ 0.10 m) the marl units could not be modelled easily from constructing sections alone at the scale of the sections used in the stage 1 modelling. The marl seams, therefore, were modelled using a simplistic method. The base of the Lewes Nodular Chalk was taken as equivalent to the Glynde Marl 1. This surface was exported from GSI3D as an Esri ascii grid file and imported into ArcGIS as a raster. The average vertical distance between the Glynde Marl 1 and the other marls was calculated from the new borehole information in the Patcham Catchment. The average distances were used to calculate raster surfaces for the other marls by adding these distances as offsets to the Glynde Marl 1 surface. The steps undertaken in ArcGIS are outlined in Table 6.9. The limitation of this method is that it discounts local variations in sediment thickness and local loss of the marl seams both of which are known to occur in the Chalk. By incorporating these layers into the Patcham Catchment geological model, however, it visually highlights their potential presence and the possible effect which they may have on groundwater flow in the unsaturated and saturated zones of the aquifer.

<table>
<thead>
<tr>
<th>Number</th>
<th>Layer Type</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rock mass</td>
<td>Base of the weathered zone/ engineering rockhead</td>
</tr>
<tr>
<td>2</td>
<td>Water table</td>
<td>Peak 2000 groundwater flooding</td>
</tr>
<tr>
<td>3</td>
<td>Water table</td>
<td>March 1993</td>
</tr>
<tr>
<td>4</td>
<td>Water table</td>
<td>September 1993</td>
</tr>
<tr>
<td>5</td>
<td>Stratigraphic</td>
<td>Lewes Marl</td>
</tr>
<tr>
<td>6</td>
<td>Stratigraphic</td>
<td>Bridgewick Marl 1</td>
</tr>
<tr>
<td>7</td>
<td>Stratigraphic</td>
<td>Caburn Marl</td>
</tr>
<tr>
<td>8</td>
<td>Stratigraphic</td>
<td>Glynde Marl 1</td>
</tr>
<tr>
<td>9</td>
<td>Stratigraphic</td>
<td>Southerham Marl 1</td>
</tr>
<tr>
<td>10</td>
<td>Stratigraphic</td>
<td>New Pit Marl 2</td>
</tr>
<tr>
<td>11</td>
<td>Stratigraphic</td>
<td>New Pit Marl 1</td>
</tr>
<tr>
<td>12</td>
<td>Stratigraphic</td>
<td>Iford Marl 2</td>
</tr>
<tr>
<td>13</td>
<td>Stratigraphic</td>
<td>Iford Marl 1</td>
</tr>
</tbody>
</table>

Table 6.8 Discrete layers incorporated into the GSI3D subsurface viewer of the Patcham Catchment geological model

The surfaces for these discrete layers could not be incorporated into the subsurface viewers in raster format and required conversion to lenses. A lens in GSI3D sits outside the generalised vertical section sequence and may cross-cut the stratigraphic boundaries in the model. A lens, however, requires a top and a base surface. The existing surfaces for the discrete layers were taken as the base surfaces of the lenses and top surfaces were created. To create the top surfaces an offset was added to the discrete layer using Spatial Analyst Toolbar > Raster Calculator. For the base of the weathered zone and the water table this offset was 0.5 m and for the marls this offset was 0.10 m. All top and base for each lens were
then exported to an Esri ascii grid format. These were then converted to GSI3D TINs before incorporation into the subsurface viewers.

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
</table>
| 1    | Base of Lewes Nodular Chalk export from GSI3D as an Esri ascii grid file  
      | File > Export > Grid *.asc |
| 2    | Esri ascii grid file import to ArcGIS as a Esri raster using:  
      | ArcToolbox > Import to Raster > Ascii to Raster |
| 3    | Imported raster assumed equivalent to Glynde Marl 1. Calculate rasters for other marls  
      | by adding offset to Glynde Marl 1 using:  
      | Spatial Analyst Toolbar> Raster Calculator |
| 4    | Export all marl rasters to Esri ascii grid files  
      | ArcToolbox > Export from Raster > Raster to Ascii |

Table 6.9 Steps undertaken in ArcGIS to model Marl surfaces

6.3 Results

The Hallue Catchment geological model when finished comprised 41 sections and 11 modelled units. The spacing of the geological sections is approximately 1-3 km in a north-south orientation and 1-1.5 km in an east-west orientation (see Figure 6.1). The Patcham Catchment geological model when finished comprised 42 sections and 26 modelled units. The spacing of the geological sections is approximately 0.5-2 km in a north-south orientation and 0.3-2 km in an east-west orientation (Figure 6.3 and Figure 6.4). All the geological sections produced during the GSI3D modelling process for both catchments are contained in Appendix VII. Based on the density of data available, the spacing of sections and the methods used, both the Hallue and Patcham Catchment geological models should be considered as lying somewhere between overview and systematic models - in relation to the categories proposed by Kessler et al. (2004; 2008). The bedrock geological map of the Hallue Catchment, which was revised as a result of the geological modelling process to incorporate the Upper Santonian, is shown in Figure 6.2.

The main outputs from the modelling of both the Hallue and Patcham Catchments were the models packaged within the GSI3D subsurface viewer. A separate GSI3D subsurface viewer was prepared for both research catchment geological models. The subsurface viewer contains an un-editable standalone version of each of the geological models. The executable files for both the Patcham and Hallue Catchment GSI3D subsurface viewers are contained in Appendix VII with the subsurface viewer instruction manual. The subsurface viewers require no additional software and can be installed on as many computers as required.
The subsurface viewer has four windows which are similar to the four windows used in the GSI3D 1.5.2 modelling software. The three main windows are the map, section and 3D windows (Figure 6.9) – with the fourth being the borehole log window. Within the subsurface viewer the geological models can be viewed in plan or in 3D (Figure 6.9). The model can be rotated in 3D space and the model units can be vertically or horizontally offset, made transparent or turned off. The model can also be queried to produce synthetic cross sections, horizontal slices or borehole logs. The GSI3D subsurface viewer therefore allows a model to be distributed as a single self-contained electronic file which recipients can use to review the geological model and gain a conceptual understanding of the geology of the modelled area.

Additional information in the subsurface viewers included maps and the discrete layers discussed in section 6.2.3. The maps included in the Patcham Catchment viewer showed the location of boreholes used in the model, the groundwater flooding area, the location of springs during flooding and the location of karst features. The map included in the Hallue Catchment viewer showed the location of the Hallue River and the location of known springs. The discrete layers incorporated into the subsurface viewers as lenses can be viewed in the same manner as the main modelled units. Furthermore, these layers are also shown in synthetic borehole logs, cross sections or horizontal slices when the models are queried. The GVS (generalised vertical section) for both the geological models was configured to allow the Chalk model units to be viewed in either stratigraphical units by stage or sub-stage or as UK lithostratigraphical units. This can be changed in the subsurface viewer by switching legends in the “NAME” box on the top left of the window to “uk_strat” (lithostratigraphy) for the Hallue Catchment viewer or “age” (chronostratigraphy) for the Patcham Catchment viewer. By incorporating two legends into the subsurface viewers, the models can be viewed in their local stratigraphical systems or switched to an equivalent system for easier visual comparison. Furthermore, the Patcham subsurface viewer may be switched to lithology.
Figure 6.9 Screenshot of the Hallue and Patcham Catchment geological models in the GSI3D viewer. A: Hallue Catchment geological model B: Patcham Catchment geological model
6.4 Comparison and Discussion

The GSI3D geological models of the Patcham and Hallue catchment, due to the density of data and sections, are considered as somewhere between overview and systematic models equivalent and compatible with 1:50,000 geological maps (Kessler et al., 2004; Kessler et al., 2008). The use of the Central South Downs Vulcan model surfaces (Robins, 2001; Robins et al., 2003) to assist in the construction of the geological model of the Patcham Catchment effectively means that the Patcham Catchment geological model is a refinement of the former geological model. The Patcham Catchment geological model may, therefore, be considered as having a greater data density than the Hallue Catchment geological model which had no precedent. The Hallue Catchment model, however, is the larger of the two models with an extent of 247 km$^2$ compared to the 102 km$^2$ of the Patcham Catchment model. In terms of complexity, the Patcham Catchment geological model contains 13 geological units (excluding Marl horizons) as opposed to the 9 of the Hallue Catchment geological model (Figure 6.9 and Figure 6.10). The geological units represented in both geological models comprise the geological units present in the aquifer of both research catchments.

The modelling process and preparation of the subsurface viewers has further helped to develop the three dimensional understanding of the geological structures in the research catchments which were initially discussed in Chapters 3 and 4. In the Hallue Catchment these structures consist of the Ponthieu Anticline (structure D2), structure E, structure I and the synclinal area to the north of the village of Forceville. In the Patcham Catchment, this refers to the Pyecombe Syncline, Henfield Syncline and Patcham Syncline. These structures can be seen in the geological models to occur through the entire sequence down to the base of the aquifer, the top of the ‘Dieve Bleues’ in the Hallue Catchment and the top of the Zig Zag Formation in the Patcham Catchment.
Figure 6.10 Screenshot of the Patcham and Hallue Catchment geological models in the GSI3D viewer including the base of the weathered zone and the typical average water table. A: Hallue Catchment geological model B: Patcham Catchment geological model
The modelling process also confirmed that the dominant UK Chalk Formation in the Hallue Catchment is the Seaford Chalk Formation although there are small areas of Lewes Nodular and Newhaven Chalk Formations present. The Lewes Nodular Chalk Formation is present at outcrop around the village of Bavelincourt and Hédauville. The outcrop at Bavelincourt occurs where the Hallue has incised into the core of the Ponthieu Anticline. The aquifer effectively thins in this area and springs are common. The Newhaven Chalk Formation was observed in exposures near the villages of Puchievillers, Lahoussoye and Franvillers. To represent this unit in the model and determine the outcrop extent, the base of the Upper Santonian or Newhaven Chalk was predicted. This method predicted two areas of Upper Santonian or Newhaven Chalk in synclines to the southeast and northwest of the catchment (Figure 6.2). These synclinal areas agree well with the areas where Upper Santonian or Newhaven Chalk was observed in exposures.

The unit that has the highest density of fractures or discontinuities within the unsaturated zone of the Chalk aquifer is the weathered zone. The volume of the weathered zone within the research catchments can be estimated using the base of the weathered zone (engineering rockhead) surface and topographical DTMs. The predicted model for the base of the weathered zone is derived from plotting fracture data from site investigation exploratory holes against topography from areas of Chalk outcrop. The predicted surface for the base of the weathered zone can then be calculated using the formula shown in Figure 6.6 and a topographical DTM. By using a topographical DTM to predict this surface, variation in the slope gradient on valley sides as result of aspect were inherently accounted for in the form of the DTM. The impact of slope gradient on the base of the weathered zone was also then accounted for when the base of the weathered zone was calculated.

The weathering model was tested by plotting the predicted levels for the base of the weathered zone against the in-situ measured profile from the Ramsgate Harbour Approach Road Tunnel (Figure 6.7). This predicted profile appears reasonable when compared to the pre-construction and construction profiles of Newman et al. (2003). It also generally displays a form consistent with conceptual models of Williams (1987), Mortimore et al. (1996) and Lord et al. (2002). The model, however, is simplistic and could be improved by including more exploratory hole fracture data.
and reviewing the effect of factors such as Chalk type, variation in periglacial conditions and the presence of Quaternary deposits. The model is also only produced from data in areas of Chalk outcrop and is based on the assumption that the Chalk downland has undergone little denudation since the end of the Pleistocene (Jones, 1999b). The model is not, therefore, suitable for predicting engineering rockhead when the Chalk is in subcrop.

The software and modelling process used to prepare the geological models for the research catchments was to a degree experimental. GSI3D 1.5.2 was designed for modelling near-surface Quaternary deposits but in this work it was used primarily for modelling Chalk bedrock geology. At the beginning of this research programme, it was unclear whether GSI3D 1.5.2 could be used successfully to model bedrock geology. The GSI3D 1.5.2 workflow, however, mimics the normal geological modelling process by requiring the user to draw cross sections. Once a framework of intersecting cross sections has been constructed, the cross sections are used to interpolate a 3D geological model. This approach means that the data is fully interrogated in the modelling process and more robust and realistic geological models are produced. The GSI3D 1.5.2 software specific data files are simple text files which are easy to review and edit directly if required. To draw a dense enough grid of cross sections to get a good TIN interpolation, however, can be an intensive process. Where there is little topographical relief or dip, and the geological map cannot be used to infer geological boundaries below ground, a minimum density of subsurface data is required. GIS software, such as ArcGIS, is also required for manipulation and preparation of data before it can be used in GSI3D.

The Hallue and Patcham models were developed with the data available using a cognitive approach (Royse, 2010). The advantage of using modelling software such as GSI3D, however, is that if more data became available the models could be revised and the geological interpretation, therefore, does not need to remain static. The facility to capture GSI3D models into read-only subsurface viewers was a relatively new feature at the time this work was undertaken. The incorporation of discrete layers as lenses and the interchangeable legends in the subsurface viewer were also relatively new approaches to using the subsurface viewers. In addition to these features, it was intended that the GVS file in the GSI3D subsurface viewers
of the research catchments would contain attributes of mean porosity, mean dry density and mean hydraulic conductivity from the lab and field tests. When the GSI3D viewers were created, these attributes were removed from the GVS file because of technical difficulties. Attributed 3D geological models, as demonstrated by Royse et al. (2009), are the natural progression of this work. An attributed 3D geological model would provide information to end-users on the structural geology of an area and the physical properties of the geological units. This may mean, in its simplest form, interrogation of the model in the subsurface viewer to produce a synthetic borehole stick or cross section of the geology and physical properties of the ground or, in a more advanced form, models are imported directly into rock or groundwater modelling software for further analysis. The GSI3D subsurface viewers of the Hallue and Patcham Catchment geological models, however, provide good examples of the use of the software in a collaborative research project as a tool to capture and disseminate geological information.

6.5 Conclusion

The geological modelling work presented in this chapter has synthesised, into a digital format, field data collected in the research catchments with third party data, so that the geology of the research catchments can be readily visualised in 3D, interrogated and the results disseminated. As part of the modelling process, third party exploratory hole data derived from ground investigations on areas of Chalk outcrop were analysed and a method developed for predicting and modelling a surface for the base of the weathered zone or engineering rockhead. By developing the geological models in this manner, and combing stratigraphical field data with non-stratigraphical discrete surfaces such as water tables and engineering rockhead, understanding has been gained about:

(i) the structural geology of the Patcham and Hallue catchments
(ii) the three dimensional relationship of weathering to geomorphology in areas of Chalk outcrop
(iii) the evolution and form of the water table relative to stratigraphy and structural geology
(iv) the strengths and weaknesses of using GSI3D 1.5.2 and ArcGIS Desktop 9.0 for geological modelling
(v) the strengths and weaknesses of using GSI3D subsurface viewer for visualisation, interrogation and dissemination of the geological models

The work presented in this chapter represents the digital realisation of the conceptual model of a chalk valley presented in Chapter 1. The 3D digital geological models produced may form a basis for further research in either the Patcham or the Hallue Catchments. The application of the geological models to conceptualisation of the research catchments is discussed Chapter 7.
Chapter 7 Conceptualisation of the Research Catchments: Application of the Geological Models to Hydrogeological Understanding

7.1 Introduction

This chapter seeks to evaluate the hydrogeological implications of the geological field observations and modelling presented in Chapters 3-6, and to demonstrate how geological field observations and modelling may be used to enhance understanding of the aquifer and its hydrogeological behaviour. To develop these discussions, the geological field observations and models are reviewed in the context of the general hydrogeological characteristics of the research catchments and the key findings from the FLOOD1 research project, and associated studies, which were conducted concurrently with the research presented in this thesis.

The geological models presented in Chapters 3-6 should be considered as providing a conceptual and digital representation of the geology observed within the research catchments. The spatial distribution of lithostratigraphic units and features within these models, which have hydrogeologically significant properties, are ultimately controlled by the geological structure of the Chalk. Geological structure alone, however, does not indicate whether the physical properties of these features are hydrogeological significant at any one location or whether they will influence processes within the aquifer. It is the interplay of geomorphology, rock mass properties, structural geology and the groundwater system which controls the hydraulic properties of these features.

The processes within the deep unsaturated zone of the Chalk aquifer, and the relationship between these processes and the Chalk lithostratigraphy, were investigated at the FLOOD1 recharge sites. By combining the understanding of the unsaturated zone processes observed at the recharge sites with the geological models of the research catchments, the geological models may be demonstrated to be tools which can aid assessment of the scale and extent of hydrogeological processes and facilitate characterisation and conceptualisation of the aquifer, thereby fulfilling the hypothesis outlined in Chapter 1.
7.2 Overview of Long Term Groundwater Monitoring

The geological models of the Hallue and Patcham catchments enable spatial assessment of the distribution of lithostratigraphic features in the aquifer and, in particular, facilitate comparison of the distribution of these features between the saturated and unsaturated zones. To understand the implications of the differences in the distribution of lithostratigraphic features between the research catchments, a general review of the hydrogeological characteristics of the research catchments is required.

Long term groundwater level monitoring, collected from borehole and wells within and near to the Hallue and Patcham catchments, may provide an indication of the hydrogeological characteristics of the research catchments and the differences they display in terms of groundwater level response to recharge. These time series data are currently held by the Environment Agency in the UK and BRGM in France. The frequency of the data is variable over the respective time series with some gaps in data collection. Consecutive readings, however, were typically collected at monthly to weekly intervals, with the first readings for the Hallue Catchment collected in 1970 and for the Patcham Catchment 1975. Table 7.1 provides summary statistics of the time series reviewed for each catchment and Figure 7.1 shows the location of the monitoring boreholes.

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Monitoring Borehole</th>
<th>Start Date</th>
<th>End Date</th>
<th>Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Min (m NGF/OD)</td>
</tr>
<tr>
<td>Hallue</td>
<td>Cardonnette</td>
<td>07/01/1970</td>
<td>19/12/2013</td>
<td>39.16</td>
</tr>
<tr>
<td></td>
<td>Harponville</td>
<td>07/01/1970</td>
<td>25/12/2006</td>
<td>60.15</td>
</tr>
<tr>
<td></td>
<td>Hebuterne</td>
<td>28/11/1997</td>
<td>25/12/2006</td>
<td>110.79</td>
</tr>
<tr>
<td></td>
<td>Lahoussaye</td>
<td>15/05/1998</td>
<td>25/12/2006</td>
<td>36.04</td>
</tr>
<tr>
<td></td>
<td>Senlis-Le-Sec</td>
<td>08/01/1970</td>
<td>15/12/2013</td>
<td>60.13</td>
</tr>
<tr>
<td></td>
<td>Talmas</td>
<td>08/01/1970</td>
<td>15/12/2013</td>
<td>93.00</td>
</tr>
<tr>
<td></td>
<td>Vauchelles-Les-Authie</td>
<td>08/01/1970</td>
<td>25/12/2006</td>
<td>80.53</td>
</tr>
<tr>
<td>Patcham</td>
<td>Casterbridge Farm</td>
<td>20/01/2009</td>
<td>07/04/2008</td>
<td>37.42</td>
</tr>
<tr>
<td></td>
<td>Devils Dyke Farm</td>
<td>30/05/1977</td>
<td>19/03/2010</td>
<td>96.50</td>
</tr>
<tr>
<td></td>
<td>Faulkner Bottom</td>
<td>07/08/1978</td>
<td>29/08/2013</td>
<td>106.83</td>
</tr>
<tr>
<td></td>
<td>Lower Standean</td>
<td>02/07/1979</td>
<td>30/03/2010</td>
<td>39.70</td>
</tr>
<tr>
<td></td>
<td>North Bottom</td>
<td>09/11/1979</td>
<td>30/03/2010</td>
<td>57.88</td>
</tr>
<tr>
<td></td>
<td>Pyecombe Old Rectory</td>
<td>26/11/1975</td>
<td>19/03/2010</td>
<td>68.68</td>
</tr>
</tbody>
</table>

Table 7.1 Summary statistics for long term groundwater level monitoring in the Hallue and Patcham catchments
Comparison of the summary statistics between the catchments (Table 7.1) has highlighted some key differences in long term groundwater level response characteristics. Although minimum, maximum and mean values for each time series
are variable within and between the catchments, probably due to the location of the monitoring boreholes within the catchment and the hydraulic gradient, the range and standard deviation values of the time series indicate distinctive differences between the catchments. For example, the range and standard deviation values for the time series from the Hallue Catchment vary between 5.11 m and 24.63 m and 1.10 m and 3.14 m respectively, whereas the range and standard deviation values for the Patcham Catchment vary between 14.67 m and 42.92 m and 2.39 m and 12.73 m. Consideration of the typical values, by excluding extremes, emphasise this difference further, with most values in the time series from the Hallue Catchment having a range and standard deviation which fall between 10.45 and 16.45 m and 2.19 m and 3.14 m respectively and in the Patcham Catchment having a range and standard deviation between 32.39 m and 42.92 m and 6.75 m and 8.55 m respectively.

This difference in the magnitude of groundwater level fluctuation can be seen graphically in Figure 7.2 where, for ease of comparison, the time series have been plotted over the same period and level range on the x and y axes. The Hallue Catchment can be seen to have experienced less extreme groundwater level fluctuations with approximately half to a third of the range experienced in the Patcham Catchment. The Hallue Catchment groundwater levels also display more progressive changes with the highest and lowest groundwater levels observed occurring after successive years where groundwater levels have been rising or falling respectively. This behaviour is perhaps best demonstrated by the monitoring boreholes at Harponville and Senlis-Le-Sec which are located within the Hallue Catchment (Figure 7.1). The Patcham Catchment groundwater levels, however, tend to show weak or no progressive change between successive years with annual maximum groundwater levels returning to around the minimum observed groundwater level for the majority of the time series. This behaviour is perhaps best demonstrated by Casterbridge Farm, Ladies Mile No. 3 and Pyecombe Old Rectory which all recess to a consistent minimum level. Lower Standean, North Bottom and to a lesser extent Faulkner Bottom, however, may exhibit some weak longer term progressive change in groundwater levels over successive years. This is perhaps best demonstrated by comparing successive annual minimum levels. This
behaviour, however, is not as clear or consistent as is seen in the Hallue Catchment as demonstrated by the autocorrelation correlograms presented Figure 7.3.

Figure 7.2 Long term groundwater monitoring time series for boreholes within and near to the Hallue (A) and Patcham (B) catchments
Autocorrelation, or specifically positive autocorrelation, is an indication of persistence within a system or the tendency for a system to remain in the same state from one observation to the next. The autocorrelation coefficient \( r_\tau \) (Davis, 1986, 2002) is, in effect, the linear or Pearson’s correlation coefficient for a sample time series against a lagged version of itself. In Figure 7.3, the autocorrelation coefficient \( r_\tau \) is shown for monthly lags of up to plus 24 months for the time series from monitoring boreholes Harponville, Senlis-Le-Sec, Ladies Mile No. 3, Lower Standean and North Bottom.

The correlograms for the two Hallue Catchment boreholes, Harponville and Senlis-Le-Sec, show that there is statistically significant autocorrelation (greater than 95% confidence interval) for at least six to seven months after a groundwater level observation. After this period, for lags of between eight to fifteen months, autocorrelation within the system is masked by seasonal effects. Beyond fifteen months lag there is no further statistically significant autocorrelation, as is seen graphically in Figure 7.2, possibly due to the longer term progressive changes in groundwater level between successive years. The correlograms for the three Patcham Catchment boreholes, Ladies Mile No. 3, Lower Standean and North Bottom, show that there is statistically significant autocorrelation for two to three months after a groundwater level observation. After this period, positive autocorrelation occurs at around ten to fourteen month and twenty-four month lags due to seasonal effects. Lower Standean and North Bottom display stronger seasonal autocorrelation compared to Ladies Mile No. 3, thereby providing additional support for these time series displaying some weak but progressive longer term changes in groundwater level over successive years.

The longer autocorrelation or persistence of groundwater levels in the Hallue Catchment, combined with the observed longer term progressive changes in groundwater levels over successive years observed in all the Hallue time series (Figure 7.2), suggest the effects of recharge in the catchment are cumulative – based on the implications of these groundwater level characteristics proposed by Adams et al. (2008). In contrast, the shorter autocorrelation or persistence of groundwater levels in the Patcham Catchment, combined with weak or no longer term progressive changes in groundwater levels over successive years in the
Patcham time series, suggest there is little or no cumulative recharge effects in the catchment.

Figure 7.3 Correlograms of the autocorrelation coefficient ($r_t$) for long term groundwater monitoring time series from boreholes within the Hallue and Patcham catchments. Correlograms are for Harponville (A), Senlis-Le-Sec (B), Ladies Mile No. 3 (C), Lower Standean (D) and North Bottom (E). The 95% confidence interval, or significance level, shown is based on plus or minus two times the large-lag standard error (Anderson, 1976)
Due to these characteristics, Adams et al. (2008) and Adams et al. (2010) described the groundwater levels in the South Downs and Brighton area as being “self-contained” or “flashy”. Adams et al. (2008) attributed differences in groundwater level response to either regional conditions or catchment characteristics. The catchment characteristics which Adams et al. (2008) suggested could contribute to the differences in catchments are listed in Table 7.2.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catchment Size</td>
<td>The larger the catchment, the greater the cumulative effect of recharge.</td>
</tr>
<tr>
<td>Position in the Catchment</td>
<td>The levels measured in a borehole are a reflection of both recharge at that point and contribution from upstream in the catchment. Measurements made high up in a catchment have a reduced contribution, there being a smaller upstream catchment.</td>
</tr>
<tr>
<td>Chalk Properties</td>
<td>Both saturated and unsaturated. If the unsaturated zone has low matric conductivity and a high proportion of bypass flow, it might be expected that there is less long-term (“delayed”) drainage through the unsaturated zone. Additionally, the lower the transmissivity, the longer it will take for recharge to be transported out of the catchment, and the greater the cumulative effect.</td>
</tr>
<tr>
<td>Effects of Superficial Deposits</td>
<td>Extensive impermeable cover could change the pattern of recharge across the catchment.</td>
</tr>
</tbody>
</table>

Table 7.2. Catchment differences which influence groundwater level response characteristics. Adapted from Adams et al. (2008).

It is reasonable that some of the differences observed in groundwater level characteristics between the Hallue and Patcham catchments are due to catchment size. As outlined in Chapter 1, the Patcham Catchment is smaller at approximately 40 km² compared to the Hallue Catchment at approximately 220 km². The inference by Adams et al. (2008) that the effects of recharge are cumulative in larger catchments would agree with the longer term changes in groundwater level observed over successive years in the Hallue Catchment. Adams et al. (2010) also described the groundwater level characteristics of the Patcham Catchment as being consistent with it having relatively well developed and connected secondary fracture porosity in a small catchment close to a major discharge area such as the coast. Adams et al. (2010), however, did not indicate why the secondary fracture porosity would be well developed in the Patcham Catchment, why this may be different to other catchments or why, close to a major discharge area with well developed
secondary porosity, reasonably large fluctuations in groundwater level were occurring.

Variation in groundwater level characteristics in the Hallue and Patcham catchments due to borehole position are perhaps demonstrated by comparing the time series for Lahoussoye with Senlis-Le-Sec or Pyecombe Old Rectory with Ladies Mile No. 3. Lahoussoye and Pyecombe Old Rectory are both close to the edges of the catchments and near discharge points. For Lahoussoye, the discharge points being the Hallue and Ancre rivers and for Pyecombe Old Rectory the Chalk escarpment springs. As a result, they both display smaller ranges with shorter duration for peak groundwater levels when compared to Senlis-Le-Sec and Ladies Mile No. 3 respectively (Table 7.1)

The characteristic signature of the time series from the Hallue and Patcham catchments (Figure 7.2), with smaller ranges and longer term progressive change in groundwater level seen over successive years in the Hallue Catchment, compared with the larger ranges and shorter term annual fluctuations of the Patcham Catchment, suggest that, in addition to differences in catchment size, different recharge processes are occurring in the unsaturated zones of the two catchments. Observations by Molyneux (2012), Rutter et al. (2012), Gallagher et al. (2012) and Adams et al. (2008) from boreholes in the Patcham Catchment, and particularly the NHB2 borehole at the FLOOD1 recharge site, suggest the Patcham Catchment may be susceptible to a higher proportion of bypass recharge due to the characteristics of the Chalk. The difference in the properties of the Chalk and the effects of superficial deposits between the catchments may, therefore, also provide an explanation for the difference in the recharge processes and the groundwater level characteristics of the catchments, and it is the difference in these geological factors which the field observations and geological models, presented in this thesis, may illuminate.
7.3 Key Findings from the FLOOD1 Recharge Sites

The lithostratigraphical frameworks applied to mapping and modelling the Hallue and Patcham catchments in this thesis were also utilised by the FLOOD1 research project partners BRGM and BGS, as well as Molyneux (2012), for parallel research into the unsaturated zone processes and hydraulic properties of the Chalk in the Hallue, Patcham and Pang catchments. The results and conclusions from this research are particularly relevant to understanding how lithostratigraphy may affect the hydrogeological properties of the Chalk and, therefore, how the geological models maybe used to aid conceptualisation and comparison of the Hallue and Patcham Catchments.

The main focus of the FLOOD1 hydrogeological field investigations involved installation of recharge sites to monitor unsaturated zone processes and water level response to rainfall in the research catchments. Detailed interpretation of the Hallue Catchment, Warloy-Baillon recharge site data is provided by Amraoui et al. (2008) and the Patcham and Pang Catchments, North Heath Barn and East Ilsley recharge site data by Adams et al. (2008), Molyneux (2012) and Rutter et al. (2012). The monitoring data collected from the recharge sites was supplemented by laboratory analysis of Chalk samples derived from the cored boreholes (Amraoui et al., 2008; Molyneux, 2012), areal and borehole geophysical surveys conducted prior to installation of monitoring equipment (Adams et al., 2008; Baltassat et al., 2008; Robelin, 2008; Gallagher et al., 2012; Molyneux, 2012) and in-situ hydrogeological field tests (Machard de Gramont, 2007).

From these investigations, Molyneux (2012), in particular, focused on hydrogeological characterisation of the Chalk in relation to detailed lithostratigraphy. By undertaking systematic index testing (intact dry density, porosity and hydraulic conductivity) of samples classified by Chalk lithostratigraphy from the Patcham Catchment, NHB2 and Pang Catchment, EI2 boreholes, and supplemented with additional borehole core and field samples from the North Downs, South Downs and Hallue Catchment, Molyneux (2012) was able illuminate differences in the hydraulic properties of the Chalk matrix - building on the work of Mortimore and Fielding (1990), Bloomfield et al. (1995) and Allen et al. (1997). From the broad range of
samples tested for index properties, Molyneux (2012) undertook a targeted laboratory investigation of the soil moisture characteristic (SMC) curve and the surface (fracture) component of unsaturated zone storage. The results from the laboratory investigation were used delineate storage and flow regimes in fractured chalk, and to assess the variability of the Chalk soil moisture characteristic curve in terms of lithostratigraphy. The results from these investigations were then related to the monitoring data from the North Heath Barn and East Ilsley recharge sites, and also observations from borehole geophysical and camera surveys of the NHB2 borehole plus additional Environment Agency boreholes in south east England.

A key conclusion from the investigations of Molyneux (2012) was whilst stratigraphical and geographical differences in Chalk matrix hydraulic properties were found to exist, they exerted relatively weak control on the hydrogeological properties of the Chalk. In contrast, intra-formational variations in hydraulic conductivity, due to the occurrence of marl seams, were found to exert strong localised control on the hydrogeological properties of the Chalk (Figure 7.4). Clastic marl horizons, composed primarily of detrital clays of terrigenous origin, were observed to provide hydraulic conductivity contrasts of between <0.5 to ~1.5 orders of magnitude whilst plastic marls, composed primarily of clays of volcanogenic origin, were found to provide hydraulic conductivity contrasts of over 4 orders of magnitude with the surrounding matrix material. Related observations to those of Molyneux (2012) regarding marl seams in the Chalk have been made by a number of other authors. Zaidman et al. (1999), from field based geophysical investigations, concluded that marl seams impacted infiltration in the unsaturated Chalk of East Yorkshire causing joint saturation above horizons rich in marl seams. Lord et al. (2002) stated marl seams in chalk often create perched water tables, with swelling of the montmorillonite clay in the marl often leading to locally fractured chalk above and beneath the seam. Jones and Robins (1999) presented, in a discussion on lithological controls on aquifer properties, a fluid electrical conductivity log for the Victoria Gardens Borehole in Brighton where water inflow horizons in the saturated zone were commonly associated with marl seams as well as flints and hardgrounds.
Figure 7.4 Schematic profile of hydraulic conductivity at NHB2 from Molyneux (2012). Some marl horizons have been omitted for clarity and marl thickness is not to scale.

The impact of this on the deep unsaturated zone of the Chalk at the Patcham and Hallue catchment recharge sites was found to be significant. Figure 7.5 summarises the location of discrete marl seems, flint bands and hardgrounds with matric potential profiles for the jacking tensiometers in the P6 and NHB2 boreholes between 22/11/2006 and 19/04/2007. Griotte marl zones and wispy marls, equivalent to the clastic marls of Molyneux (2012), horizons of small flints and
sponge beds are not depicted for clarity. Jacking tensiometers were installed to 60.5 m BGL in NHB2 and 26.5 m BGL in the P6 (Amraoui et al., 2008) - due to the shallower unsaturated zone at the recharge site in the Hallue Catchment.

Superficial inspection of Figure 7.5 highlights the difference in heterogeneity of the unsaturated Chalk at the Warloy-Baillon recharge site compared to the North Heath Barn recharge site. This difference is partly due to the unsaturated zone occurring in different parts of the Chalk sequence at the recharge sites, the unsaturated portion of P6 intersects Coniacian chalk (upper Lewes Nodular to lower Seaford Chalk Formations - Figure 3.4) and the unsaturated portion of NHB2 intersects the New Pit to lower Lewes Chalk Formations (Figure 3.12), as well as catchment specific differences in lithostratigraphy with the Hallue Catchment generally displaying less well develop lithological features and a more homogeneous sequence (Section 3.4).

The matric potentials (negative potential or suction) measured by the jacking tensiometers in NHB2 (Figure 7.5), as described in detail by Adams et al. (2008), Molyneux (2012) and Rutter et al. (2012), were found to be consistently high, greater than -250 hPa and commonly greater than -50 hPa – at times measuring zero or positive pressures. In comparison, matric potentials measured by the jacking tensiometers in P6, described in detail by Amraoui et al. (2008), were found to be lower, with values as low as -595 hPa measured in the 10 m BGL jacking tensiometer and the occurrence of matric potentials greater than -50 hPa being rare. Figure 7.5 illustrates one of these periods occurring between the 21/02/2007 and 28/03/2007 which Amraoui et al. (2008) noted led to a rapid rise in the water table. Wellings (1984), reinforced subsequently by the observations of Jones and Cooper (1998), suggested that the Chalk fracture system was likely to conduct water when matric potentials rose above approximately -50 hPa. The observation of rapid water table rise by Amraoui et al. (2008), therefore, indicated this process had occurred at the Warloy-Baillon recharge site. Price et al. (2000), based on experimental analysis, presented a model for fissure flow in the unsaturated zone of the Chalk which indicated that when suctions fall, or matric potentials rise, irregularities on the surface of matrix blocks are filled with water which eventually leads to narrow fissures becoming filled and fissure flow in the unsaturated zone.
Figure 7.5 Comparison of matric potential profiles of the deep unsaturated zone from the jacking tensiometers in P6 in the Hallue Catchment and NHB2 in the Patcham Catchment. Each data series represents the matric potential profile at a point in time with the lighter coloured portion of the profile denoting the shallow tensiometer data from recharge sites. Each set of graphs have the same scale on the x-axis and present equivalent time series. Flint horizons (black dotted horizontal lines), marl seams (green horizontal lines) and hardgrounds (orange dashed lines) are depicted. Arrows indicate wetting (pointing right) and draining sequences (pointing left).
Price *et al.* (2000) went on to suggest that fissure flow can be generated at any depth in a profile, and in a sequence of uniform vertical permeability, it is likely to originate near the water table rather than high in the unsaturated zone. Molyneux (2012) demonstrated that the Chalk sequence in the NHB2 borehole does not have uniform vertical permeability and marl seams represent layers of low hydraulic conductivity relative to the Chalk matrix (Figure 7.4). Molyneux (2012) and Rutter *et al.* (2012), therefore, with supporting qualitative evidence from time series camera surveys in the NHB2 borehole prior to installation of the jacking tensiometers (Adams *et al.*, 2008; Gallagher *et al.*, 2012; Molyneux, 2012), interpreted the high matric potentials encountered by the jacking tensiometers in NHB2 as being due to the presence of the marl seams. They concluded that vertical drainage of the Chalk matrix is reduced by the low hydraulic conductivity marl seams and, as a consequence, relatively high matric potentials are maintained in the Chalk matrix above the marl seams. If the hydraulic conductivity of the marl seam was sufficiently low, or infiltration sufficiently intense, matric potentials above the marls would become close to zero or positive. This would have the effect of creating water films under tension on fracture surfaces, as suggested by Price *et al.* (2000), or perched water tables in the unsaturated zone. Water films were observed on the NHB2 borehole wall, which can be considered as analogous to a fracture surface, during six camera surveys between February and October 2006 (Adams *et al.*, 2008; Gallagher *et al.*, 2012; Molyneux, 2012). Adams *et al.* (2008), Gallagher *et al.* (2012) and Molyneux (2012), based on these observations, suggested that once a water film had formed, it would be free to flow along the borehole wall under gravity until matric potentials further down the borehole were low enough for the water to be absorbed back into the matrix.

Rutter *et al.* (2012), based on the monitoring data from the North Heath Barn recharge site, presented a general sequence of events for activation of the fracture network and bypass flow during the winter recharge period (Table 7.3). This sequence of events is probably also applicable to more homogenous sequences, such as at the Warloy-Baillon recharge site, but the occurrence of matric potentials of greater than -50 hPa would be less frequent and the duration of water films on fracture surfaces shorter as the matrix is more able to drain and reabsorb the water films than at North Heath Barn.
Step | Description
--- | ---
1 | In late autumn, the soil moisture deficit is eliminated
2 | If rainfall input continues, shallow tensiometers show a rapid increase in matric potential
3 | At greater depths, matric potential rises at most depths to greater than -50 hPa (-0.5 m H2O) – assumed threshold for the fracture system becoming active
4 | If rainfall continues at sufficient intensity, a film of water develops on the borehole walls, matric potential is recorded at all depths to be close to zero, and there is a rise in groundwater level
5 | If input ceases, matric potential at shallow depths becomes negative almost immediately, and the groundwater level rise slows within 1 or 2 days. The slowing of the groundwater recovery before the borehole wall dries out suggests that, although there is still a film of water, the rate of transport is slowing down, probably because input has ceased at the surface.
6 | Between 7 and 14 days later, the borehole wall dries out. Shortly after the borehole wall no longer has a continuous film of water, the groundwater level starts to recess

Table 7.3 General sequence of events for activation of the fracture network and bypass flow during winter recharge in the NHB2 borehole. Based on Rutter et al. (2012).

Although not commented on by Amraoui et al. (2008), there is also some indication that a similar relationship between matric potential and lithostratigraphy may occur in P6 to a less extreme extent than in NHB2. The data from P6 appears to show consistently higher matric potentials at the tensiometers around 14 m BGL and 23.5 m BGL (Figure 7.5). The tensiometers present at these depths are positioned directly above a flint horizon and the Shoreham Marl 2. The Shoreham Marl 2 is the main marl seam observed in the unsaturated zone at P6 and marks the boundary between the Lower and Middle Coniancian Chalk (Lewes and Seaford Chalk Formations) in the Hallue Catchment. The Shoreham Marl 2, although volcanogenic in origin (Wray, 1999; Mortimore et al., 2001) like many of the ‘plastic’ marl seams classified by Molyneux (2012) in NHB2, was observed to be only a few millimetres thick in the Hallue Catchment (Sections 3.2.3.1 and 3.4). Inspite of this, it appears to have created a vertical permeability contrast and maintained relatively high matric potentials above it. A similar, but less pronounced, effect is recorded by the tensiometer at 14 m BGL with the influence of the flint band below it becoming more pronounced at matric potentials below approximately -200 hPa.

A further consideration with regard to the matric potential data from the jacking tensiometers in P6 is the influence of the weathered zone. Molyneux (2012), when comparing the data from the East Ilsley recharge site in the Pang Catchment with the data from North Heath Barn rechage site in the Patcham Catchment, observed that the profile at EI2 was able to drained relatively freely through the matrix and acted as a homogeneous medium, which contrasted with NHB2 profile. Molyneux (2012), postulated that, although both sites had significant marl seams in the
unsaturated zone e.g. Glynde and Southerham (Figure 3.15), the marl seams at EI2 were located primarily within the weathered zone of the chalk whereas at NHB2 the marl seams were located primarily below the weathered zone. The implication of this being that the increased fracturing in the rock mass associated with the weathered zone at EI2 would create more intermediate storage on chalk surfaces and asperities, increasing the capacity to accommodate water influx, and also physical disruption of lithological horizons such as marl seams, thereby increasing connectivity across lithological contrasts and reducing their ability to act as aquitards. Additionally, the pore size distribution of the chalk matrix and marls and, therefore, also the soil moisture characteristic curve, would be altered by weathering and near surface processes – as suggested by Bloomfield et al. (1995) and demonstrated by Bloomfield (1999). Molyneux (2012) summarised this by stating that essentially more low potential storage sites are available in a highly fractured rock mass than in a relatively unfractured one. Based on the fracture data from the P6 borehole core and the weathered zone model presented in Figure 6.6, it is likely that the unsaturated zone, and majority of the jacking tensiometers installed in P6, fall predominantly within the weathered zone or zone of unloading. The conclusions of Molyneux (2012) regarding the lithological contrasts in EI2, therefore, may also be applicable to P6.

7.4 Proportions of Model Units in the Unsaturated Zone

The main Chalk units which contain marl seams and are represented in the geological model of the Hallue Catchment are the Upper Turonian-Lower Coniacian (C3c-C4a – equivalent to Lewes Nodular Chalk), Middle-Upper Coniacian (C4bc – equivalent to Seaford – Belle Tout Beds) and Lower Campanian (C6c – equivalent to Newhaven). Within the geological model of Patcham Catchment the main Chalk units which contain marl seams are the West Melbury and Zig Zag Formations of the Grey Chalk Subgroup and the Holywell Nodular, New Pit, Lewes Nodular, Seaford (Belle Tout Beds) and Newhaven formations of the White Chalk Subgroup. The results presented by Molyneux (2012) indicated that the intra-formational variations in hydraulic conductivity between marl seams and the Chalk matrix were found to be most strongly marked in the White Chalk Subgroup. The base of the White Chalk Subgroup, or top of the Grey Chalk Subgroup, is also generally regarded as the base of the aquifer in the Patcham Catchment. The percentages of
these units within the unsaturated zone of the catchments are indicated in Figure 7.6.

Figure 7.6 Estimated distribution of Chalk units in the saturated (i) and unsaturated (ii) zones of the Hallue (A-B) and Patcham (C-E) catchment geological models for different water table surfaces. Units depicted are Cenozoic deposits (CENO), West Melbury (WMCH), Zig Zag (ZZCH), Holywell (HCK), New Pit (NPCH), Lewes (LECH), Seaford (SECK), Newhaven (NCK) and Culver (TACH). Water table surfaces used are indicated to left of charts.
The percentage distribution of the Chalk units within the saturated and unsaturated zones of the Hallue and Patcham catchment geological models highlights some key differences between the catchments (Figure 7.6). For the Hallue Catchment, the water table surfaces of November 1966 and Peak 2001 were used to calculate the percentages. The November 1966 surface represents typical end of recession groundwater levels and the Peak 2001 surface represents extremely high groundwater levels. For the Patcham Catchment, the water table surfaces of March 1993, September 1993 and Peak 2000 were used to calculate the percentages. The March and September 1993 surfaces represent typical beginning and end of recession groundwater levels and the Peak 2000 surface represents extremely high groundwater levels.

A key observation from the percentages presented in Figure 7.6 is, although the water table surfaces used represent significant vertical variation in groundwater level, the percentage of the Chalk units within the unsaturated zone of the respective catchments, and particularly the dominant units, varies little as a result of this groundwater level variation. For example, the percentage of the Seaford Chalk Formation (SECK) in the unsaturated zone of Hallue Catchment model for November 1966 is 77.52% and for Peak 2001 is 73.57%. Similarly, the percentage of the Seaford Chalk Formation in the unsaturated zone of the Patcham Catchment model for March 1993 is 27.79%, September 1993 is 26.22% and Peak 2000 is 27.72%. The implications of this are that the characteristics of the unsaturated zone of a Chalk groundwater catchment in terms of the proportion and distribution of geological units are approximately constant, irrespective of groundwater level, and these factors are ultimately defined by the geomorphology and structural geology of the catchment. This suggests recharge processes within a Chalk catchment may also display a specific set of characteristics which are typical of the proportion and distribution of units.

The percentages given in Figure 7.6, in light of the findings from the UK FLOOD1 recharge sites (Adams et al., 2008; Gallagher et al., 2012; Molyneux, 2012; Rutter et al., 2012), may allow the Hallue and Patcham catchments to be defined in terms of proportions of Chalk units in the unsaturated zone which are susceptible to high matric potentials and frequency of fracture or ‘bypass’ flow. The Lewes Nodular and New Pit Chalk Formations were demonstrated to be susceptible to high matric
potentials and fracture or ‘bypass’ flow due to the presence of low hydraulic conductivity marl seams - when they occurred below the weathered zone (Molyneux, 2012; Rutter et al., 2012). It is reasonable to assume that the Holywell Nodular and Newhaven Chalk Formations in the White Chalk Subgroup may also be susceptible to this behaviour due to the presence of discrete marl seams, as well as the Zig Zag and West Melbury Marly Chalk Formations in the Grey Chalk Subgroup due to the presence of discrete marl seams and higher marl content in the Chalk matrix (Mortimore et al., 2001). Based on the percentages presented in Figure 7.6 from the geological models, the unsaturated zone of the Patcham Catchment comprises 71.08 - 72.67% Chalk units which may be susceptible to fracture or ‘bypass’ flow in the unsaturated zone. In comparison, the Hallue Catchment comprises 9.35 - 22.48% Chalk units which may be susceptible to fracture or ‘bypass’ flow in the unsaturated zone. The differences in percentage of these units between the Patcham and Hallue catchments may provide an indication as to the different groundwater level characteristics shown in Figure 7.2 and Figure 7.3.

In the Hallue Catchment, where the percentage of Chalk units which are susceptible to fracture or ‘bypass’ flow in the unsaturated zone is lower (9.35-22.48%), the groundwater levels display smaller ranges, progressive cumulative change in groundwater level over successive years and longer autocorrelation in the groundwater level time series. In the Patcham Catchment, where the percentage of Chalk units which are susceptible to fracture or ‘bypass’ flow in the unsaturated zone is higher (71.08 - 72.67%), the groundwater levels display larger ranges, show weak or no progressive change between successive years and shorter autocorrelation in the groundwater level time series. In addition, the percentage of the Seaford Chalk Formation (73.57 - 77.52%) in the Hallue Catchment, which is less likely to be susceptible to fracture or ‘bypass’ flow in the unsaturated zone, is almost equivalent to the percentage of Chalk units in the Patcham Catchment which are likely to be susceptible to fracture or ‘bypass’ flow (71.08 - 72.67%). Within the 73.57 - 77.52% of the Seaford Chalk Formation in the Hallue Catchment, 31.68%-35.26% is comprised of the extremely homogeneous C5d-e (Lower-Middle Santonian) unit which, also recognised by Mortimore and Pomerol (1987) and Robaszynski et al. (2005), appears to be specific to northern France, has no marl seams and is almost completely devoid of flint (Chapter 3 – Section 3.4). The Hallue and Patcham
catchments, in terms of groundwater level characteristics, may, therefore, represent two opposite ends of a spectrum.

This difference suggests the potential capacity to buffer the effects of recharge and for unsaturated zone fracture surface storage in the Chalk of the Hallue Catchment can be considered as theoretically greater than in the Patcham Catchment for the equivalent volume of rock. In the Patcham Catchment, more of the fracture surface storage is already being used throughout the year, as demonstrated by the borehole camera surveys (Adams et al., 2008; Gallagher et al., 2012; Molyneux, 2012), and does not require much additional input to activate the fracture system and for bypass flow to occur in the unsaturated zone (Molyneux, 2012; Rutter et al., 2012) – leading to a short lag between recharge input and a rise in groundwater levels. In contrast, the Chalk matrix in the unsaturated zone of the Hallue Catchment is able to drain more easily through the matrix and must first reach a matric potential of -50hPa (Wellings, 1984; Jones and Cooper, 1998; Amraoui et al., 2008) before additional input may be stored on fracture surfaces or water films developed sufficiently to allow facture or ‘bypass’ flow (Price et al., 2000) – leading to a longer lag between recharge and a rise in groundwater levels. In this sense, the Chalk in the unsaturated zone of the Hallue Catchment is able to buffer the effects of recharge, by being dominantly composed of the more homogeneous Seaford Chalk Formation, which has a lower susceptibility for fracture or ‘bypass’ flow and which permits drainage through the matrix, and by also having a greater availability for fracture surface storage in the unsaturated zone. This indicates that the high groundwater levels of 2001 experienced in the Hallue Catchment (Figure 7.2) would have occurred as result of successive years of high recharge. It can be inferred, therefore that, as the proportion of Chalk units which are susceptible to fracture or ‘bypass’ flow increases within the unsaturated zone of a Chalk groundwater catchment, the more the groundwater level characteristics will be like that of the Patcham Catchment.

In both the Hallue and Patcham Catchments geological models (Figure 7.6), the weathered zone makes up a small percentage of the unsaturated zone, comprising 1.07% - 1.24% of the unsaturated zone in the Hallue Catchment and 0.48% - 0.56% of the unsaturated zone in the Patcham Catchment. The small percentages suggest the weathered zone is unlikely to have a catchment level effect on groundwater level characteristics, as is probably the case for the Chalk units, but is more likely to have
a local effect on the shallow subsurface, particularly in valleys, where the weathering process has overprinted or diminished the physical properties of lithological features in the Chalk units. Molyneux (2012) interpreted this to be the case in the unsaturated zone at the East Ilsley recharge site to explain the relatively less pronounced effect the marl seams at EI2 had on matric potentials in the unsaturated zone compared to NHB2. Considering jacking tensiometers were installed to similar depths in both EI2 and P6, and the relatively small proportion of the unsaturated zone the weathered zone comprises, it potentially raises a question as to how representative the jacking tensiometer data from EI2 and P6 is of the processes occurring in the deep unsaturated zone in both the Pang and Hallue catchments.

The Hallue Catchment differs from Patcham Catchment in terms of percentage of Cenozoic deposits in the unsaturated zone (Figure 7.6). In the Hallue Catchment these deposits comprise 8.12% – 8.54% of the unsaturated zone whereas in the Patcham Catchments these deposits comprise 0.59% - 0.77%. This difference relates in part to the difference in geological evolution and geomorphological maturity of the two catchments – with more periglacial deposits, such as Limon des plateaux (loess), preserved in the Hallue Catchment compared to the Patcham Catchment. The hydraulic behaviour of these deposits was not specially investigated or monitored at the FLOOD1 recharge sites, however, the mineralogical and field saturated hydraulic conductivity data from the soils investigated in the vicinity of the North Heath Barn recharge site (Chapter 5) indicated that the field saturated hydraulic conductivity of soils developed over some of these deposits, specifically Head and Clay-with-flints, fall within the range of $10^{-8}$ – $10^{-5}$ m/s. The lowest field saturated hydraulic conductivity value measured was from a soil developed over Clay-with-flints and was $4.55 \times 10^{-8}$ m/s. The soil had the highest clay and metal oxide mineral content of the permeameter locations (Table 5.2, Figure 5.7 and Figure 5.14). Due to the mineralogical components, this location was interpreted as being Clay-with-flints which had developed from both the slow dissolution of the Chalk and illuviation of clays from previously overlying Palaeogene deposits (Avery et al., 1959; Loveday, 1962; Hodgson et al., 1967; Catt and Hodgson, 1976; Quesnel et al., 2003). The field saturated hydraulic conductivity of soils developed directly over the weathered Chalk bedrock was found to be the highest of the permeameter locations at around $2.86 \times 10^{-5}$ m/s – although comminuted matrix supported chalk (CIRIA grade Dm) or ‘putty chalk’ was probably
not present at the site and this may have a lower hydraulic conductivity (Roberts and Preene, 1990).

The relatively low percentage of these deposits in the unsaturated zone of the Patcham Catchment suggests that predominantly recharge is directly to the Chalk, and these deposits are more likely to have a local impact on the unsaturated zone rather than a catchment level impact. These deposits in the Hallue Catchment, however, may have a more significant role on the unsaturated zone. Adams et al. (2008) suggested an extensive cover of impermeable superficial deposits could change the pattern of recharge in a catchment (Table 7.2). A large area within the Hallue Catchment is covered with ‘Limon des plateaux’ and ‘Colluvion’ (Figure 6.1), equivalent to loess and Head deposits in the UK. Much of the ‘Limon des plateaux’ was observed, during the field investigations, to be underlain by ‘Formations résiduelles à silex’ equivalent to Clay-with-flints ‘sensu stricto’ in the UK. If the mineralogical clay content of these deposits is high (>20-30% - Section 5.4), particularly in ‘Limon des plateaux’ and ‘Formations résiduelles à silex’, they may reduce infiltration and direct recharge to the Chalk, potentially slowing the groundwater level response to recharge. The spread of pore sizes in these materials may also provide a buffer for storage of rainwater, delaying release into the Chalk and, therefore, reducing the frequency of fracture or ‘bypass’ flow (Cooper et al., 1990). These deposits may also protect the unsaturated Chalk, during the summer months, from drying and the development of significant soil moisture deficit - thereby maintaining more constant matric potentials in the unsaturated Chalk. These characteristics are generally compatible with the groundwater level response within the Hallue Catchment discussed in Section 7.2.

As an additional point, during periods of high recharge, or where these deposits have mineralogical clay and metal oxide content of >20-30% (Section 5.4) and a hydraulic conductivity <1x10^{-7} (Klinck et al., 1998), they may also promote localised runoff and point recharge at the margins of the deposits or through voids in the deposits. This is feasible in both catchments but, due to the more extensive cover, perhaps more significant in the Hallue Catchment. Desiccation cracks, roots or burrows in the ‘Formations résiduelles à silex’ (Clay-with-flints), or fractures in the underlying Chalk which have propagated into the ‘Formations résiduelles à silex’ (Clay-with-flints), may create voids which, under certain conditions, allow point
recharge (Klinck et al., 1998). Evidence for this process may perhaps be seen in the common occurrence of narrow sub-vertical dissolution pipes seen in the Chalk below Thanétien, ‘Limon des plateaux’, ‘Colluvion’ and ‘Formations résiduelles à silex’ deposits in the Hallue Catchment, some of which were found to contain cross-laminations in the fill material indicating periodic flow and possible point recharge has occurred (Figure 5.13).

7.5 Distribution of Marl Seams in the Unsaturated Zone

The observations and findings from the FLOOD1 recharge sites in the Hallue and Patcham catchments has highlighted the importance of marl seams on recharge processes within the unsaturated zone of Chalk (Adams et al., 2008; Gallagher et al., 2012; Molyneux, 2012; Rutter et al., 2012). Simmers (1998) stated that realistic recharge estimation depends on first identifying the probable flow mechanisms and important features influencing recharge for a given locality. Principal recharge mechanisms to an aquifer, as defined by Lerner et al. (1990), are as follows:

- Direct: occurring by vertical percolation through the unsaturated zone
- Indirect: by percolation through the beds of surface watercourses
- Localised: an intermediate form of recharge, resulting from the concentration of water along preferential flow paths in the absence of well-defined channels

Direct recharge was observed throughout the FLOOD1 monitoring at both Warloy-Baillon in the Hallue Catchment and North Heath Barn in the Patcham Catchment (Adams et al., 2008; Amraoui et al., 2008; Molyneux, 2012; Rutter et al., 2012). Molyneux (2012), based on the combination of laboratory and field investigations, also suggested that stratigraphically-constrained localised recharge would be significant to the operation of the Chalk aquifer. The spatial scales of localised recharge visualised by Gee and Hillel (1988), and summarised by Simmers (1998) (Table 7.4), indicate that the type of stratigraphically-constrained localised recharge potentially occurring in the Patcham Catchment, based on the effects of the marl seams observed at the NHB2 borehole, would operate at a meso-scale. Molyneux (2012), however, suggested this may be more like hundreds of metres, or macro-scale, if the lithological feature was aerially extensive and uninterrupted.
The location of temporally occurring, vertically-constrained, localised recharge in the unsaturated zone of the Hallue and Patcham catchments, as a result of discrete marl seams, may be predicted using the geological models of the catchments. The effective extent of the marl seams in the unsaturated zone can be considered as being defined by the position of the water table and the base of the weathered zone (Figure 7.7). Below the water table the marl seams will be in the saturated zone and above the base of the weathered zone the physical properties of the marl seams will be degraded and vertical recharge will no longer be constrained (Figure 7.7) – as indicated by the Molyneux (2012) interpretation of the EI2 jacking tensiometer data.

<table>
<thead>
<tr>
<th>Scale</th>
<th>Description</th>
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<tbody>
<tr>
<td>Micro-scale</td>
<td>Pathways, several centimetres or decimetres apart, such as those formed by shrinkage cracks, roots and burrowing animals.</td>
</tr>
<tr>
<td>Meso-scale</td>
<td>Flow paths, with a spacing of several metres or tens of metres, initiated by local topographic or lithological variations.</td>
</tr>
<tr>
<td>Macro-scale</td>
<td>Flow paths, spaced hundreds (or more) metres apart, caused by major landscape features such as karst sinks or playa basins.</td>
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Table 7.4 Spatial scales of localised recharge visualised by Gee and Hillel (1988), and summarised by Simmers (1998)

A spatial analysis was performed using the November 1966 water table for the Hallue Catchment and the September 1993 water table for the Patcham Catchment to define the lower extent of the marl surfaces, and the model for the base of the weathered zone (Section 6.2.3.1) to delineate the upper extent of the marl surfaces (Figure 7.7). The marl seams chosen for this analysis were those encountered in the P6 borehole in the Hallue Catchment (Figure 3.4) and the NHB2 borehole in the Patcham Catchment (Figure 3.12), which occur within the New Pit and Lewes Chalk Formations (Middle Turonian – Lower Coniacian). The Shoreham Marl 2 was also included for the Patcham Catchment. This marl seam approximates to the top of the Lewes Nodular Chalk or base of the Seaford Chalk Formation and was included for comparative purposes although it was not encountered in NHB2. The results from this analysis are presented in Figure 7.8.
The analysis, presented in Figure 7.8, highlights the significant difference in the number, areal extent and distribution of marl seams in the unsaturated zones of the Hallue and Patcham catchments. Three of the marl seams used in the analysis are present in the unsaturated zone of the Hallue Catchment whereas ten of the marl seams used in the analysis are present in the unsaturated zone of the Patcham Catchment (compare Figure 7.8, Figure 7.9 and Figure 7.10). The areal extent of marl seams in the Hallue Catchment unsaturated zone is 125.97 km$^2$ and the total combined surface area of the marls is 155.23 km$^2$. The areal extent of marl seams in the Patcham Catchment unsaturated zone is 58.20 km$^2$ and the total combined surface area of the marl seams is 302.57 km$^2$. This analysis highlights that, despite the Hallue Catchment being the larger catchment and having the larger extent of marl seams in the unsaturated zone, the Patcham Catchment has a greater number and, therefore, also surface area of marl seams.

The Shoreham Marl 2 in the Hallue Catchment was observed to be thin (Table 3.3), less well-developed than in the South Downs (Mortimore, 1986), and less well developed than the Middle – Upper Turonian marls in the Hallue Catchment. The impact of Shoreham Marl 2 on the matric potential in the unsaturated zone of P6 was also found to be less pronounced than that of the Middle – Upper Turonian marls in the unsaturated zone of NHB2 (Section 7.3 - Figure 7.5). If only the Middle
Upper Turonian marls are compared between the catchments, ignoring Shoreham Marl 2, the extent and surface area of the marl seams is 35.70 km$^2$ and 37.00 km$^2$.
for the Hallue Catchment compared to 50.60 km$^2$ and 272.15 km$^2$ for the Patcham Catchment. These values further highlight the difference between the unsaturated zones of the catchments and indicate that vertically constrained localised recharge is likely to be more prevalent in the Patcham Catchment than the Hallue Catchment. This also supports the differences highlighted in section 7.4 with regard to the proportions of chalk units in the unsaturated zone and implications for groundwater level response.

It should be noted that as only the marl seams encountered in the P6 and NHB2 boreholes were used in this analysis (Figure 3.4 and Figure 3.12), Figure 7.8 may be considered as an under representation of these features in the unsaturated zone – particularly in the Patcham Catchment. The Upper Santonian (C5f) to Lower Campanian (C5l), equivalent to Newhaven Formation, marls in the Hallue Catchment, which are also present in the unsaturated zone (Figure 7.6), were found to be thin (~1 mm) and perhaps less likely to be hydrogeologically significant (Table 3.3). Figure 7.8, therefore, is probably more representative of the effective marl seams within the unsaturated zone of the Hallue Catchment. In the Patcham Catchment, however, marl seams are likely to also be present within the Zig Zag, Holywell and Newhaven Chalk Formations in the Patcham Catchment unsaturated zone. Plus an additional seventy griotte marl zones/wispy marls, or clastic marls, were observed in the NHB2 borehole core. It is, therefore, likely that the entire areal extent of the Patcham Catchment unsaturated zone north of Patcham village, and the urban extent of Brighton, contains lithological contrasts associated with marl seams.

The results from this analysis effectively zone or divide, for a given water table, the catchments into areas where the unsaturated zone maybe susceptible to fracture or ‘bypass’ flow and where stratigraphically constrained localised recharge is feasible. In areas outside of the marl extents, where stratigraphically constrained localised recharge is less likely, the dominant recharge mechanism would be assumed to be direct recharge through the Chalk matrix. Within the marl extents, under certain recharge conditions, temporary perched water tables or stratigraphically constrained saturated conditions may occur potentially leading to lateral localised recharge along the marl seams (Figure 7.7) thereby temporarily altering recharge routes.
Figure 7.9 Geological section through the Hallue Catchment geological model with the base of the weathered zone, marl seams and water tables (November 1966 and Peak 2001) depicted. Lines of section are illustrated on Figure 7.8 A.
Under these conditions each marl seam, in effect, would have its own catchment, as defined in Figure 7.8, with the lateral localised recharge along the marl seam dictated by the structural gradient of that surface and the extent of that surface in the unsaturated zone - constrained by the base of the weathered zone, the position of the principal water table and any significant fractures which would cause the flow to down step – as suggested by Mortimore et al. (1996). The analysis presented in Figure 7.8, therefore, may also be considered as defining the maximum extent and scale of lateral localised recharge in the Hallue and Patcham catchments.

Anecdotal evidence for lateral localised recharge along marl seams is documented by Mortimore (1993) who noted seepages along marl seams in the Newhaven Chalk Formation (upper Santonian – Lower Campanian) at the base of the secondary escarpment in the South Downs in West Sussex, and water flowing from above the upper surface of the New Pit Marl 2 (Middle Turonian) at the base of the cliffs in Senneville, near Fécamp, in Normandy. Lawrence (2005) also observed water flowing above marl seams at the base of cliffs in East Sussex during the winter of 2000/2001. Giles and Lowings (1990) suggested that low permeability horizons in the unsaturated zone around Ellisfield, Lasham and Medstead, in the upper Itchen Catchment in Hampshire, could explain anomalously small groundwater level fluctuations due to lateral localised recharge. As demonstrated for the Hallue Catchment, (Sections 7.2 and 7.4, Figure 7.8), however, smaller groundwater level fluctuations may be an indication of an unsaturated zone which is relatively absent in low permeability horizons and dominated by more homogenous Chalk units such as the Seaford Chalk Formation. The occurrence of conjugate fractures and increases in fracturing above and in association with marl seams was emphasised by Mortimore (1993), Mortimore et al. (1996) and Lord et al. (2002). The related increase in fracture connectivity and rock mass permeability may add some support to Giles and Lowings (1990) suggestion. Molyneux (2012) also suggested that hydraulically stratified recharge routes, saturated conditions and ephemeral localised recharge, maybe a partial explanation as to the occurrence of nitrate, turbidity and bacteriological contamination at production boreholes following periods of heavy rainfall. The type of analysis presented in Figure 7.8, therefore, may aid assessment of these phenomena or similar in other Chalk catchments, and could be applied to other hydrogeologically significant lithological features in the Chalk unsaturated zone.
Figure 7.10 Geological section through the Patcham Catchment geological model with the base of the weathered zone, marl seams and water tables (March 1993, September 1993 and Peak 2000) depicted. Lines of section are illustrated on Figure 7.8 B. Section 5 illustrates the progressive position of the groundwater divides for different water tables and the Ladies Mile No. 3 groundwater flooding trigger level for Patcham. Section 6 illustrates a profile through the Faulkners Bottom groundwater mound.
7.6 Estimation of Fracture Storage in the Unsaturated Zone

The findings from the FLOOD1 recharge sites (Adams et al., 2008; Amraoui et al., 2008; Gallagher et al., 2012; Molyneux, 2012; Rutter et al., 2012) and laboratory analysis of Molyneux (2012), as discussed in section 7.3, has highlighted the significance of fracture surface storage and water films in the deep unsaturated zone of the Chalk, thereby confirming the model of Price et al. (2000). The findings also confirmed that this process may occur anywhere in the unsaturated zone and is more prevalent in certain Chalk units where vertical permeability is not uniform due to lithological contrasts – particularly as a result of marl seams.

Price et al. (2000) proposed that unsaturated zone fracture storage could account for the discrepancy in groundwater storage in Chalk catchments noted by Lewis et al. (1993), as well as the rate of response of the water table to recharge events and the resilience of Chalk catchments to drought. Similarly, this component of groundwater storage may be a contributing factor, in the form of delayed drainage, to the extended duration of groundwater flooding noted in the UK and France during the winter of 2000/2001 (Anon, 2004; Adams et al., 2008; Amraoui et al., 2008; Noyer et al., 2008).

The Hallue and Patcham geological models may be used to estimate the potential volume of water which could be stored in this form in the unsaturated zone on recession of the peak 2000/2001 water tables. Molyneux (2012) calculated the thickness of water films held on the surface of laboratory specimens at zero matrix potential to be on average $3 \times 10^{-5}$ m thick with an average uncertainty of $\pm 1 \times 10^{-5}$. At zero matrix potential, the water film thickness represents the maximum film thickness that would be held on a fracture surface under effectively unsaturated conditions. An increase in matrix potential at this point would cause the fracture to start to fill, i.e. saturation to occur, and a decrease in matrix potential would cause water from the film to start to be re-absorbed into the matrix. This value can be considered as the water film thickness held on fracture surfaces if the water table fell instantaneously. It, therefore, allows an approximation of the maximum volume of water which could be stored in the unsaturated zone under these conditions.
In Chapter 4, fracture measurements from exposures and boreholes were used to determine the typical chalk rock mass and fracture characteristics for the chalk units present within the research catchments (Table 4.1 and Table 4.3). By equating the fracture measurements to the CIRIA chalk classification scheme (Lord et al., 2002) it was felt that useful generalisations could be made, which would be comparable to other sources of fracture data, such as arising from engineering ground investigations, and be applicable to other areas of Chalk outcrop. In terms of CIRIA chalk grades for unweathered chalk, the typical grades determined from the exposures and boreholes were grades A-C and suffixes 1-2 (Table 4.1 and Table 4.3). This agreed with the engineering rockhead analysis presented in Chapter 6 (Section 6.2.3.1), where grades with suffixes of 3-5 were typical of weathered chalk, the distribution of which displayed a relationship to topography, and grades with suffixes of 1-2 were typical of unweathered chalk, which displayed little or no relationship to topography. The fractures measured in the research catchments were found to generally fall into three distinct sets with variation in inclination related to lithostratigraphy (Chapter 4 – Section 4.4.4). Two sets were generally inclined – sub-vertical (bedding normal) and one set was sub-horizontal (bedding parallel). If these sets are assumed to be orthogonal and their spacing and aperture are equated to CIRIA chalk grades, then a 1 m$^3$ volume of chalk would have the theoretical available surface area for water film storage as shown in Table 7.5.

The fractures are assumed in Table 7.5 to be simple parallel surfaces with no surface roughness. Where fractures are closed, CIRIA grade A, the available surface area for water films is assumed to be half that of open fractures, CIRIA grades B or C. Open fractures will have two surfaces available to sustain water films. Closed fractures are assumed to having an interstice and surface area capable of sustaining water films but no greater than the width of a single water film i.e. $3 \times 10^{-5}$ m. By multiplying the fracture surface area by the average film thickness at zero matrix potential, the volume of water held in water films can be estimated for different CIRIA chalk grades in a 1 m$^3$ volume of chalk (Table 7.5). As the CIRIA classification scheme discontinuity spacing categories are open ended for grade suffixes 5 and 1, the most conservative discontinuity spacings have been assumed. It is interesting to note that the volume of the water films expressed as a percentage of the volume of rock for CIRIA grades B/C3 or B/C4 (0.288%) falls within the 0.25-0.30% range.
quoted by Lewis et al. (1993) as being the required volume of water release from the unsaturated zone to account for the discrepancy in groundwater storage in Chalk catchments. CIRIA grade suffixes of 3 and 4 probably approximate to the average fracture spacing in the upper portion (~30 m) of the Chalk aquifer – as review of Figure 6.6 would indicate.

<table>
<thead>
<tr>
<th>Grade Suffix</th>
<th>Discontinuity Spacing (mm)</th>
<th>Fracture Surface Area (m²)</th>
<th>Water Film Volume (m³)</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Per Fracture Set</td>
<td>Per 1m³ Block Grade A</td>
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<td>Per Fracture Set</td>
<td>Per 1m³ Block Grade A</td>
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<td>1</td>
<td>Min</td>
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Table 7.5 Estimated volume of water held in water films on fracture surfaces for different CIRIA chalk grades at zero matrix potential in a 1 m³ volume of chalk. Thickness of water film at zero matrix potential is assumed to be 3 x 10⁻³ m. Water volume expressed as a percentage of the volume of rock is given in brackets. Values used in calculations for Table 7.6 are highlighted grey.

The water table surfaces used in the geological models of the research catchments may be used to estimate the theoretical volume of Chalk which could have drained following the peak 2000/2001 groundwater levels by calculating the difference in the volume of the unsaturated zone between that of the peak water tables and the typical end of recession water tables - November 1966 for the Hallue Catchment and September 1993 for the Patcham Catchment. This volume can then be used to estimate the maximum water film volume in the unsaturated zone for the typical CIRIA chalk grades encountered in the catchments. The results of these calculations are presented in Table 7.6.

The fracture surface water film volumes, presented in Table 7.6, are estimated for approximately the minimum and maximum CIRIA Chalk grades associated with both weathered and unweathered chalk (refer also to Figure 6.6). Due to the larger
Table 7.6 Estimated maximum theoretical water film volumes in the unsaturated zone of the Hallue and Patcham Catchments following the peak 2000 and 2001 water tables. The volumes were calculated using the water table surfaces Peak 2001 and November 1966 for the Hallue Catchment and Peak 2000 and September 1993 for the Patcham Catchment. The groundwater released is estimated by multiplying the drained model volume by the storage coefficients. The storage coefficients used were $5.5 \times 10^{-2}$ for the Hallue Catchment which is the median of values quoted by Crampon et al. (1993), and $2.3 \times 10^{-3}$ which is the geometric mean storage coefficient quoted by Jones and Robins (1999) from pump tests in the South Downs. Water film volume as a percentage of groundwater released volume is given in brackets.

catchment size, the Hallue has a greater volume of water which could potentially be stored in this form for the equivalent grade. The combined water film volume from both weathered and unweathered chalk would equate to the total volume of water held as water films on fracture surfaces after the water table has fallen. The water film volumes, as a percentage of the water released from storage, show an order of magnitude range between the minimum and maximum grades within a domain (weathered/unweathered chalk) and a two order of magnitude range between the minimum and maximum grades for the catchment. The minimum and maximum values per catchment represent end members and, in reality, the fracture surface area and water film volume is likely to fall somewhere between these extremes. If, for example, the combined maximum grade for weathered chalk (A3) and the minimum grade for unweathered chalk (B/C2) are considered as representing an intermediate fracture surface area for the drained volume of rock, the combined
water film volume would be 2,005,787 m$^3$ for the Hallue Catchment and 567,172 m$^3$ for the Patcham Catchment. If expressed as a percentage of the water which would theoretically be released from storage, this volume would be 2% for the Hallue Catchment and 39% for the Patcham Catchment. These volumes, however, are approximations of a maximum value. In the Hallue Catchment, based on the findings from the Warloy-Baillon recharge site (Amraoui et al., 2008), it is likely that as the water table recedes water held on fracture surfaces would be reabsorbed into the matrix and the calculated maximum potential volume of water which could be stored in this form would never occur. This water would, however, reach the water table via slow, or ‘delayed’, drainage through the matrix. In the Patcham Catchment, however, the maximum potential volume of water held on fracture surfaces is more likely to occur, as indicated at the North Heath Barn recharge site, where water films were sustained for much longer durations (Adams et al., 2008; Gallagher et al., 2012; Molyneux, 2012; Rutter et al., 2012). This observation from the North Heath Barn recharge site, coupled with knowledge of the heterogeneity of the unsaturated zone, suggests that slow or delayed drainage of the matrix is less significant in the Patcham Catchment and rapid fracture or ‘bypass’ flow in the unsaturated zone is more prevalent. The relative differences in these processes between the catchments may provide some explanation to the differences in duration of groundwater flooding i.e. groundwater flooding persisted for months in the Hallue Catchment and Somme compared to weeks in the Patcham Catchment (Anon, 2004; Adams et al., 2008; Amraoui et al., 2008; Noyer et al., 2008).

The water film volumes expressed as a percentage (Table 7.6) are approximately an order of magnitude less for the Hallue Catchment than the Patcham Catchment for the equivalent CIRIA chalk grade. This is due to the storage coefficients which were used to estimate the volume of water which would be theoretical released in response to the water table fall. The storage coefficients, 5.5 x 10$^{-2}$ for the Hallue Catchment and 2.3 x 10$^{-3}$ for Patcham Catchment, were derived from Crampon et al. (1993), who reproduced values from Roux (1963), and Jones and Robins (1999) respectively. The order of magnitude difference between these values may be due to differences in how they were derived or the characteristics of the aquifer between the Hallue Catchment and the South Downs. The value used for the Hallue Catchment is the median of values estimated by Roux (1963) from the ratio of the
volume of water drained from storage by gravity flow to the volume of aquifer drained. The value used for the Patcham Catchment is the geometric mean of values derived from pump tests in the South Downs (Jones and Robins, 1999). Despite the difference, these values are generally similar to values used by Lewis et al. (1993) for the southern province Chalk in the UK, with $10^{-2}$ associated with the aquifer $<10$ m below top of Chalk and $10^{-3}$ associated with the aquifer $>30$ m below top of Chalk – the intermediate 10-30 m having a mix of both depending on the Chalk unit the rest water level resided in.

A possible explanation for the difference in the storage coefficients, which relates to aquifer characteristics, is the composition of the saturated zone in the Hallue Catchment. The effective saturated zone of the aquifer in the Hallue Catchment is comparatively thinner than the Patcham Catchment (compare Figure 7.9 and Figure 7.10). This is a consequence of the Chalk sequence being condensed (Chapter 3 - Section 3.4, Figure 3.15), the base of the aquifer being the Middle Turonian ‘Dieve bleues’ (New Pit Formation) which is higher in the Chalk sequence than the Cenomanian (Zig Zag and West Melbury Formation) which form the base of the aquifer in the Patcham Catchment, and the variation in topographic relief being relatively less than the Patcham Catchment (Chapter 3 – Section 3.4). The weathered zone, as a relative proportion of the saturated zone of the aquifer, may, therefore, be greater in the Hallue Catchment than in the Patcham Catchment. This is supported by the percentages in Figure 7.6, whereby the weathered zone comprises 0.04-0.22% of the saturated portion of the Hallue Catchment geological model compared to 0.02-0.06% of the Patcham Catchment geological model. The weathered zone also comprises a greater percentage of the unsaturated zone in the Hallue Catchment as discussed in section 7.4. In addition, the relatively smaller groundwater level ranges observed in the Hallue Catchment (Section 7.2 and Table 7.1) may also suggest a catchment which is relatively more permeable and able to drain more readily. The implication of this is that the storage coefficients, derived by Roux (1963) from drainage of the catchment, would reflect this physical characteristic and be greater as a result.

The values presented in Table 7.6 represent an attempt to quantify the maximum potential volume of water stored in water films on fracture surfaces, within the zone
of groundwater fluctuation, following the peak 2000/2001 groundwater levels. The values calculated may represent crude estimates but the CIRIA grades applied were based on typical values from field surveys and ground investigations (Chapter 4 and Chapter 6). Physical characterisation and classification of fracturing has been a key focus of many studies related to both the engineering (e.g. Lamont-Black, 1995; Mortimore, 2001a; Lord et al., 2002; Lawrence, 2007; Mortimore, 2012) and hydrogeology (e.g. Younger and Elliot, 1995; Bloomfield, 1996, 1999; Nativ et al., 2003) of the Chalk. By attempting to combine the CIRIA engineering chalk classification scheme (Lord et al., 2002) with current understanding of fracture surface storage in the unsaturated zone, and up scaling this using 3D geological models, it is felt that a relevant and valid crossover can be demonstrated. Further work would be required, however, to refine this approach.

7.7 Location of Groundwater Emergence and Extent of the Catchments

The sites of groundwater emergence in the Hallue and Patcham catchments during the winter of 2000/2001, which the FLOOD1 recharge sites were located in the vicinity of, share similar geomorphological and hydrogeological characteristics. In the case of the Hallue Catchment, groundwater emergence occurred in a dry valley to the east of the village of Warloy-Baillon and in the Patcham Catchment groundwater emergence occurred in the dry valley occupied by London Road (A23) and Patcham village on the outskirts of Brighton (Figure 7.1). In the Hallue Catchment, the valley is situated up catchment of the present day location of perennial groundwater emergence for the Hallue River, and is noted, on BRGM 1:50,000 geological maps and the Institut Géographique National (IGN) 1:25,000 maps, as being the valley of an ephemeral tributary stream called the Ravin. In the Patcham Catchment, Patcham village (Figure 7.11), and further up catchment Braypool and Pyecombe, were sites of historical groundwater emergence which fed an ephemeral stream called the Wellesbourne.

The Wellesbourne ran from Patcham to the sea at Pool Valley in Brighton. One of its principal sources was a pond in front of All Saints Church, Patcham (Figure 7.11).
It was partially culverted in the nineteenth century and, with the construction of the Patcham Waterhall Pumping Station in 1889, ceased to have a regular surface expression (Carder, 1990; Collis, 2010). It has been suggested that the groundwater...
flooding in Patcham village during the winter of 2000/2001 may have been exacerbated by the sewerage system north of this culvette being insufficient to carry the volume of groundwater (Bartlett, 2005) leading to the system becoming surcharged (Binnie Black & Veatch, 2001). Irrespective of this factor, however, it would be expected, under exceptionally high groundwater levels as occurred in 2000/2001, that groundwater emergence would manifest up catchment in the same locality as the source of the historical Wellesbourne stream (Figure 7.11).

While knowledge of the location and frequency of historical groundwater emergence, combined with early warning systems such as developed by the Environment Agency for Patcham (Binnie Black & Veatch, 2001) or proposed by Adams et al. (2010), allow prediction of the location and timing of groundwater flooding events, review of the geological models of the catchments may provide some explanation as to why these locations have developed as sites of groundwater emergence.

The valley network and topographic relief in both the Hallue and Patcham catchments displays a subtly concordant relationship to geological structure (Figure 7.12). This is perhaps best demonstrated by comparing the position of structural axes to topographic elevations and potentiometric contours in the catchments (Figure 7.12). Structural highs, particularly anticlinal axes, are commonly coincident with topographic highs. The valleys where groundwater emergence occurred in 2000/2001, near to the FLOOD1 recharge sites, tend to be on the limbs of these anticlinal structures or coincide with intervening synclinal inflexions. The form of the water table also subtly reflects the geological structure with groundwater mounds often associated with anticlinal ‘domes’, although the overall gradient is towards the River Somme for Hallue Catchment and the sea for the Patcham Catchment. Similar spatial relationships have been documented by Giles and Lowings (1990) and Mortimore (1993) for the Itchen Catchment in Hampshire, and indicated generally by Jones and Robins (1999) for the South Downs.

The structures which illustrate this concordant relationship, both with topography and the water table, are the Ponthieu Anticline (D1) and structure E in the vicinity of the Hallue Catchment (Figure 4.1, Figure 4.2 and Figure 7.12) and the Hollingbury
Figure 7.12 Spatial comparison of topography, groundwater potentiometric contours, fold axes and faults in the Hallue and Patcham catchments. Sections are illustrated on Figure 7.9 and Figure 7.10.

Dome (D) and the Patcham Syncline (E) in the Patcham Catchment (Figure 4.13, Figure 4.14 and Figure 7.12). These spatial relationships, however, are not universal and may be inverted. Mortimore (1993) emphasised this with regard to structure and
topography using the Caburn Syncline (C), which forms the high ground of Mount Caburn in Lewes, as an example. Examples of discordant relationships between topography and structure in the catchments are illustrated by the tip of the Ponthieu Anticline (D1) being cross cut by the main Hallue River valley and the eroded core of the Pyecombe Anticline (A) on the northern edge of the Patcham Catchment.

The point of intersection in the Hallue Catchment coincides with an inflection in the Hallue’s course and the occurrence of a number of springs - possibly due to thinning of the aquifer over the axis of the anticline. In the Patcham Catchment, the Pyecombe-Patcham valley switches between being orientated parallel to the Pyecombe Anticline (A) axis in the north of the catchment to oblique in the centre of the catchment. The section which is oblique coincides with the location of historical spring emergence from Pyecombe and Braypool (Carder, 1990; Collis, 2010). The association of springs with these two eroded structures suggests groundwater emergence and erosion (spring sapping) on the limbs of the structures, may have had a role in the development of the cross-cutting valleys.

Despite variation in degree of concordance, the groundwater mounds associated with the anticlinal structures appear to be points of groundwater divergence or groundwater divides (Figure 7.12). Similarly, the synclinal inflexions tend to be associated with groundwater convergence – such as the Patcham Syncline (E). This is logical as the elevation of the base of the aquifer in the catchments, the Middle Turonian ‘Dieve bleues’ in the Hallue Catchment and the Cenomanian Grey Chalk Subgroup in the Patcham Catchment, are ultimately controlled by the structural geology of the Chalk. Generally, groundwater emergence in the Hallue and Patcham catchments tends to occur in valleys which coincide with the geological structures that focus groundwater flow either by thinning of the aquifer on the flanks or axes of anticlinal structures or by converging flow into synclinal inflexions. The presence of karstic faults, such as the Patcham Court Farm fault (I - Figure 7.12) (Lamont-Black, 1995), in these locations also suggests that these sites of groundwater focus and emergence are well established, as would be implied by the models of Rhoades and Sinacori (1941) and Price (1987), and potentially may have formed when groundwater was more chemically aggressive during periglacial conditions - as discussed by Younger (1989). It is this interplay between the form and hydraulic
gradient of the water table and topography, both influenced by the structural geology of the Chalk to varying degrees, which appears to define the location of groundwater emergence.

Changes in form and elevation of the water table also lead to movement in the position of the catchment groundwater divide (Ineson and Downing, 1964). Parker (2011) noted this a particular issue in Chalk catchments. As groundwater levels rise, the saturated zone increases vertically and, as a consequence, the catchment may also expand laterally towards the edges where the base of the aquifer is at its highest elevation. In the Hallue Catchment this is towards the Ponthieu Anticline (D1) and structure E and in the Patcham Catchment towards the Chalk escarpment (Figure 7.13). The catchment divide for the peak 2001 water table (Figure 7.13) indicates that while the Hallue Catchment is constrained by the surrounding catchments, there is expansion towards the groundwater peaks associated with the Talmas, Cardonnette and Hebuterne monitoring boreholes in the west, north-west and north of the catchment. These monitoring boreholes, at the peak of 2001, experienced groundwater levels of between 3.8 – 8.3 standard deviations above the mean for the respective time series (Figure 7.2 and Figure 7.14).

The catchment divide for the peak 2000 water table (Figure 7.13) indicates that the Patcham Catchment has a physical limitation imposed by the Chalk escarpment which leads to the catchment expanding laterally along the escarpment towards the groundwater peaks defined by the Devils Dyke Farm and Faulkners Bottom monitoring boreholes. Devils Dyke Farm, at the peak of 2000, experienced groundwater levels of up to 5.5 standard deviations above the mean for the timeseries. The maximum groundwater level during the peak of 2000 was not recorded in the Faulkners Bottom monitoring borehole – the value used in Figure 7.13 being the closest at 122 m OD or 0.5 standard deviations above the mean. The North Bottom, Lower Standean and Ladies Mile No. 3 monitoring boreholes, which are located within the north-east of the Patcham Catchment close to the groundwater divide, were monitored regularly, however, and experienced groundwater levels of between approximately 2.5 - 4 standard deviations above the mean for the respective time series (Figure 7.2 and Figure 7.14).
Figure 7.13 Position of Hallue and Patcham Catchment groundwater divides for different water tables. Sections are illustrated on Figure 7.9 and Figure 7.10.

Expansion of the catchment towards the Faulkner Bottom groundwater mound, in particular, may also lead to a change of flow direction which affects the Patcham Catchment and has relevance to groundwater emergence in Patcham. Under
normal groundwater levels, for example March and September 1993 in Figure 7.13, the groundwater divide in the north-east portion of the Patcham Catchment resides approximately at, or just east of, the monitoring boreholes of Ladies Mile No. 3, Lower Standean and North Bottom (Figure 7.13). Groundwater flow east of the divide is either eastwards towards the Winterbourne (A27) valley or south-east towards the Lewes Road valley. The Hollingbury Dome (Figure 7.10 – Section 5 and Figure 7.12 – D) on the eastern edge of the Patcham Catchment appears to act as an intermediate groundwater divide, enforcing this division of flow between the different catchments. During the extreme groundwater levels of 2000, the influence of the groundwater mound at Faulkner Bottom appears to have increased (Figure 7.10 – Section 6 and Figure 7.13) and the Patcham Catchment groundwater divide moved eastwards as a result (Figure 7.10 – Section 5 and Figure 7.12). Groundwater which would normally flow eastwards would, therefore, have been directed westwards, or over spilled, into the Patcham Catchment. This temporary diversion of groundwater flow westwards to the Patcham Catchment may provide some explanation for the apparent contradictory finding by Adams et al. (2005), based on the results of a simple GIS analysis, that groundwater flooding problems should be more severe in the Lewes Road valley in Moulsecombe than in Patcham.

The fluctuation of the groundwater divide in the north-east area of the Patcham Catchment appears to be supported by the long term groundwater monitoring time series for the Lower Standean, North Bottom and, to a lesser extent, Faulkner Bottom monitoring boreholes (Figure 7.2 and Figure 7.14). The timeseries for these boreholes display short term, high and low groundwater levels either side of their respective means, compared to other monitoring boreholes in the Patcham Catchment which tend to display short term highs but recess to consistent base levels (e.g. Pyecombe Old Rectory, Casterbridge Farm and Ladies Mile No. 3). This is demonstrated in Figure 7.14, by plotting the long term monitoring time series for the Patcham Catchment as standard deviations from the mean. Lower Standean and North Bottom consistently display lows of greater than one standard deviation from their respective means with Faulkners Bottom periodically displaying this behaviour. This characteristic of the time series may be a result of the boreholes being located on the edge of the catchment in a zone of fluctuation in the groundwater divide. The variation in groundwater level being enhanced by
Figure 7.14 Long term groundwater monitoring timeseries for boreholes within and near to the Hallue (A) and Patcham (B) catchments expressed as standard deviations from the mean. $Z_i = 0$ is equivalent to the mean piezometric level for the time series, $Z_i = -1$ is equivalent to one standard deviation below the mean and $Z_i = 1$ is equivalent to one standard deviation above the mean.
expansion and contraction of the catchment and the associated increase and decrease in connectivity and extent of the catchment up hydraulic gradient of the boreholes.

The variation in the position of the groundwater divides for March 1993, September 1993 and Peak 2000, relative to the Hollingbury Dome (D) and the Ladies Mile No. 3 monitoring borehole, is illustrated in Figure 7.10 – Section 5. Ladies Mile No. 3 is the monitoring borehole which is used by the Environment Agency to enable early warning of groundwater flooding in Patcham (Binnie Black & Veatch, 2001). The Ladies Mile No. 3 borehole is located on the northern edge of the Hollingbury Dome (Figure 7.12 - D), just to the west of the axis of the structure. During extreme groundwater levels, as the influence of the Faulkners Bottom groundwater mound spreads, and the Patcham Catchment expands, Ladies Mile No. 3 is critically positioned at the Hollingbury Dome (D) groundwater divide to observe the groundwater level as water is diverted from flowing eastwards to westwards. The trigger level of 49.5 m OD is, therefore, the level at which sufficient flow is being diverted into the Patcham Catchment, and groundwater levels have risen sufficiently, that the water table intersects the land surface and groundwater emergence occurs.

Lateral expansion of the Hallue and Patcham catchments, due to the development of groundwater mounds at high groundwater levels, coupled with the potential for changes in the direction of groundwater flow, may also be contributing factors to the characteristic extended duration of groundwater flooding noted in the UK and France during the winter of 2000/2001 (Anon, 2004; Adams et al., 2008; Amraoui et al., 2008; Noyer et al., 2008). Similarly to that observed in the Hallue and Patcham catchments, Hughes et al. (2011) described how the location of groundwater flooding in the Pang and Lambourn Catchments, for August 2000 to May 2001 and November 2002 to May 2003, related to the development and evolution of groundwater mounds. The findings from the Hallue and Patcham catchments suggest that the key to understanding these processes is understanding the interplay of groundwater levels with geological structure. The discussion presented here has sought to do this by comparing water table surfaces, long term
groundwater monitoring time series and the 3D geological models developed for the Hallue and Patcham catchments.

7.8 Conclusion

The discussions presented in this chapter have sought to evaluate the hydrogeological implications of the geological field observations and modelling presented in Chapters 3-6. By combining the results from the field investigations and geological modelling with the understanding of the hydrogeological processes operating within the research catchments, derived from long term groundwater monitoring and the FLOOD1 recharge sites, understanding has been gained about:

(i) how 3D geological models may be used to quantify the proportions of Chalk units susceptible to fracture or ‘bypass; flow in the unsaturated zone and how this may relate to the characteristics of groundwater level fluctuation in a catchment

(ii) how 3D geological models may be used as tools to estimate and map the hydrogeologically effective extent of lithotratigraphic features (e.g. marl seams), which disrupt vertical recharge and may lead to lateral localised recharge, in the unsaturated zone

(iii) how 3D geological models may be used as tools to estimate volumes of fracture surface storage, in the form of water films, in the unsaturated zone

(iv) how structural geology and geomorphology may influence the location of groundwater emergence and the extent of groundwater catchments

The analysis presented in this chapter has demonstrated how 3D geological models may be used as tools to conceptualise, estimate, and map the effects of lithostratigraphy, structural geology and geomorphology on the distribution of hydrogeological processes in the unsaturated zone of the Chalk aquifer. By enabling better understanding of hydrogeological processes in relation to lithostratigraphy, structural geology and geomorphology, the 3D geological models, maps and methods presented in this thesis may be used to aid conceptualisation of Chalk catchments – particularly with regard to unsaturated zone processes. This potentially has implications for recharge estimations, conceptualisation of pollution
pathways and delineation of source protection zones. Recommendations for further development of these methods and the final conclusions from this thesis are presented and discussed in Chapter 8.
Chapter 8  General Conclusions

This chapter draws general conclusions from the preceding chapters by reviewing the methods of investigation, the key findings from the data and the current understanding of the geology of the research catchments. Conceptual ground models for the Hallue and Patcham research catchments, relevant to hydrogeology and engineering geology, are presented and future developments of the work are discussed.

This thesis has presented findings from research conducted in the Hallue Catchment, a tributary of the Somme, northern France and in the Patcham Catchment, situated in the Brighton block of the South Downs, in southeast England. These catchments were also the focus of the European funded INTERREG III-A FLOOD1 hydrogeological research project. The research encompassed a broad range of subjects and techniques appropriate to understanding and developing ground models of Chalk catchments.

The field investigations in the research catchments focused on the three main research areas: Chalk stratigraphy and mapping, structural geological and geomorphology, with some work on Quaternary geology. The field data were used to revise the geological maps of the research catchments and develop new geological models to aid hydrogeological conceptualisation of the catchments. These five aspects of the research are discussed in the following sections.

8.1  Stratigraphy and Mapping of the Catchments

The status of the Chalk stratigraphy and mapping between the Hallue and the Patcham catchments varied significantly at the onset of this research. Much attention in this thesis has been given to understanding the context of the chalk geology and to using stratigraphical frameworks to compare and contrast the Chalk geology in both research catchments – as outlined in the objectives of Chapter 1.

In the Hallue Catchment, much of the current geological mapping and concept of the geology was based on fieldwork and analyses conducted between 1969 and 1977 by Bureau Recherches Géologique et Minières (BRGM). The most striking
issue associated with the geological maps which covered the Hallue Catchment, Amiens (Dupuis et al., 1972a), Albert (Mennessier et al., 1976a), Baupaume (Delattre and Mériaux, 1977) and Doullens (Delattre et al., 1974), was the variation in the geological units differentiated on each sheet (Chapter 3 - Table 3.1). The greatest difference is eight mapped units, for the Upper Turonian to Upper Campanian Chalk, displayed on the Albert sheet and two mapped units, for the Upper Turonian to Coniacian Chalk, displayed on the Baupaume sheet. A further complication, which highlighted differences in interpretation by the respective geologists, was some equivalent boundaries, which were mapped on adjoining sheets, did not match at the sheet boundaries.

In the Patcham Catchment, the geological mapping had been re-interpreted in a digital form for the Environment Agency and Southern Water in 1999-2000, and overall the Chalk lithostratigraphy in the South Downs was well understood from the work of Mortimore (1979, 1983a, 1986) and Bristow et al. (1997). The re-interpreted digital map of Brighton and Worthing sheets 318/333 (British Geological Survey, 2006a), incorporating the new Chalk formations, was based on remote sensing techniques, the macrofossil biozonal map of Gaster (1951), field notes of Mortimore (Mortimore, 2007) and a reconnaissance survey undertaken by the British Geological Survey over 4 weeks by 2-4 geologists (Aldiss, 2007; Hopson, 2009). It was considered, therefore, that the Chalk mapping and stratigraphical framework in the Patcham Catchment was significantly more advanced than the Hallue Catchment, but further fieldwork, using the techniques of Bristow et al. (1997), would be beneficial to validate the revised mapping.

Mortimore and Pomerol (1987) demonstrated that lithological and biostratigraphical marker horizons, used in the UK southern province Chalk lithostratigraphical system, could be correlated to the Chalk of Northern France. Pomerol et al. (1987), Pomerol (1988a, b; 1996) and Robaszynski et al. (2005) demonstrated the relationship of these marker horizons to the French stratigraphical system, developed by Monciardini (1978, 1980), and a combined stratigraphical framework was applied for mapping purposes on the BRGM maps of Bléneau, Courtenay, and Arcis-sur-Aube. The fieldwork conducted in the Hallue Catchment built on this work (Chapter 3). Exposures and boreholes were systematically logged to identify
lithological and biostratigraphical marker horizons in the Hallue Catchment. These data provided the basis for development of a lithostratigraphical framework which was used to revise and unify the bedrock geological map of the Hallue Catchment. The exposure logs and bedrock geological map highlighted previously undifferentiated geological structures as well as confirming known geological structures (Chapter 2). This framework also allowed direct correlation and comparison with the Chalk sequence present in the Patcham Catchment.

The fieldwork in the Patcham Catchment built on the re-interpreted Brighton and Worthing geological map (British Geological Survey, 2006a). Field brash and landform observations, with core and geophysical logs, were used to validate and refine the geological mapping further. The new borehole information and mapping in the Patcham Catchment allowed geological structures to be better defined. The field brash observations also provided detail on the occurrences of unusual chalk lithologies, typically associated with the geological structures, such as chalk containing dissolution tubules and hardened chalk with slickensides and shattered flint.

The results from the first phase of fieldwork allowed the lithology, stratigraphy and catchment scale geomorphology to be reviewed and compared, in the context of the regional geological evolution presented in Chapter 2, between the two research catchments. Central to this comparison was the questions posed in Chapter 1 on the geology of the Chalk aquifer. The findings from this comparison formed a basis for understanding the differences in the geology of the aquifer, the data collected from the experimental recharge sites and the occurrence of groundwater flooding between the research catchments.

The stratigraphical range of the Chalk at outcrop, and retrieved at subcrop in boreholes, was found to be similar between the two research catchments. The stratigraphical range sampled during the field investigations in the Patcham Catchment, however, was greater than in the Hallue Catchment. In the Hallue Catchment, the range at outcrop consisted of Upper Turonian to Lower Campanian Chalk with Middle Turonian Chalk also retrieved in boreholes. This is equivalent to the New Pit to Newhaven Chalk Formations in the UK. In the Patcham Catchment,
the range at outcrop and retrieved in boreholes consisted of Cenomanian to Lower Campanian. This is equivalent to the West Melbury to Newhaven Chalk Formations. The common units, which were studied in the field and from borehole core in both catchments, were the Middle Turonian to Middle Santonian or New Pit to Seaford Chalk Formations.

The lithological properties of the main stratigraphical units were generally found to be similar but with some key differences at bed level. The Middle Turonian or New Pit Chalk Formation in both catchments lacked flint, contained well developed marl seams and was found to be of medium density. In the Hallue Catchment, this chalk had a darker appearance than in the Patcham Catchment which is thought to relate to higher clay content. The Upper Turonian to Lower Coniacian or Lewes Nodular Chalk Formation in both catchments contained regular flint horizons, well developed marl seams, regular intervals of nodular chalk and was found to be of medium to high density. The Middle Coniacian to Upper Coniacian or Belle Tout and Cuckmere Beds of the Seaford Chalk Formation in both catchments contained regular flint horizons and was found to be of medium density.

In the Hallue Catchment, from the Lower to Middle Santonian, or the Haven Brow Beds of the Seaford Chalk Formation, there was a lack of flint present in the sequence and the chalk was found to have a low to medium density. The Lower Santonian chalk was massive with no regular sedimentary structure but in the Middle Santonian there was a return of regular fracturing (Section 8.2). Similar occurrences in the Lower and Middle Santonian Chalk were documented by Robaszynski et al. (2005) from the Poigny borehole in the eastern Paris Basin. Around the base of the Upper Santonian, or Newhaven Chalk Formation, in the Hallue Catchment flint started to reappear in the sequence. In the Patcham Catchment, the Lower to Middle Santonian sequence or Haven Brow Beds of the Seaford Chalk Formation contained regular flint horizons.

Further to the lithological properties of the chalk units, key lithological marker horizons were identified in both the Hallue and the Patcham Catchment. These lithological marker horizons were present in the Middle Turonian to Middle Coniacian Chalk or New Pit to Seaford Chalk Formations - Belle Tout/Cuckmere
Beds. The particular lithological marker horizons identified were the Glynde, Southerham, Caburn, Bridgewick and Shoreham Marls, and the Lewes Tubular, Shoreham Tubular and Seven Sister flint bands. Correlation of the marl horizons (Figure 3.15) has demonstrated that the Middle Turonian to Lower Coniacian Chalk sequence in the Hallue Catchment is around half the thicknesses of that in the Patcham Catchment. The relative difference in the thickness of the chalk sequence is likely to relate to differences in the proximity of the research catchments to the depositional centres of the basin. The Patcham Catchment would have been closer to the depositional centre located in the Weald (Figure 2.1 and Figure 2.8).

The unified Chalk bedrock map of the Hallue Catchment allowed comparison of the relationship between geomorphology and Chalk stratigraphy (Figure 3.8). Bristow et al. (1997) outlined the typical geomorphological characteristics of the Chalk units for mapping purposes in southern England. These geomorphological characteristics were generally found to be consistent in the Patcham Catchment. In the Hallue Catchment, despite relatively fewer chalk units being present at outcrop, the geomorphological characteristics of the Upper Turonian to Upper Coniacian, or Lewes Nodular Chalk Formation to Cuckmere Beds of the Seaford Chalk Formation, were found to be similar to the UK. That is, subtle low gradient (1-3°) convex slopes, similar to the dip slope of the escarpment in the South Downs. The Lower to Middle Santonian, or Haven Brow Beds of the Seaford Chalk Formation, differed from the typical geomorphological characteristics in southern England. This unit displayed higher gradient slopes (0 - 14°) with a negative break of slope at the base and a positive break at the top. The geomorphological character of this unit in the Hallue Catchment was thought to result from its more massive structure. This change in lithology may have made the unit more resistant to erosion and thereby producing higher gradient slopes in a similar manner to the New Pit Chalk Formation in the UK. The Upper Santonian to Lower Campanian or Newhaven Chalk Formation in the Hallue Catchment formed low gradient slopes associated with the plateau areas and did not display strong geomorphological expression. This differed from the Newhaven Chalk Formation in southern England which is associated with the development of the secondary escarpment in the South Downs (Bristow et al., 1997). This difference may have been a consequence of the low regional dip in the Hallue Catchment which limited escarpment formation. Overall the Patcham
Catchment was found to be more geomorphological mature than the Hallue Catchment - with greater variation in topography and less preservation of Cenozoic deposits.

8.2 Structural Geology of the Catchments

To evaluate the distribution of the lithostratigraphical units in the aquifer, the stratigraphical data and revised mapping for the research catchments was used to construct structure contours. In Hallue Catchment, structure contours were produced on the top of the Lower Coniacian or the Lewes Nodular Chalk Formation. In the Patcham Catchment structure contours were produced on the base of the Lewes Nodular Chalk. These contours confirmed known geological structures and highlighted new structures. As found by many authors working on the Chalk (e.g. King, 1921; Mortimore and Pomerol, 1987, 1991a; Mortimore, 2011), the majority of the geological structures identified in the research catchments were anticlinal or synclinal monocline and pericline folds. The key geological structures which have affected the Hallue Catchment were identified as the Somme Syncline, the Ponthieu Anticline, the Arquèves-Colincamps Anticline (structure E - Figure 4.1), the Hallue Valley Fold/Fault (structure I - Figure 4.1) and the Forceville Syncline (Figure 3.6 and structure J - Figure 4.2). The key geological structures which have affected the Patcham Catchment were identified as the Pyecombe Anticline, Henfield syncline, Caburn Syncline, Hollingbury Dome, Patcham Syncline, Patcham Adit Faults and the Coldean Lane Fault.

The Somme Syncline and Ponthieu Anticline are large-scale structures which extend for tens of kilometres and dictate the overall regional dip of the Chalk in the Hallue Catchment. The Arquèves-Colincamps Anticline, Hallue Valley Fold/Fault and Forceville Syncline are smaller scale folds within the Hallue Catchment which locally influence the dip of the Chalk. The Weald-Artois Anticline is a very large structure which extends for approximately 200 km and dictates the regional dip of the Chalk in the Patcham Catchment. The Pyecombe Anticline, Henfield syncline, Caburn Syncline, Hollingbury Dome and Patcham Syncline are smaller scale folds which locally influence the dip of the Chalk. The Pyecombe Anticline, Henfield Syncline and Caburn Syncline extend for tens of kilometres within the South Downs and into the Weald. The Hollingbury Dome and Patcham Syncline are smaller scale
folds which extend for a few kilometres and are located within the Patcham Catchment.

The field data collected in the Hallue Catchment provided supporting evidence for the existence of the Arquèves-Colincamps Anticline and Hallue Valley Fold/Fault – as well as confirming the influence of the larger scale Somme Syncline and Ponthieu Anticline. The Forceville Syncline was previously unidentified in the Hallue Catchment. Only Coniacian chalk is shown in this area on the Baupaume geological map whereas field data collected from exposures north of the village of Forceville provided evidence for Lower Santonian chalk and the syncline (Figure 3.6). The field data collected in the Patcham Catchment provided supporting evidence for the Pyecombe Anticline, Henfield syncline, Hollingbury Dome and Patcham Syncline - as well as confirming the regional dip. The field data helped refine the form and extent of the Pyecombe Anticline, which was found to be tighter and higher amplitude than previously understood.

The folds identified within the Hallue and Patcham catchments were found to have a similar form. The length of the axes of the smaller scale folds were also similar e.g. the Forceville Syncline and the Patcham Syncline. The larger folds tended to have shorter axes in the South Downs than in the Somme. The ratio of the amplitudes to axis length of the folds in the South Downs and the Patcham Catchment were typically three times greater than that of the Somme and the Hallue Catchment. This difference is thought to relate to the difference in the basement structures underlying the Chalk in the research catchments. The Patcham Catchment located in the South Downs on the flanks of the Weald-Artois Anticline – a large inversion structure – has tighter higher amplitude structures than in the Hallue Catchment located in the Paris Basin north of the main basin axis and south of the London-Brabant Massif (Figure 2.1 and Figure 2.8). Irrespective of the differences, however, the fold structures have affected the entire Chalk sequence in both research catchments. They, therefore, have dictated the elevation and form of the base of the aquifer and the direction of groundwater flow.

Groundwater flow in low matrix-permeability carbonate rocks such as the Chalk is largely controlled by fracture networks (Price, 1987; Downing et al., 1993; Lewis et
Cooke et al. (2006) recognised that the stratigraphical features that control fracture initiation and termination within a sequence of sedimentary rock strata define the mechanical stratigraphy of the sequence. They concluded that for a variety of carbonate mechanical stratigraphical sequences, dominant fluid flow characteristics, such as horizontal high flow zones and flow compartmentalization, could be evaluated using fracture spacing and connectivity within fracture networks that are predicted from sedimentary stratigraphy. In light of this, further field data were collected on fracturing to evaluate the fracture stratigraphy of the Chalk units in the research catchments.

In the Hallue Catchment, fracture data were collected from scanline surveys at exposures which covered the range of lithostratigraphical units present from Upper Turonian to Lower Campanian - or the Lewes Nodular to Newhaven Chalk Formations. Additionally, large hand specimen samples were also collected to assess the orientation and density of vein fabrics. In the Patcham Catchment, fracture data was collected from borehole optical televiewer surveys at boreholes which covered the range of lithostratigraphical units present from Cenomanian to Upper Turonian - or the Zig Zag to Lewes Nodular Chalk Formations.

Stereographic projections and histograms of the fracture data were used to determine the typical inclination, orientation and fracture spacing of the Chalk units in each research catchment (Figure 4.4, Figure 4.5, Figure 4.17 and Figure 4.18). This work was extended in the Hallue Catchment to review the typical aperture and persistence of the fractures (Figure 4.6 and Figure 4.7) and the relationship between the inclination, orientation and density of vein fabrics and fractures (Figure 4.11 and Table 4.2) for the different Chalk units. As found by Mortimore et al. (1990b), Mortimore (1993), Lamont-Black (1995) and Mortimore et al. (1996), the fracturing dip and orientation data presented in this thesis showed a change in characteristics with stratigraphy and structural geology. In the Hallue Catchment, this was seen as a transition from inclined fractures (60-70°) to sub-vertical fracturing (80-89°) to inclined fractures with the transition from Upper Turonian/Lower Coniacian to Middle Coniacian/Lower Santonian to Lower Campanian Chalk. This is approximately equivalent to the transition from Lewes Nodular to Seaford to Newhaven Chalk.
Formations. In the Patcham Catchment, the change in fracturing characteristics was less pronounced but there was a subtle transition from sub-horizontal to inclined to sub-horizontal and inclined fractures with the transition from the Cenomanian to Lower/Middle Turonian to Upper Turonian. This is equivalent to the transition from Zig Zag to Holywell/New Pit to Lewes Nodular Chalk Formations.

The fracture spacing data collected in the research catchments displayed less variation with stratigraphy and appeared in some cases to be site-specific. The fracture spacing data was presented as histograms according to the categories outlined by BSI (2003) and the modal spacing was taken as typical for that exposure or Chalk unit (Figure 4.5 and Figure 4.17). In the Hallue Catchment, the fracture spacing was found to be typically wide spaced (2000 to 600 mm) for the Upper Turonian to Upper Coniacian Chalk and medium spaced (600 to 200 mm) for the Lower Santonian to Lower Campanian Chalk. This division is equivalent to the Lewes Nodular Chalk Formation to the Belle Tout and Cuckmere Beds of the Seaford Chalk Formation, and the Haven Brow Beds of the Seaford Chalk Formation to the Newhaven Chalk Formation. The one exception to this was seen at exposure HA13 where close spaced (200 to 60 mm) fracturing was dominant. This close spaced fracturing, however, was related to site-specific faulting. In the Patcham Catchment, the relationship of fracture spacing to stratigraphy was again less pronounced than in the Hallue Catchment. If reviewed by formation, the Zig Zag Chalk Formation was dominated by wide to very wide spaced (>2000 mm) fractures, the Holywell Chalk Formation by medium to wide spaced fractures, the New Pit Chalk Formation by medium to very wide spaced fractures and the Lewes Nodular Chalk Formation by very wide space fractures. The comparison between vein fabric spacing and fracture spacing alludes to the potential controls on this variation with strata (Figure 4.11 and Table 4.2). This indicated that where the matrix is more homogenous, i.e. where vein fabrics are more widely spaced, the spacing of fractures is also greater. Chalk units which have experience a higher degree of syn-depositional reworking and bioturbation, therefore, show a generally greater primary fracture spacing.

The fracture aperture data collected in the Hallue Catchment displayed little relationship to stratigraphy. The majority of Chalk units were found to have a typical
fracture aperture equivalent to CIRIA grade A (Closed) or grade B (<3 mm). The exception to this was seen in the Upper Turonian and Lower Coniacian Chalk, or Lewes Nodular Chalk Formation, at exposures HA57A and HA57B where almost equal numbers of fractures had apertures equivalent to CIRIA grade C (>3 mm). This is consistent with the observations of Miller (2000) who noted that the Lewes Formation exhibited greater dilation on fractures due to the presence of high density nodular chalks. Exposures HA13, HA23, HA27 and HA51 were also found to have a proportion of fractures equivalent to CIRIA grade C - which related to localised fracture zones or faults at these exposures. The fracture persistence data collected in the Hallue Catchment indicated that the majority of chalk units showed a fracture persistence of > 1 m and < 4 m. The exceptions to this observation were mostly related to sub-horizontal fractures which had a persistence of typically >5 m and in some cases > 10 m. The fractures with greater persistence appear to be associated with chalks that also contained marls i.e. The Upper Turonian, Lower Coniacian and Lower Campanian Chalk. Bloomfield (1996) inferred that sub-horizontal fractures, such as these, would control, in combination with faults, fast flow in the aquifer fracture system.

Dip and dip direction of vein fabrics were statistically compared, using a Watson-Williams’ statistical test of mean directions (Mardia, 1972), against the dip and dip direction of the fractures measured from the scanlines (Section 4.4.1). The results from this test indicated that the mean dip and dip direction of the vein fabrics was equivalent to the mean dip and dip direction of the primary fractures. This indicates that the vein fabrics and fractures are likely to have formed from the same stress field, and the Chalk has been affected by this stress field during sedimentation (vein fabrics) and after lithification (fractures). The strikes of the fractures were also compared to the strikes of the fold axes in the Hallue and Patcham Catchment using a statistical test for the equality of two sets of directional vectors. It was found that, within the research catchments, that the fracture strikes and fold axes structures showed statistically similar trends. The orientation of the structures in the Chalk, therefore, may be considered as related on multiple scales from vein fabrics in the matrix to large scale folds.

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The methods of fracture data collection used in both research catchments had inherent limitations, which led to constraints in the resulting data sets. In the Hallue Catchment, perhaps the most significant limitation to the scanline method was that many of the exposures were too small to measure the full persistence of fractures and the fractures often continued out of section. This especially applied to sub-horizontal fractures. A further potential constraint on the fracture dataset was directional sampling bias. Typically at each exposure scanlines were conducted in horizontal and vertical alignments on one exposure face. If, however, multiple faces were present at an exposure these were also surveyed to minimise directional bias. The trend and plunge of the scanlines were recorded and a Terzaghi weighting was applied to compensate for this bias. In the Patcham Catchment, perhaps the most significant limitation to the borehole optical televiewer method was the inability to resolve fractures which had an aperture of <1 mm. This, therefore, meant only fractures with equivalent apertures to CIRIA grade B and C are measured and all grade A fractures were missed. A significant number of fractures in the Chalk have an aperture of < 1 mm - as indicated by Figure 4.19 in Chapter 4. Additionally, the optical televiewer dataset, as with the scanline survey dataset, had potential for directional sampling bias. The optical televiewer survey, however, was treated like a scanline survey and the trend and plunge of the borehole was used to compensate the data.

8.3 Quaternary Geology, Geomorphology and Soils

A key objective for the INTERREG III-A FLOOD1 research project was the installation of recharge sites to monitor the unsaturated and saturated zone of the Chalk aquifer. In the Patcham Catchment, fieldwork was undertaken to assess the shallow ground conditions in the area proposed for the shallow recharge site instrumentation prior to it being installed. The fieldwork comprised a series of reconnaissance surveys to provide information on topography, ground electromagnetic conductivity, soil field saturated hydraulic conductivity, particle size and mineralogy.

The topographical and ground conductivity data was collected using a Leica GPS1200 and Geonics EM31 respectively. Electronic data storage and logging functions in both instruments allowed rapid collection of data. The topographical
data was used to produce topographical profiles over the site (Figure 5.8 and Figure 5.9). The ground conductivity data was used to indicate the presence and distribution of Quaternary deposits and karst within the site. The topographical profiles highlighted the presence of a series of asymmetrical dry valleys, typical of the South Downs, which had slope gradients varying between 1° and 15°. The ground conductivity was found to vary over the site with three areas of relatively high ground conductivity separated by areas of relative lower ground conductivity. The majority of the areas of high ground conductivity were found to coincide with Quaternary Clay-with-flints and Head deposits - as shown on the Brighton and Worthing geological map (British Geological Survey, 2006a). The Head deposits were located in the axes of the dry valleys and the Clay-with-flints deposits on the crests of the interfluves. The ground conductivity values ranged up to ~14 mS/m for the Head deposits and up to ~19 mS/m for the Clay-with-flints deposits. The average ground conductivity for the survey was calculated as 8.9 mS/m. One significant high ground conductivity area was identified in the south-east part of the survey area and did not coincide with any mapped Quaternary deposits. This was determined by sampling the soil and mineralogical analysis to be an area of unmapped Clay-with-flints. This indicates that the mapped extent of Clay-with-flints in the Patcham Catchment, currently around 2 km², is likely to be an underestimate.

Soil field saturated hydraulic conductivity, determined using a Guelph field permeameter, was measured at each area of varying ground conductivity. At each permeameter location, a soil sample was collected for grain size and mineralogical analysis of the fine grained sediments in the soil. The purpose of this was to determine the clay content, as this was thought may affect soil hydraulic conductivity, and to aid identification of the parent material of the soil. The soil field saturated hydraulic conductivity was found to vary between $2.86 \times 10^{-5}$ to $4.55 \times 10^{-8}$ m/s over the survey area. It was also found to vary with ground conductivity and the location of Quaternary deposits. The high ground conductivity areas associated with the locations of Clay-with-flint deposits were found to have the lowest values of field saturated hydraulic conductivity at $4.03 \times 10^{-6}$ m/s and $4.55 \times 10^{-8}$ m/s. The high ground conductivity areas associated with the location of Head deposits were found to have slightly higher values of field saturated hydraulic conductivity of $6.48 \times 10^{-6}$ m/s and $1.49 \times 10^{-5}$ m/s. The areas of relatively lower ground conductivity associated
with soils directly overlying Chalk bedrock were found to have the highest values of field saturated hydraulic conductivity of $1.27 \times 10^{-5}$ and $2.86 \times 10^{-5}$.

The soil samples collected at the Guelph permeameter locations were found to have either silica or calcite as the dominant soil forming mineral. The majority of soil samples were primarily composed of silt size particles with one calcite dominated soil composed of clay size particles. The silica dominated soil types were typically located in the south of the survey area whereas the calcite dominated soil types were typically located in the north of survey area. The minor mineralogical soil constituents provided an indication of the soil parent material and were found to have a significant influence on the soil hydraulic conductivity. The minor mineralogical constituents of the soil comprised smectite, illite, kaolinite, feldspar and goethite. These soil minerals are likely to have been derived from the Clay-with-flints deposits in the south and west of the survey area - which in turn have formed from weathering of Palaeogene deposits and dissolution of the Chalk (Avery et al., 1959; Hodgson et al., 1967; Catt and Hodgson, 1976; Catt, 1986; Quesnel et al., 2003).

The field saturated hydraulic conductivity for locations where the soils contained smectite as a minor constituent were found to be generally lower than where the soil contained illite. Typically, the field saturated hydraulic conductivity was around $10^{-6}$ m/s for soils containing smectite and around $10^{-5}$ m/s for soils containing illite. The one exception to this observation was a soil which contained illite (8 %) and goethite (4.6 %) and was found to have the lowest soil field saturated hydraulic conductivity measured - $4.55 \times 10^{-8}$ m/s. This soil was overlying an area of Clay-with-flints and it was hypothesised that the goethite might reduce the hydraulic conductivity of the soil by filling and cementing the soil pore spaces. The soil which had the lowest proportion of clay and metal oxide minerals (74.4% calcite, 24.8% silica and 0.8% illite), conversely, was found to have the highest field saturated hydraulic conductivity - $2.86 \times 10^{-5}$ m/s. The mineralogy and particle size of this soil, combined with the relatively lower ground conductivity, indicated that this soil directly overlaid, and had primarily formed from, the Chalk bedrock. This location is likely to be most representative of a Chalk profile from surface to depth within the survey area - and was chosen for the installation of the shallow recharge site instrumentation.
The field saturated hydraulic conductivity was found to display a strong negative correlation to the proportion of clay and metal oxide minerals in the soil as determined by the XRD analysis i.e. increases in this fraction of minerals lead to a reduction in the field saturated hydraulic conductivity. This correlation was stronger than comparison of fines and clay particle size proportions (fines and clay fraction) to field saturated hydraulic conductivity. Klinck et al. (1998) stated that where the hydraulic conductivity of Clay-with-flints is less than $1 \times 10^{-7}$ m/s surface runoff will occur for most rainfall events, leading to point or focused recharge on the margins of the deposits or through voids. For hydraulic conductivities of greater than $1 \times 10^{-7}$ m/s most effective rainfall will infiltrate the Chalk. The data collected from the North Heath Barn survey area, indicates this threshold would be exceeded when the mineralogical component of clays and metal oxides exceed approximately 20-30\% in the soil (Figure 5.14). The XRD analyses of samples from the Hallue and wider Patcham Catchment (Table 5.3 and Table 5.5), have demonstrated that the clays and metal oxides in Formations résiduelles à silex / Clay-with-flints deposits commonly equate to or exceeded 20-30\%. If these deposits are relatively continuous, this would suggest that surface runoff and point recharge on the margins and through voids in the deposits would be a significant process. The observed regular occurrence of Formations résiduelles à silex / Clay-with-flints and karst at Chalk exposures in Hallue Catchment (Figure 5.13) suggests that runoff and point recharge processes maybe significant in the Hallue Catchment.

The results from North Heath Barn survey suggested that the combination of EM31 ground conductivity, field permeameter and mineralogical assessment using XRD analysis may aid rapid assessment and prediction of the susceptibility of soils and Quaternary deposits to runoff recharge processes and focused recharge. The survey also highlighted the variation in ground profiles over a relatively small area within the Patcham Catchment and indicated that one recharge site is perhaps not sufficient to represent the range of recharge process occurring within a catchment.

8.4 Geological Modelling of the Catchments

Digital geological models were produced for the Hallue and Patcham research catchments to synthesise the field data presented in Chapters 3-5. The software
used for this work, GSI3D 1.5.2 (Geological Surveying and Investigation in 3D), allowed the models to be developed iteratively through the staged construction of a network of intersecting cross sections. The GSI3D software was intuitive to use as it involved drawing cross-sections from map and borehole information; it utilised very simple text or GIS data formats and did not require comprehension of complex geostatistical interpolation methods. GSI3D 1.5.2, however, was originally designed for modelling shallow Quaternary deposits rather than bedrock geology. The data for these models comprised the revised geological maps of the research catchments, the exposure logs from the Hallue Catchment and the borehole logs from the Patcham Catchment. To assist with modelling the Chalk bedrock, and also maintain three-dimensional consistency, the structure contours presented in Chapter 4 (Figure 4.2 and Figure 4.14) were converted to an ASCII grid format using ArcGIS 9.0 and imported into GSI3D. The modelling process using GSI3D allowed the form of the geological structures, discussed in Chapter 2, to be further investigated and better understood. In addition to the stratigraphical modelling, it was intended that spatial data relevant to hydrogeology and engineering geology were incorporated within the models – thereby creating ground models. To this end, surfaces which represented engineering rockhead, or the base of the weathered zone, and water tables were incorporated into both models.

A novel approach was developed to simulate the base of the weathered zone (engineering rockhead) surface using fracture spacing data from ground investigation boreholes in the South Downs, North Downs and Salisbury Plain. Williams (1980, 1987), Mortimore et al. (1996) and Lord et al. (2002) showed that engineering rockhead, or the base of the weathered zone, in areas of Chalk outcrop was intrinsically related to topography. The topography of the Chalk outcrop in Southern England has also remained relatively static since the end of the Devensian (Jones, 1999b). Based on this understanding a predictive model was developed which simply required topographical information to predict the base of the weathered zone. The fracture spacing data was converted to equivalent CIRIA grades and the boundary between CIRIA grade suffix 3 and 2 was taken as the boundary between weathered and unweathered Chalk for this analysis. The relative elevation of the boreholes, based on the geomorphological region, were plotted against the depth of CIRIA grade suffix 3 and two curves fitted to the data (Figure 6.6). Curve B was
then used to generate a predicted engineering rockhead surface for the research catchments using a bare earth digital terrain model. The model was tested against a published weathering profile (Newman et al., 2003) and it was found to predict the profile adequately.

Figure 8.1 Hallue Catchment geological model

The engineering rockhead, water tables and stratigraphical units were combined into a single standalone GSI3D viewer for each research catchment (Figure 6.9, Figure 6.10 and Appendix VII). The function to capture GSI3D models into standalone GSI3D viewers was developed by the BGS during this work. The GSI3D viewers allowed the models to be disseminated in a read-only format that could be viewed and interrogated but not edited. The final GSI3D models produced during this work took advantage of this new function. The final Hallue Catchment GSI3D model captured in the GSI3D viewer was constructed from 41 sections and comprised 11 modelled units including the engineering rockhead and typical water table surface of November 1966. The final Patcham Catchment GSI3D model captured in the GSI3D viewer was built from 42 sections and comprised 26 modelled
units including surfaces for engineering rockhead, the groundwater flooding water table from 2000, typical beginning and end of recession water tables from March and September 1993 and nine marl seam units from the New Pit and Lewes Nodular Chalk Formations.

Figure 8.2 Patcham Catchment geological model.

The models captured in the GSI3D viewers represent the final conceptual models for the geology of the Hallue and Patcham catchments (Figure 8.1 and Figure 8.2). These models can be interrogated to produce synthetic cross sections, synthetic borehole logs and may be iteratively updated as new data becomes available. They, therefore, have powerful advantages to the typical models produced for engineering geology or hydrogeology purposes. In engineering geology, a geological model is typically a two-dimensional section drawing produced in CAD. As discussed by Turner (2006), CAD based systems, although they may incorporate 3D modelling and cross section functions, are unsuitable for modelling often poorly defined yet complex geological units. Similarly, in the field of hydrogeology, GIS software packages are typically used to produce trend surfaces, but these have no function
for maintaining three-dimensional consistency between modelled surfaces and are weak at providing standard outputs such as synthetic cross sections and borehole logs. The Hallue and Patcham Catchment models should be considered as overview and systematic models (Kessler et al., 2004; Kessler et al., 2008). This implies that they are limited in their accuracy to being equivalent to a 1:50,000 geological map.

8.5 Conceptualisation of the Catchments

The hydrogeological implications of the geological field observations and digital geological models presented in Chapters 3-6 were evaluated. In particular the digital geological models were used to compare and contrast the geological differences between the catchments. The implications of these differences were discussed in the context of the hydrogeological characteristics of the catchments based on a review of the long term groundwater monitoring from the catchments and the findings from the FLOOD1 research project and associated studies.

The review of the long term groundwater monitoring time series data for the catchments highlighted some key hydrogeological differences. The Hallue Catchment has experienced less extreme groundwater level fluctuations at approximately half to a third of the range experienced in Patcham Catchment (Table 7.1). The Hallue Catchment groundwater levels also display more progressive changes with the highest and lowest groundwater levels occurring after successive years where groundwater levels have been rising or falling respectively (Figure 7.1 and Figure 7.14). The Patcham Catchment groundwater levels tend to show weak or no progressive change between successive years with annual maximum groundwater levels returning to around the minimum observed groundwater level for the majority of the time series. These observations were reinforced by undertaking an autocorrelation analysis of the times series for five of the monitoring boreholes – two from the Hallue Catchment and three from the Patcham Catchment (Figure 7.3). This analysis demonstrated the groundwater levels in the Hallue Catchment display autocorrelation or persistence for at least six to seven months after an observation whereas groundwater levels in the Patcham Catchment display autocorrelation for two to three months. The implications of these findings were interpreted as the effects of recharge in the Hallue Catchment are cumulative whereas in the Patcham Catchment there are little or no cumulative recharge effects. The differences
between the Hallue and Patcham catchments which were thought may influence these recharge and groundwater level response characteristics, based on Adams et al. (2008), were catchment size, difference in the properties of the Chalk and the effects of superficial deposits.

Key findings from the FLOOD1 recharge sites, particularly from the jacking tensiometers, provided information on processes occurring within the deep unsaturated zone of the Chalk aquifer in the catchments. The matric potential (negative potential or suction) data recorded from the jacking tensiometers at the North Heath Barn recharge site showed that the deep unsaturated zone was at high matric potential for prolonged periods, commonly greater than -50 hPa, the generally interpreted threshold for activation of the Chalk fracture system (Wellings, 1984; Jones and Cooper, 1998), and at times measured zero or positive pressures. In contrast, the data recorded from the Warloy-Baillon recharge site rarely demonstrated high matric potentials greater than -50 hPa (Amraoui et al., 2008). The condition of the deep unsaturated zone at the North Heath Barn recharge site was interpreted as being the result of the presence of low hydraulic conductivity marl seams reducing the capacity for vertical drainage in the Chalk matrix and forcing water from the Chalk matrix onto fracture surfaces (Adams et al., 2008; Gallagher et al., 2012; Molyneux, 2012; Rutter et al., 2012). At the Warloy-Baillon recharge site a thin marl seam and flint band were seen to affect the readings at two of the jacking tensiometers but the overall more homogeneous chalk and, the effect of the majority of the tensiometers being installed in the weathered zone, indicated that there was no barrier to vertical drainage of the Chalk matrix. At Warloy-Baillon, matric potentials greater than -50 hPa only occurred when infiltration exceeded the hydraulic conductivity of the matrix, as observed between 21/02/2007 and 28/03/2007 (Amraoui et al., 2008), and water films on fracture surfaces were interpreted as being a rare occurrence.

The digital geological models of the research catchments were utilised to assess the proportions of Chalk units in the unsaturated zone for different water table surfaces. This analysis highlighted that although the water table surfaces used represented significant vertical variation in groundwater level, the proportions of the Chalk units within the unsaturated zone of the respective catchments, and
particularly the dominant units, varied little as a result of this groundwater level variation. The implication of this was twofold; firstly, the characteristics of the unsaturated zone of a Chalk groundwater catchment, in terms of the proportion and distribution of geological units, are approximately constant irrespective of groundwater level, thereby indicating that the recharge characteristics of deep Chalk unsaturated zone are approximately constant in a catchment, and secondly, this proportion and distribution of the geological units is ultimately defined by the geomorphology and structural geology of the catchment. The percentage of Chalk units in the unsaturated zone which contained marl seams and, based on the findings from the FLOOD1 recharge sites, may be susceptible to fracture or ‘bypass’ flow, were found to be 9.35 - 22.48% for the Hallue Catchment and 71.08 - 72.67% for the Patcham Catchment. In contrast the percentage of Chalk units in the unsaturated zone which are relatively homogeneous and may be dominated by drainage through the matrix (e.g. Seaford Chalk Formation) comprised 73.57 - 77.52% in the Hallue Catchment and 26.22% - 27.79% in the Patcham Catchment. Within the 73.57 - 77.52% in the Hallue Catchment, 31.68% - 35.26% is comprised of the extremely homogeneous C5d-e (Lower-Middle Santonian) unit which, also recognised by Mortimore and Pomerol (1987) and Robaszynski et al. (2005), may be specific to northern France, has no marl seams and is almost completely devoid of flint (Chapter 3 – Section 3.4).

These proportions provided an insight into the differences in the observations from long term groundwater level monitoring and recharge sites in the Hallue and Patcham catchments and suggest that, in terms of the effects of Chalk composition on recharge and groundwater level characteristics, the catchments may represent two opposite ends of a spectrum. In the Hallue Catchment, the capacity to buffer the effects of recharge, and for unsaturated zone fracture surface storage, can be considered as theoretically greater than in the Patcham Catchment for the equivalent volume of rock due to the dominance of more homogeneous Chalk units in the unsaturated zone. In the Patcham Catchment, more of the fracture surface storage is already being used throughout the year due to the presence of more heterogeneous Chalk units containing marl seams, as demonstrated by borehole camera surveys (Adams et al., 2008; Gallagher et al., 2012; Molyneux, 2012), and does not require much additional input to activate the fracture system and for bypass
flow to occur in the unsaturated zone (Molyneux, 2012; Rutter et al., 2012), thereby leading to a short lag between recharge input and a rise in groundwater levels. In contrast, the Chalk matrix in the unsaturated zone of the Hallue Catchment is able to drain more easily through the matrix and must first reach a matric potential of -50hPa (Wellings, 1984; Jones and Cooper, 1998; Amraoui et al., 2008) before additional input may be stored on fracture surfaces or water films developed sufficiently to allow fracture or ‘bypass’ flow (Price et al., 2000) – leading to a longer lag between recharge and a rise in groundwater levels. It can be inferred, therefore that, as the proportion of Chalk units which are susceptible to fracture or ‘bypass’ flow increases within the unsaturated zone of a Chalk groundwater catchment, the more the groundwater level characteristics will be like that of the Patcham Catchment.

A higher proportion of weathered Chalk in the unsaturated zone of the Hallue Catchment, 1.07% - 1.24% compared to 0.48% - 0.56% of the Patcham Catchment, coupled with the higher proportion of Cenozoic deposits, 8.12% – 8.54% compared to 0.59% - 0.77%, are thought to emphasise the differences of the Chalk units in the respective unsaturated zones. That is, the high fraction of the weathered zone in Hallue Catchment further degrading any lithological contrasts which may promote fracture or ‘bypass’ recharge, and the higher proportion of Cenozoic deposits, particularly thick coverage of ‘Limon des plateaux’ and presence of ‘Formations résiduelles à silex’, may buffer or slow the impact of recharge, potentially slowing the groundwater level response but also limiting the development of a soil moisture deficit in the summer months - thereby maintaining more constant matric potentials in the unsaturated Chalk. During periods of high recharge, however, these deposits may also promote localised runoff and point recharge at the edge of the deposits or through voids in the deposits. Evidence of this process is perhaps demonstrated by the frequent occurrence of infilled dissolution pipes in the Hallue Catchment (Figure 5.13).

Using the digital geological models, a spatial analysis was undertaken of the effective extent of the marl seams in the unsaturated zone of the Hallue and Patcham catchments. The effective extents were determined using the respective water tables to define the lower boundary and the model for the base of the
weathered zone (Section 6.2.3.1) to delineate the upper boundary (Figure 7.7) The marl seams included in this analysis were those identified in the P6 and NHB2 borehole cores. This analysis showed that three of the marl seams analysed were present in the unsaturated zone in the Hallue Catchment whereas ten of the marl seams used in the analysis were present in the Patcham Catchment (Figure 7.8, Figure 7.9 and Figure 7.10). The areal extent of marl seams in the Hallue Catchment unsaturated zone was found to be 125.97 km$^2$ and the total combined surface area of the marls is 155.23 km$^2$, compared to 58.20 km$^2$ and 302.57 km$^2$ for the Patcham Catchment. This analysis highlights that, despite the Hallue Catchment being the larger catchment and having the larger extent of marl seams in the unsaturated zone, the Patcham Catchment has a greater number and, therefore, also surface area of marl seams. If marl seams not encountered in the NHB2 borehole are also considered, it is likely that the entire areal extent of the Patcham Catchment unsaturated zone north of Patcham village, and the urban extent of Brighton, contains lithological contrasts associated with marl seams.

The results from this analysis effectively zoned or divided, for a given water table, the catchments into areas where the unsaturated zone may be susceptible to fracture or ‘bypass’ flow and where stratigraphically constrained localised recharge is feasible. In areas outside of the marl extents, the dominant recharge mechanism would be assumed to be direct recharge through the Chalk matrix. Within the marl extents, under certain recharge conditions, temporary perched water tables or stratigraphically constrained saturated conditions may occur potentially leading to lateral localised recharge along the marl seams (Figure 7.7) thereby temporarily altering recharge routes. Under these conditions each marl seam, in effect, would have its own catchment, as defined in Figure 7.8, with the lateral localised recharge along the marl seam dictated by the structural gradient of that surface and its extent in the unsaturated zone as constrained by the base of the weathered zone, the position of the principal water table and any significant fractures which would cause the flow to down step. The analysis presented, therefore, may be considered as defining the maximum extent and scale of lateral localised recharge in the Hallue and Patcham catchments (Figure 7.8).
The surface area and potential volume of fracture surface storage within the zone of groundwater fluctuation was estimated for the Hallue and Patcham catchments. This component of unsaturated zone groundwater storage was proposed by Price et al. (2000) to account for the discrepancy in groundwater storage in Chalk catchments noted by Lewis et al. (1993) and may be a contributing factor, in the form of delayed drainage, to the extended duration of groundwater flooding noted in the UK and France during the winter of 2000/2001 (Anon, 2004; Adams et al., 2008; Amraoui et al., 2008; Noyer et al., 2008). By calculating the fracture surface area, and applying the average water film thickness from Molyneux (2012), the maximum volume of water which could be stored in this form was estimated for a cubic metre of Chalk for different CIRIA chalk grades. It was noted that the volume of the water films expressed as a percentage of the volume of rock for CIRIA grades B/C3 or B/C4 (0.288%) fell within the 0.25-0.30% range quoted by Lewis et al. (1993) as being the required volume of water release from the unsaturated zone to account for the discrepancy in groundwater storage in Chalk catchments. CIRIA grade suffixes of 3 and 4 probably approximate to the average fracture spacing in the upper portion (~30 m) of the Chalk aquifer as review of Figure 6.6 would indicate. The water film volumes for the maximum grade for weathered chalk (A3) and the minimum grade for unweathered chalk (B/C2) were then multiplied by the respective volumes of Chalk between peak and typical end of recession water table surfaces. The combined water film volume for weathered and unweathered Chalk was estimated at 2,005,787 m³ for the Hallue Catchment and 567,172 m³ for the Patcham Catchment. If expressed as a percentage of the water which would theoretically be released from storage from the fall in the water table, based on published values of the storage coefficients for the catchments, this volume would be 2% for the Hallue Catchment and 39% for the Patcham Catchment.

In the Hallue Catchment, based on the findings from the Warloy-Baillon recharge site (Amraoui et al., 2008), it is likely that as the water table recedes water held on fracture surfaces would be reabsorbed into the matrix and the calculated maximum potential volume of water which could be stored in this form would never occur. This water would, however, reach the water table via slow, or ‘delayed’, drainage through the matrix. In the Patcham Catchment, however, the maximum potential volume of water held on fracture surfaces is more likely to occur as indicated at the North
Heath Barn recharge site, where water films were sustained for much longer durations (Adams et al., 2008; Gallagher et al., 2012; Molyneux, 2012; Rutter et al., 2012). This observation from the North Heath Barn recharge site, coupled with knowledge of the heterogeneity of the unsaturated zone, suggests that slow or delayed drainage of the matrix is less significant in the Patcham Catchment and rapid fracture or ‘bypass’ flow in the unsaturated zone is more prevalent. The relative differences in these processes between the catchments may provide some explanation to the differences in duration of groundwater flooding i.e. groundwater flooding persisted for months in the Hallue Catchment and Somme compared to weeks in the Patcham Catchment (Anon, 2004; Adams et al., 2008; Amraoui et al., 2008; Noyer et al., 2008).

The difference in the water film volumes expressed as a percentage of the water which would theoretically be released from storage also highlighted an additional difference between the catchments. The storage coefficient used for the Hallue Catchment was the median of values estimated by Roux (1963) from the ratio of the volume of water drained from storage by gravity flow to the volume of aquifer drained, and was an order of magnitude higher than the value used for the Patcham Catchment based on Jones and Robins (1999). It was theorised this may be due to the relatively greater proportion of the weathered zone in the saturated zone of the aquifer in the Hallue Catchment compared to the saturated zone of the aquifer in the South Downs. This was supported by the percentages in Figure 7.6, whereby the weathered zone comprises 0.04-0.22% of the saturated portion of the Hallue Catchment geological model compared to 0.02-0.06% of the Patcham Catchment geological model.

Finally, the location of groundwater emergence and the extent of the groundwater catchments were considered relative to the understanding developed during this study regarding the structural geology of the Hallue and Patcham catchments. Although historical records may provide information on the location of groundwater emergence at exceptional groundwater levels (e.g. Figure 7.11), review of potentiometric contours of the peak groundwater levels from 2000/2001 with topographic information and the axes from geological structures highlight some common features of these locations. In both the Hallue and Patcham catchments,
topographic relief and the form of the water table commonly display a subtly concordant relationship to geological structure e.g. groundwater mounds often associated with anticlinal ‘domes’. This was also observed by Giles and Lowings (1990) and Mortimore (1993). The valleys where groundwater emergence occurred in 2000/2001, near to the FLOOD1 recharge sites, tended to be either on the limbs of these anticlinal structures or coincide with intervening synclinal inflexions, and generally where valleys coincide with geological structures which focus groundwater flow by thinning of the aquifer on the flanks or axes of anticlinal structures or by converging flow into synclinal inflexions. It is this interplay between the form and hydraulic gradient of the water table and topography, both influenced by the structural geology of the Chalk to varying degrees, which appears to define the location of groundwater emergence.

Evidence from the Hallue and Patcham catchment also suggests that the extent of groundwater catchments changes in relation to geological structure. As groundwater levels rise, the saturated zone increases vertically and, as a consequence, the catchments expand laterally towards the edges where the base of the aquifer is at its highest elevation. In the Hallue Catchment this is towards the Ponthieu Anticline (D1) and structure E, and in the Patcham Catchment towards and parallel to the Chalk escarpment. In the Patcham Catchment, this expansion may lead to groundwater, which would normally flow eastwards away from the catchment, to be directed westwards into the catchment (Figure 7.13). Expansion of Chalk groundwater catchments in this manner may also be a contributing factor to the characteristic extended duration of groundwater flooding noted in the UK and France during the winter of 2000/2001 (Anon, 2004; Adams et al., 2008; Amraoui et al., 2008; Noyer et al., 2008). The evidence from the Hallue and Patcham catchments suggest that the key to understanding these processes is understanding the interplay of groundwater levels with the geological structure.

The overall hypothesis of this study was to show whether sufficiently representative geological models of the Hallue and Patcham catchments could be constructed to improve the understanding of the aquifer and its hydrogeological behaviour. By using the geological models to compare and contrast the catchments in the context of their hydrogeological characteristics, observed from long term groundwater
monitoring and the FLOOD1 recharge sites, this hypothesis has been tested, and the aim of utilising the digital geological models to assess the impact of stratigraphy, geological structure and geomorphology has been achieved.

Rutter et al. (2012) stated the results from the North Heath Barn recharge site should not be applied to Chalk sites without consideration of the catchment and the site characteristics. This study has demonstrated how geological field observations and geological modelling may be used to characterise a Chalk catchment, and provide a framework with which to extrapolate current understanding of the Chalk unsaturated zone. As 3D geological modelling tools continue to develop and become more widely used, and numerical modelling advances to better represent unsaturated zone processes in the context of geological reality (Ireson et al., 2009; Ireson and Butler, 2013), their integration will become inevitable and more accurate simulations will result. This study has demonstrated, by applying understanding of the Chalk unsaturated zone processes observed at the FLOOD1 recharge sites, how geological models may be used as tools which can aid assessment of the scale and extent of hydrogeological processes and facilitate characterisation and conceptualisation of the Chalk aquifer.

8.6 Future Developments

This thesis has presented data from fieldwork on the Chalk in Southern England and Northern France. Much of the research and data presented in this thesis was, in the traditional sense of field geology, observational rather than experimental. The majority of these new field data was used to characterise the stratigraphy, lithology, structural geology and geomorphology of the research catchments, to develop geological models of the catchments and assess the implications for hydrogeology. Alongside this work, a number of small experimental studies were attempted to investigate certain aspects of the Chalk or trial new methods. Based on the overall conclusions of this thesis and observations from these smaller studies, potential aspects for further research may be considered as follows:

(i) Similar structural and hydrogeological relationships to those observed in the Hallue and Patcham catchments are likely to manifest themselves in other areas of Chalk outcrop. Some of these have been documented in
the literature e.g. Giles and Lowings (1990), Mortimore (1993). It seems appropriate that a more systematic study should be undertaken to catalogue the various scenarios by which the structural geology of the Chalk has influenced the distribution and emergence of groundwater and groundwater flooding in areas of Chalk outcrop.

(ii) The analysis of Chalk vein fabrics from samples collected in the Hallue Catchment presented in Chapter 2 highlighted an interesting relationship. The vein fabric spacing in the Chalk matrix appeared to have a linear relationship with the fracture spacing in the rock mass. The density of vein fabrics in the Chalk matrix may relate to a number of syn-sedimentary processes in the Chalk such as bioturbation and mass movement. It is apparent, however, that there is a relationship between heterogeneity of the Chalk matrix and the Chalk mass properties. This observation could be further developed to investigate the relationship between the occurrence and density of vein fabrics in Chalk and the formation of fractures and the strength of the Chalk.

(iii) The relationship between the mineralogy of soil and Quaternary deposits, hydraulic conductivity and the threshold for runoff was discussed in Chapter 5. From the limited data collected at the North Heath Barn survey area, mineralogical proportions of clay and metal oxide minerals between 20-30% are interpreted as being able to reduce hydraulic conductivity of soil to below $1 \times 10^{-7}$ m/s – the threshold for runoff based on Klinck et al. (1998). In the research catchments, these mineralogical proportions were commonly found or exceeded in Clay-with-flints. An investigation into the impact of these deposits on recharge to the Chalk unsaturated zone would, therefore, be worthwhile – particularly if a similarly instrument profile could be employed to that of the FLOOD1 recharge sites.

(iv) The model presented in this thesis for predicting the depth of the base of the weathered zone (engineering rockhead) using topographical data demonstrates a numerical representation of a key geological concept of the Chalk rock mass. Williams (1980, 1987), Mortimore et al. (1996) and
Lord *et al.* (2002) recognised that there was a three dimensional relationship which existed between geomorphology and Chalk weathering. By expressing this relationship numerically, the base of the weathered zone can be predicted in any area of Chalk outcrop in Southern England and Northern France. This model, however, requires further testing and development as it, currently, does not take into account such variables as:

a. The aperture of discontinuities  
b. The Chalk formation  
c. The presence of overlying and adjacent Cenozoic deposits  
d. The latitude and therefore severity of periglacial activity

The effect of these variables on the depth of weathering requires investigation and, if found to have a significant impact, the model should be further developed to account for them.

The findings from the FLOOD1 recharge sites have highlighted how knowledge of the detailed Chalk lithostratigraphy and chalk rock mass properties is vital for understanding unsaturated zone processes. The Hallue and Patcham geological models, presented in Chapter 6 and discussed in Chapter 7, have demonstrated how representative geological models may be used to aid hydrogeological conceptualisation of Chalk catchments, and particularly the unsaturated zone, by facilitating scaling, mapping and quantification of significant lithostratigraphic features. The methods used to develop these geological models could be further refined and applied to other Chalk catchments at both a local and catchment scale.
**Acronyms and Glossary**

ArcGIS – GIS (geographical information system) software package  
BGS – British Geological Survey  
BRGM – Bureau Recherches Géologique et Minières  
C3c-4a – Upper Turonian to Lower Coniacian Chalk in Hallue Catchment  
C4bc – Middle Coniacian and Upper Coniacian Chalk in Hallue Catchment  
C5de – Santonian Chalk in Hallue Catchment  
C5f – Upper Santonian to Lower Campanian Chalk in the Hallue Catchment  
dGPS – Differential Global Positioning System  
DEM – Digital elevation model  
DTM – Digital terrain model  
EI – East Ilsley  
EI2 – East Ilsley Borehole 2  
EM31 – Electromagnetic Geophysical Instrument made by Geonics Ltd  
Fm - Formation  
GIS – Geographical Information System  
GOCAD - Geological Object Computer Aided Design  
GSIS – Geoscientific information systems  
GSI3D – Geological Surveying and Investigation in 3-D  
GVS – Generalised Vertical Section  
hPa - Hectopascals  
IGN - l'Institut géographique national  
kPa - Kilopascals  
m BGL – metres below ground level  
m NGF – metres relative to IGN69 datum in France  
m OD – metres relative to Ordnance Datum  
MOIS – Marine Oxygen Isotope Stage  
NHB – North Heath Barn  
NHB2 – North Heath Barn Borehole 2  
OS – Ordnance Survey  
Raster – gridded spatial data  
SEM – Scanning electron microscope  
XRD – X-ray Diffraction Analysis
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