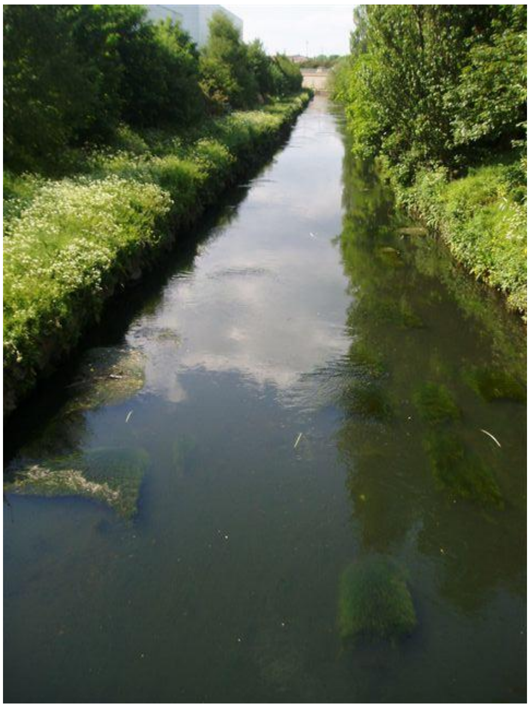
Hydraulic controls on water quality variations: The River Tame Hyporheic zone SWITCH urban test site.



Simon Shepherd

School of Geography Earth and Environmental Sciences,

University of Birmingham

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ABSTRACT

This study investigates the hydraulic control of riverbed materials on water quality variations within the Hyporheic Zone, in the area where groundwater and surface water interact. The study site is the SWITCH Urban Hyporheic Zone Test Site on the River Tame which was set up to research how to reduce risks from contaminated groundwater entering streams and rivers, and thereby increase sustainable water management. Previous studies have shown the Hyporheic Zone to be complex, with considerable heterogeneity within stream bed materials which result in highly heterogeneous permeabilities. Four transects of the river were studied close to existing piezometers and a borehole where hydraulic and water quality conditions could be monitored. Chloride (CL^-) and Nitrate (NO^{3-}) levels were analysed to represent sources from surface water and groundwater respectively. Freeze coring was used to collect intact material from the riverbed to enable sediment and hydraulic conductivity analysis to be more accurate. The results show Nitrate levels increase with depth, whereas Chloride levels fall and the patterns are less complicated through the homogenous sand. However there is some doubt over the validity of the data as several profile anomalies were recorded on site. Despite there being positive flows from the aquifer to the river the chemical profiles indicate there is mixing taking place within the riverbed.

Results show the increased permeability of riverbed sediments can lead to nitrate reaching the river with concentrations not having been significantly reduced. Despite it not being concluded, there is some evidence for denitrification within the hyporheic zone.

The data and information provided from the various methods used only allow for a limited heterogeneity to be considered and therefore the conclusions provided reflect this.

Acknowledgements

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Chapter 1 Introduction

1.1 SWITCH

The SWITCH project was partially funded by the EU in an attempt to make water management within cities more sustainable for the near future period of 30-50 years from present.

SWITCH stands for Sustainable Urban Water Management improves Tomorrow's Cities' Health. There are ten global cities involved within the SWITCH scheme, including Birmingham (UK), Zaragoza (Spain), Accra (Ghana), and Chong Qing (China).

The aims of SWITCH are to apply and develop a range of solutions to help achieve a more sustainable approach to water management within cities, and thereby tackle the growing concerns including rapid urbanisation, growing populations, and climatic change (http://www.switchurbanwater.eu).

The interest in protecting and realisation that water within urban and rural settings is not an expendable commodity has been growing for some time. A number of policy's and agendas have also highlighted the need for increased and sustainable water quality. The Water Framework Directive in particular was a key driver, issued by the European Commission, with one of the main goals being that all water bodies (both ground and surface waters) achieve at least the quality of 'good status' by 2015 (Keery *et al*. 2007; Schmidt *et al*. 2007). The relatively recent changes to water management regulations including the Water Framework Directive (2000) required that there is a greater understanding between the interactions that occur between ground and surface water (Schmidt *et al*. 2007).

Only by combining and understanding the relationships and basic principles of urban land use, groundwater and surface water quality will urban areas be effectively able to manage water quality (Sophocleous, 2002; Shepherd *et al*. 2006).

Hydrogeology developed as a separate discipline out of a need to exploit water supplies from aquifers for public and industrial users (Wilson & Thornton, 2009).

Adequate water exploitation requires the effective characterisation of the relevant aquifer, and can often be done so via pumping tests which characterise the aquifer over 10s to 100s of meters (Wilson & Thornton, 2009). The subsequent realisation that certain aquifers were significantly contaminated (Wilson & Thornton, 2009), and that the contamination or development of ground or surface water is likely to affect the other, soon became apparent (Sophocleous, 2002). The use of techniques such as pumping methods were not always completely effective at removing contaminants from groundwater due to their spatial distribution being complex, predominantly a result of aquifer properties such as hydraulic conductivity varying considerably over the smaller scale of a meter rather than tens of meters (Wilson & Thornton, 2009). Unconsolidated materials in particular vary as much as three to four orders of magnitudes over the meter scale (Wilson & Thornton, 2009).

The hyporheic zone in particular has considerable heterogeneity in terms of the stream bed materials, which result in highly heterogeneous permeabilities (Kalbus *et al*. 2009).

The hyporheic zone has recently become a major focus of attention. The hyporheic zone is considered to be the small section beneath streams and rivers where ground and surface waters interact, leading to complex chemical, biological, and physical gradients (Arntzen et al. 2006), influencing a wide range of contaminants and nutrients (Brunke & Gonser, 1997; Packman & Salehin, 2003). The way in which contaminants and nutrients are influenced by the various chemical, biological, and physical gradients in place are exclusive to the

hyporheic zone, and are not found exclusively in the surface or groundwater domains (Packman & Salehin, 2002).

The University of Birmingham has been undertaking research on the urban hyporheic zone for the past decade as part of a joint venture with the Environment Agency, and this focus of study has tied into the objectives that the SWITCH scheme aims to achieve.

The specific aim for studying the urban hyporheic zone was to further understand how the flows within the hyporheic zone related to the spatially and temporally altering attenuation ability of the zone (Cuthbert *et al*. in press).

The SWITCH Urban Hyporheic Zone Test Site was set up on the River Tame, Birmingham to achieve the goals of developing concepts and ideas that will benefit future river restoration projects by reducing risks from contaminated groundwater entering streams and rivers (Cuthbert *et al*. in press).

1.2 Previous Work

Paul Ellis first investigated the central 7.4km section of the River Tame, completing his PhD in 2003. Ellis (2003) studied the effects of contaminated groundwater coming from the Birmingham Triassic Sandstone Aquifer, upon the surface waters of the River Tame. Ellis (2003) found that approximately 6% of total baseflow to the central 7.4km reach was provided by the underlying Triassic Sandstone Aquifer. However, the effects of the contaminants (principally VOC plumes) coming from the underlying sandstone aquifer was found to only have an effect upon the local surface water quality.

MSc projects carried out in 2005 by Phillip Fitzgerald, and Tristan Wilcox studied the occurrence of the chlorinated solvent plumes identified by Ellis (2003), and their subsequent biodegradation in the hyporheic zone of the riverbed. TCE and its degradation by-products were found to be the main contaminants, with biodegradation found to occur at specific locations across the riverbed.

Caroline Walker 2006 undertook an investigation into the discharge of the contaminant plume from groundwater into the surface water by assessing two different areas of sediment; a high hydraulic conductivity (K) sand section, and a low hydraulic conductivity (K) silt section. Walker (2006) found that the silt section type of material was capable of severely retarding the contaminant, and along with sewerage effluent could lead to natural attenuation. However, the sorption of the contaminant to the silt sediments and potential for that sediment to be transported downstream during high flows and storm events, led to it being considered as a hazardous source.

1.3 Aim

The aim of the project is to understand the hydraulic control of the riverbed materials on water quality variations in the Hyporheic Zone at the SWITCH Urban Test Site.

1.4 Objectives

In order to achieve the aim of the project, improved hydraulic characterisation of the site will need to be completed, and as a result the following objectives were set:

- To characterise the riverbed's geologic materials via the use of freeze coring, and hand augering.

- Characterise the riverbank by using hand dug auger holes, resistivity survey.
- The production of grain size distributions for all of the samples collected from the freeze cores and hand dug auger holes.
- Obtaining hydraulic conductivity values from the samples collected from the freeze cores with a variety of methods including, Hazen (1892), Alyamani & Sen (1993), and the repacking of the material into a core.
- The conceptualisation of the site from the data collected by the freeze cores, hand augering within the riverbed.
- Investigate the relationships between hydraulic profile data with nearby water quality (temporal and spatial) profiles.

Chapter 2 Literature Review

2.1 Definition -The Hyporheic Zone

The hyporheic zone can be described as the saturated space beneath the stream bed and within the river bank where steam water has infiltrated (White, 1993; cited in Saenger and Zanke, 2009). Figure 2.1 depicts the zone created by the interactions of groundwater and surface water.

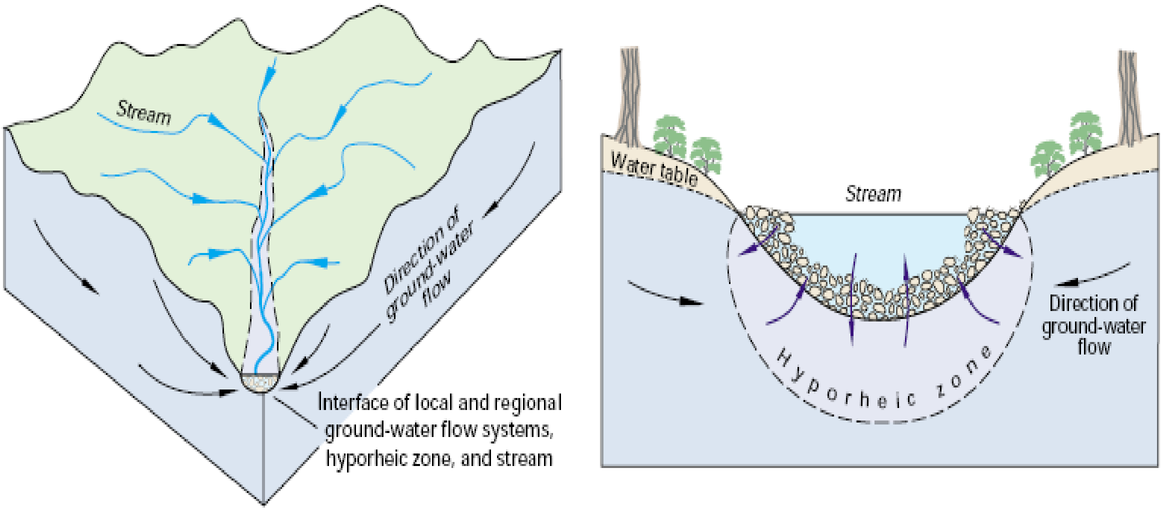

Figure 2.1: Schematic diagram of the hyporheic zone (Winter et al, 1998).

As the hyporheic zone acts as a transition between the stream water and the groundwater, it invariably displays characteristics of both (Saenger and Zanke, 2009).

This area of interaction can be determined by the increased microbial and biological diversity and activity, the contrasting redox conditions and high organic carbon content present; often a result of the steep hydraulic gradients and differences in geologic materials (Ellis *et al*. 2007; Schmidt *et al*. 2007).

On a more regional scale the exchange between ground and rivers waters depends upon the climate, the catchment geomorphology and hydrology (Brunke and Gonser, 1997). The

direction of flow can change i.e. upwelling to downwelling, depending upon the hydraulic head, which can be changed as a result of altered precipitation events and seasonal patterns (Brunke and Gonser, 1997). Rivers experiencing low flows often become controlled by the interactions of surface and ground water; with the extent of low flows in rivers being important ecologically (Fleckenstein *et al.* 2006). When there has been a period of low precipitation the baseflow for rivers originates from groundwater, whereas periods of high precipitation lead to greater hydraulic heads in the lower stream reaches and thereby encourages the infiltration of water and subsequent recharge of the aquifer (Brunke and Gonser, 1997). The extent of low flows can severely affect ecology. For example river stage levels being too low can delay salmon migration during crucial times of the year (Fleckenstein *et al.* 2006).

2.2 Importance of the Hyporheic Zone

The variability of ground to surface water exchange within the hyporheic zone has become increasingly recognised as being extremely important ecologically (Malcolm et al., 2003). In particular the importance on the exchange processes that take place within the hyporheic zone over the life-cycle of salmonid species have been studied (Malcolm et al., 2003).

The range of diversity experienced in the hyporheic zone is ultimately a factor of the physical, chemical and biological conditions and gradients present, which do not occur elsewhere and as a result influence ecological species, nutrients, and contaminants (Brunke & Gonser, 1997; Packman and Salehin, 2003).

The hyporheic zone tends to have a very heterogeneous sediment matrix varying considerably and rapidly both spatially and temporally (Keery *et al*., 2007). This heterogeneity leads to many varying gradients and thereby the hyporheic zone can have a large influence on the extent to which exchange processes occur between the surface and ground water (Brunke and Gonser, 1997). The hyporheic zone acts as a filter buffering chemical and physical differences, and is able to retain and store solutes as a result of slower travel time, and encourage biogeochemical transformations due to the residence time (Saenger and Zanke, 2009) and thereby affecting the chemical composition of the water and as a result affecting the suitability for public water supply (Keery *et al*. 2007).

The variability of ground and surface water fluxes mixing within the hyporheic zone should be carefully assessed, as the extent of the variability can be crucial with understanding the spatial and temporal processes of chemical loading between the aquifer and river (Kerry *et al*. 2007). Assessing this variability is not easy due to the difficulties in applying conventional Darcian Flux methods as a result of the large range of hydraulic parameter values observed, and the complexity in measuring the hydraulic parameter values in situ (Kerry *et al*. 2007). However, the variability is likely to be attributed to streambed topography and the spatial variability of the hydraulic conductivity of riverbed geologic materials (Keery *et al*. 2007).

Subsurface advection often controls hyporheic exchange processes and is ultimately influenced by the stream interacting with the water stored within the interstices pores (Packman and Salehin, 2003). The amount and extent to which these exchange processes take place is dependent upon the stream flow, channel morphology and stream bed characteristics, such as permeability (Arntzen *et al*., 2006). In particular the stream bed permeability is of great importance due to its control on water transfer between river and aquifer and

subsequent effect on water resources and water quality (Calver, 2001). Information for the permeabilities of geologic materials within rivers is limited and has rarely been the sole focus of studies (Calver, 2001).

2.3 The Hydraulic Conductivity Heterogeneity of Riverbed Material

Due to the difficulties of measuring hydraulic conductivity and other properties within the field, the streambed was typically treated as a layer of uniform thickness with a low saturated hydraulic conductivity in most surface-groundwater studies (Leek *et al*. 2009). The use of this simplification was common until it became apparent that the high degree of spatial variability within stream beds, affects the exchange between surface and ground water (Leek *et al*. 2009). It was also essential to stop using this simplification in order to effectively protect and manage both ground and surface water resources (Woessner, 2000).

However, very few studies have been carried out have those asses the spatial variability of streambed hydraulic conductivity (Genereux *et al*. 2008). There have been even fewer studies that have assessed the temporal variation of streambed hydraulic conductivity (Genereux *et al*. 2008).

The factors of changing geologic materials, steep hydraulic gradients, redox condition contrasts, and increased microbial and biological activity, can greatly determine the transport and outcome of contaminants in water moving through the hyporheic zone (Schmidt *et al*. 2007). The flow conditions within the hyporheic zone must be precisely assessed to accurately determine the transport and biogeochemical processes present (Conant, 2000; Schmidt *et al*. 2007). Having a reasonable estimate for vertical hydraulic conductivity in

particular can help with analysing groundwater and surface water mixing, and thereby help assess the degree water exchange and contaminant transfer (Song *et al*. 2009).

The heterogeneities created by local streambed topography, and sediment hydraulic conductivity distribution heavily influences the size of the hyporheic zones (Woessner, 2000).

From a collation of studies Calver (2001) noted that stream bed hydraulic conductivity ranged as much as eight orders of magnitude, with modelled results tending to be more conservative than those collected by field studies. The higher permeabilities of up to 100m/d are less common (Calver, 2001; cited in Cardenas & Zlotnik, 2003). The conservative values produced from modelling may in part be explained by a larger scale of focus (Calver, 2001).

The hydraulic conductivity of riverbed geologic materials is dependent on temperature; warmer waters will increase the hydraulic conductivity as waters properties such as viscosity and density will decrease (Brunke and Gonser, 1997).

On sand dominated stream beds, bedforms develop which affect stream flow and thereby alter the dynamic head and pressure (Packman and Salehin, 2003). Higher pressure occurs at the upstream ends of bedforms, low pressure occurs at the downstream end, encouraging water into through and out of the bed (Packman and Salehin, 2003).

From their study, Genereux et al. (2008) found that hydraulic conductivity was at its highest within the centre of the river channel, and also that there was variation upstream and downstream of a beaver dam.

2.4 Role of Riverbed Topography

The landscape position of riverbed materials plays just an important role as the riverbed hydrogeologic material characteristics for altering flow systems (Sophocleous, 2002). Sections with distinct topographic relief usually dominate local flow systems, whereas flatter relief sections are dominated by larger scale regional flow systems (Sophocleous, 2002). Topography dominated flows tend to be more predictable, with groundwater – surface water interactions being dominated by the position of the surface water body in relation to the groundwater system, climatic conditions, and the riverbed geologic characteristics (Sophocleous, 2002).

Localized flow systems are influenced by the nearby river-bed topography which affects the rates at which water is exchanged in sections of riverbeds that are experiencing either gaining or losing conditions (Wossener, 2000; Sophocleous, 2002). So great is the influence of local stream bed topography that stream bed features can induce water to flow down into the hyporheic zone, despite a particular stream bed section experiencing gaining conditions (Brunke & Gossener, 1997; Sophocleous, 2002).

2.5 Assessing Riverbed Material Hydraulic Conductivity

There are various methods that can be used for estimating the hydraulic conductivity of riverbed geologic materials. In situ tests have ranged from induced slug tests to falling and constant head permeameter tests, with slug tests using manually driven in piezometers

proving to be the most accurate to determine the hydraulic conductivity distribution for sand dominated streambeds (Cardenas & Zlotnik, 2003).

Accurately determining hydraulic conductivity and other hydrogeologic properties is essential for successful and sustainable groundwater management (Alyamani & Sen, 1993). Obtaining accurate estimations for these hydrogeologic parameters is difficult, with a number of studies assigning unconsolidated materials with hydraulic conductivity values based upon their grain size distribution (Alyamani & Sen, 1993). In particular the d10 value has received particular attention; the d10 value refers to the grain diameter at which 10% of a sample passes through a set of sieves during sieve analysis (Alyamani & Sen, 1993). The d10 is often associated with the smaller 'fine' particles of a material sample. Smaller diameter and fine particle sized material has a more significant effect upon hydraulic conductivity, compared to larger sized particles, and has hence been the reason for Hazen (1892) and other studies focusing upon smaller grain diameter material (Alyamani & Sen, 1993).

2.6 The Role of Fine Sediment

Fine sediments deposited on the riverbed can decrease the hydraulic conductivity, with particle size being the main controlling factor as to how much the hydraulic conductivity is affected (Brunke and Gonser, 1997).

The clogging by smaller diameter fine material of interstices between grains can act as a harmful physical barrier to species dependent on the hyporheic zone (Meyer *et al*. 2008). The amount of fines present on the riverbed can also reduce the amount of dissolved oxygen, which became especially harmful to salmonids; dissolved oxygen levels increased in the hyporheic zone by clearing the fines from the gravels (Meyer et al. 2008).

Recent land use activity has resulted in the release of fine material into river courses leading to increased storage (Collins & Walling, 2007). The increased storage of fine material on the riverbed can create significant problems such as the reduction of pore water fluxes and hyporheic exchange rate, and thereby affecting the transport of contaminants (Collins & Walling, 2007). Direct techniques for assessing the amount of stored fine materials on riverbeds have involved the use of coring and freeze coring (Collins & Walling, 2007).

The amount of surface water within the channel controls the amount of fines that are able to be transported, with higher surface flows encouraging the release of fines from the matrix thereby increasing the hydraulic conductivity in the riverbed sub-surface (Saenger and Zanke, 2009). Genereux *et al* (2008) also found that there was a lower presence of fines with cores taken from the centre of the river channel bed, and linked it towards there being a higher hydraulic conductivity within riverbed sediments at the centre of the river channel. This lower presence of smaller grain material may be attributable to higher stream velocity, (the fastest velocity within straight channel sections is in the centre) (Genereux *et al.* 2008). Another factor for lower fine sediment presence within the river channel centre could be the proximity of fine sediment sources such as the river banks (Genereux *et al.* 2008).

2.7 Advantages of Freeze Coring

Freeze coring is technique that has notable advantages over other coring methods, especially with the amount of fine material retained (Zimmerman *et al*. 2005).

Zimmerman et al (2005) discussed the bias and limitations between freeze coring and submerged bulk samples. Freeze cores are believe to not accurately represent coarser grain

sizes, whereas bulk samples obtain more material but loose a lot of fine sediment that becomes suspended and transported away (Zimmerman *et al*. 2005). Specifically the bulk sample technique can significantly underestimate the presence of material smaller than2 mm, whereas the freeze core technique can overestimate the presence of material coarser than 16mm (Zimmerman *et al*. 2005).

Previous work suggested that freeze coring was only ever likely to succeed with smaller grain sizes (silt and very small stones < 1cm) (Stocker and Williams, 1972). Stocker and Williams (1972) however, suggest that the technique can be used with cobbles and in deeper water.

Milan et al, (1999) used freeze coring to collect relatively undisturbed samples as well as collecting the vast majority of fines that can often be lost by other techniques. Freeze core techniques produce more poorly sorted samples due to their picking up higher concentrations of fine materials (Milan et al, 1999).

The greater retention of fine material by freeze coring methods highlights the poor sorting of riverbed and sub-surface materials, which are often not picked up in detail by other techniques (Milan et al, 1999).

Wagner et al (2003) highlights the benefit of using liquid nitrogen to freeze sample cores for the upper layer (80 – 160 mm) from lake and riverbeds. Traditional freeze core sampling methods are unable to; inexpensively obtain large numbers of samples, to provide near instant sample supply, retain a high proportion of the fine material present (Wagner et al, 2003).

2.8 Chemistry of the Hyporheic Zone

The difficulty in assessing hyporheic zone flow and chemical gradients in riverbed sediments hinder obtaining field measurements for biogeochemical reactions, such as nitrification and denitrification in aquatic systems (O'Connor & Harvey, 2008). Darcy's law has been used to generate simple exchange models based upon assumed hyporheic zone flow and riverbed topography (O'Connor & Harvey, 2008). However, other potential more complex modes of transport such as molecular diffusion are not included (O'Connor & Harvey, 2008).
Biogeochemical processes within the shallowest few cm of riverbed sediments are acknowledged to have the greatest impact upon the water chemistry of that water body, and as a result the majority of research tends to focus upon the interstitial layers (Sophocleous, 2002). However, greater appreciation of other processes and scales is required if the development and understanding of groundwater – surface water interactions is to be achieved (Sophocleous, 2002).

Malcolm et al., (2003) found that general hydrochemistry patterns that were found from the study included increased alkalinity, calcium concentrations, conductivity, decreased dissolved oxygen and nitrate concentrations with depth.

However, despite a great amount of research focusing upon the basic hydrodynamic processes that control the amount of hyporheic exchange, large uncertainties over substance transport, stream conditions and hyporheic exchange fluxes still remain (Packman and Salehin, 2003).

Chapter 3 Study Setting

3.1 Introduction

The River Tame is a tributary of the River Trent, draining from an approximate catchment area of 408 km^2, the majority of which belongs to the heavily urbanised areas of Birmingham, Walsall, and Wolverhampton (Ellis, 2003). The River Tame SWITCH Test Site is located in Witton, North East Birmingham to the west of the M6 motorway. The SWITCH site is approx 220 metres, the study area is approximately 45 metres. The site setting has been determined by the presence of an abstraction borehole and piezometers installed in 2007 to investigate the chemical profile of the hyporheic zone as part of SWITCH (Cuthbert *et al*. in press). This section of the River Tame flows through the 'Holford' Industrial Park (Figure 3.1), which first started construction in 1984. The intermediate area of the SWITCH site is dominated by small industrial parks and the increasing conurbation of Birmingham and the outlying areas.

The large diurnal flow variations experienced by the River Tame are significantly correlated to the sewerage effluent flows produced from Birmingham (Davie, 2003). Within sections of the River Tame, it is thought groundwater may cause surface water flows to increase by 20% due to the head gradients of groundwater to surface water (Ellis, 2003). This study aims to further assess the groundwater and surface water interactions at this site.

Figure 3.1: Aerial view of the River Tame (Google Maps, 2009) and photograph looking upstream at the -22m to +23m section of the SWITCH Site. Google maps 2009

3.2 Regional Geology

The River Tame Hyporheic Zone SWITCH Test Site is located to the west of the Birmingham fault, a north-south fault which is main geological structure in the area. The geology of the area to the west of the Birmingham fault comprises Triassic Sherwood Sandstone Group overlying Carboniferous Coal Measures. The Sherwood Sandstone thins to the west, and increases in thickness to the east towards the Birmingham Fault where the Mercia Mudstone Group overlies the Sherwood Sandstone, confining the sandstone to the east of the fault (Powell *et al*. 2000).

The Sherwood Sandstone Group comprises in upwards sequence the Kidderminster Formation, Wildmoor Sandstone Formation and Bromsgrove Sandstone Formation. (Powell et al. 2000).

The Kidderminster Formation ranges in thickness from 45m to 120m, and predominantly comprises of pebble conglomerate pebbly sandstone, with medium to coarse grained cross bedded sandstone, and sparse thin layers of mudstone beds (Powell et al. 2000). The Kidderminster Formation passes conformably in to the Wildmoor Sandstone, the transition recognised by the characteristic red colour, mottled appearance and fine grain size of the basal beds of the Wildmoor Sandstone Formation.

The Wildmoor Sandstone Formation is comprised of orange-red, fine grained soft sandstone and subordinate red-brown and green-grey thin mudstone beds (Powell et al. 2000). The maximum thickness of the Formation is proved at 120 metres. The geological map of the area (Figure 3.2) shows the underlying geology of the SWITCH Hyporheic Test Site to be Wildmoor Sandstone Formation.

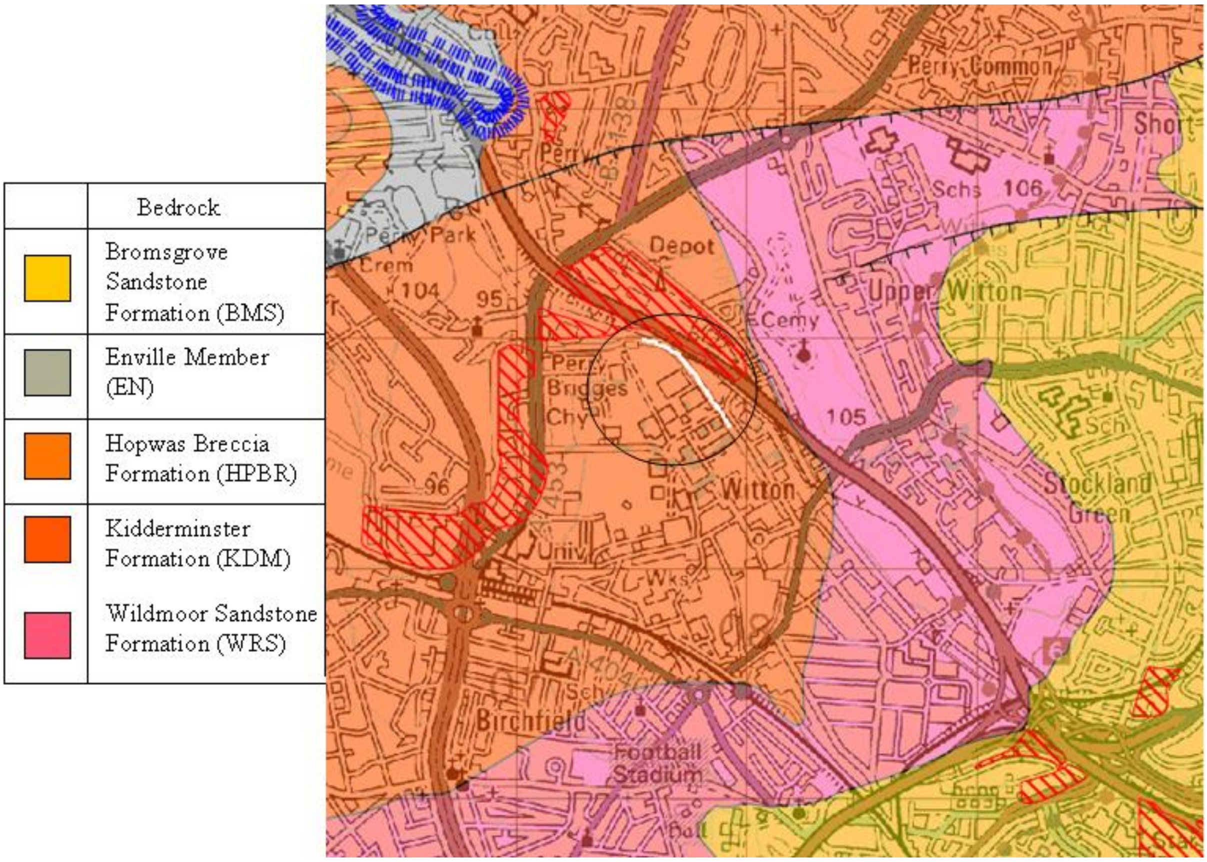

Figure 3.2: The underlying geology of the SWITCH Hyporheic Test Site (www.edina.ac.uk/digimap, 2009).

The upper boundary of the Wildmoor Sandstone Formation with the overlying Bromsgrove Sandstone is unconformable and recognised by a transition in to the characteristic pebbly sandstone of the Bromsgrove Sandstone Formation.

The Bromsgrove Sandstone Formation is described as a red brown medium to coarse grained sandstone with occasional pebbles, conglomerate pebble beds, and minor thin red mudstone and silt stone beds (Powell et al. 2000). The Bromsgrove Sandstone Formation ranges in thickness from 84 to 180 metres in the region.

The Kidderminster Formation and Wildmoor Sandstone Formations outcrop to the north west of the Birmingham Fault but are generally by overlain by drift deposits. The Bromsgrove

Sandstone Formation forms a narrow outcrop in the north west of the Birmingham Fault and is also found as small fault bounded outcrops to the south east of Birmingham.

It is currently understood that the characteristic Triassic orange, red, brown sandstones (and mixture) were deposited by rivers in basins experiencing continental rifting during an arid climate; the different qualities of the sandstone are a result of different basin deposition periods (Powell *et al.* 2000; Shepherd *et al.* 2006). The precise age of the Sherwood Sandstone Group in this area is not known but ranges from Early Triassic to Mid Triassic.

Superficial deposits are widespread across the region comprising predominantly glacial till, glaciofluvial sands and gravels and glaciolacustrine deposits (Figure 3.3). The region is also characterised by a series of incised palaeovalleys (buried valleys) infilled with interglacial and glacigenic deposits (Powell et al. 2000). Although the deposits are characteristically highly variable they consist predominantly of sand, sand and gravel with subordinate clay, and sandy clay with gravel The Proto-Tame is the most extensively palaeovalley in the area running approximately east-west in line with the Hockley Brook. Recent investigations suggest the Proto-Tame to be a deeply incised palaeovalley of the Hockley Brook (Powell et al 2000).

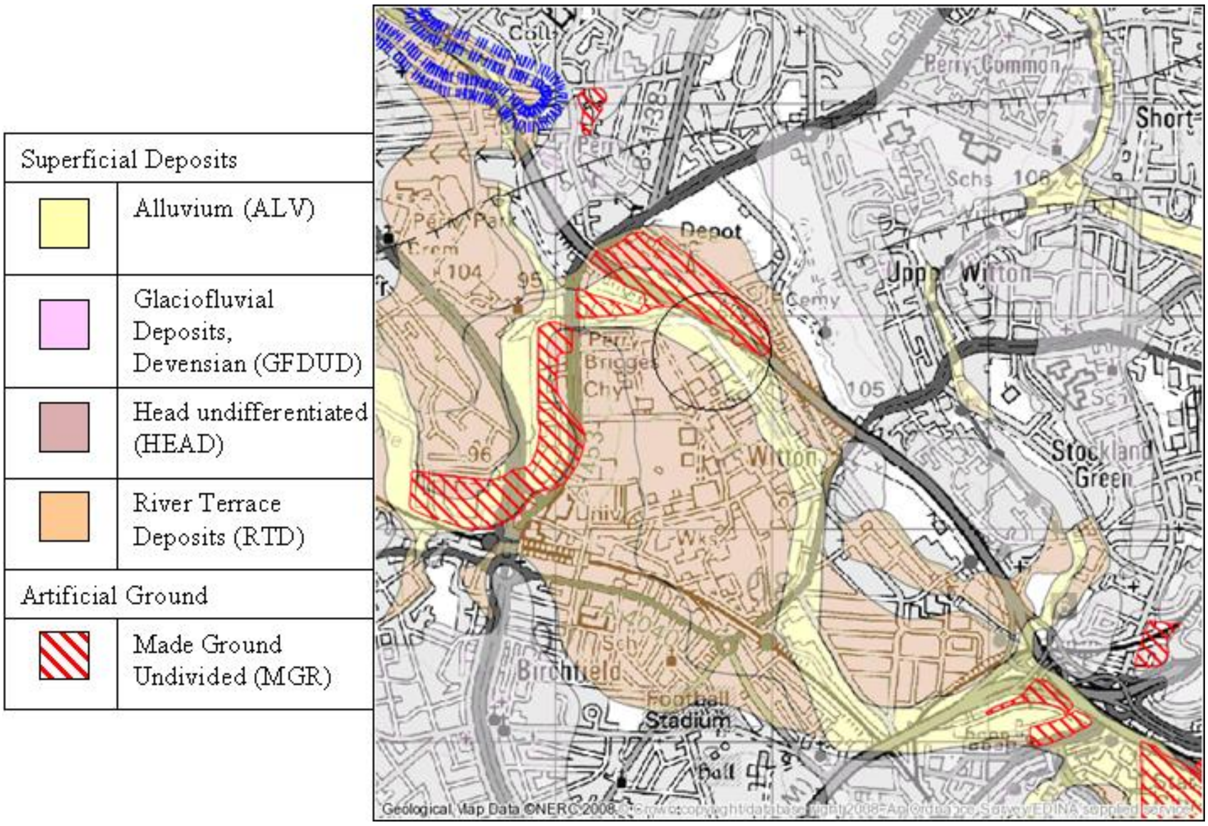

Figure 3.3: The superficial geology of the SWITCH Hyporheic Test Site (www.edina.ac.uk/digimap, 2009).

3.3 Regional Hydrogeology

The dominant aquifer for the region is the Triassic Sherwood Sandstone Group Aquifer comprising the Kidderminster, Wildmoor and Bromsgrove Sandstone Formations. Although each individual Sandstone Formation is an important sandstone aquifer, they have been grouped together as a single aquifer due to the limited amount of reliable hydraulic data (Powell et al 2000). The aquifer is unconfined to the west, becoming confined by the Mercia mudstone to the south east of the Birmingham Fault. The aquifer is considered to be a major source of water.

The Sherwood Sandstone Group Aquifer has the following qualities often generated during pumping tests; a hydraulic conductivity of approximately 2 m/d, porosity (n) and specific yield (Sy) values typically of 0.28 and 0.12 respectively (Shepherd *et al.* 2006).

Rainfall is typically between 650 and 800 mm per annum, with approximately 130mm of that becoming recharge (Shepherd *et al.* 2006).

The River Tame is the regional topographic low, and as a result the Birmingham Triassic Sandstone aquifer drains towards it. The ground water from the Birmingham Triassic Sandstone has mainly been exploited by industrial users, with the majority of aquifer depletion and falling water level heavily correlated with the high industrial activity up till 1965. (Rivett *et al*. 2005)

3.4 Anthropogenic History at the site

Birmingham is the second largest city in the UK, becoming a major industrial centre during the 18th and 19th century particularly the metal industries, with the continued spread during the 20th century by large scale industry, especially into the River Tame valley (Rivett *et al*. 2005). The majority of water supplied for public use to Birmingham came from the Elan Reservoirs in Wales. The majority of groundwater exploited was for industrial use, becoming one of the main factors for Birmingham's rapid growth (Rivett *et al*. 2005).

This long history of industry and groundwater use has led to considerable contamination of the Birmingham aquifer, and the contaminants found within the aquifer are remnants of the metal industries that once thrived in the Birmingham area. On the whole the contamination of

the Birmingham aquifer is not that excessive with there only deemed to be some small concentrated areas with very high amounts of heavy metals (Ford & Tellam, 1994). The exceptions of nitrate and barium levels however, were much more common and were frequently higher than the maximum standards for drinking water standards (Ford and Tellam, 1994).

There have been studies conducted for organic contaminants within the Birmingham aquifer, finding Trichloroethene (TCE) to be the main contaminant which was used extensively throughout the 20th century as an industrial solvent used for metal degreasing (Rivett *et al*. 2005).

3.5 Anthropogenic Alteration of the River Tame

Sections of the River Tame is heavily channelized (Beavan et al. 2001), and was likely done so to enable control over the potential flooding and erosion within the heavily urbanised area. The two historic maps published in 1945 (Figure 3.4) and 1977 (Figure 3.5) show considerable differences between the general sinuosity of the river. ArcGIS was used to compile the maps together, with the addition of highlighting the position of the River Tame at the times the area was surveyed.

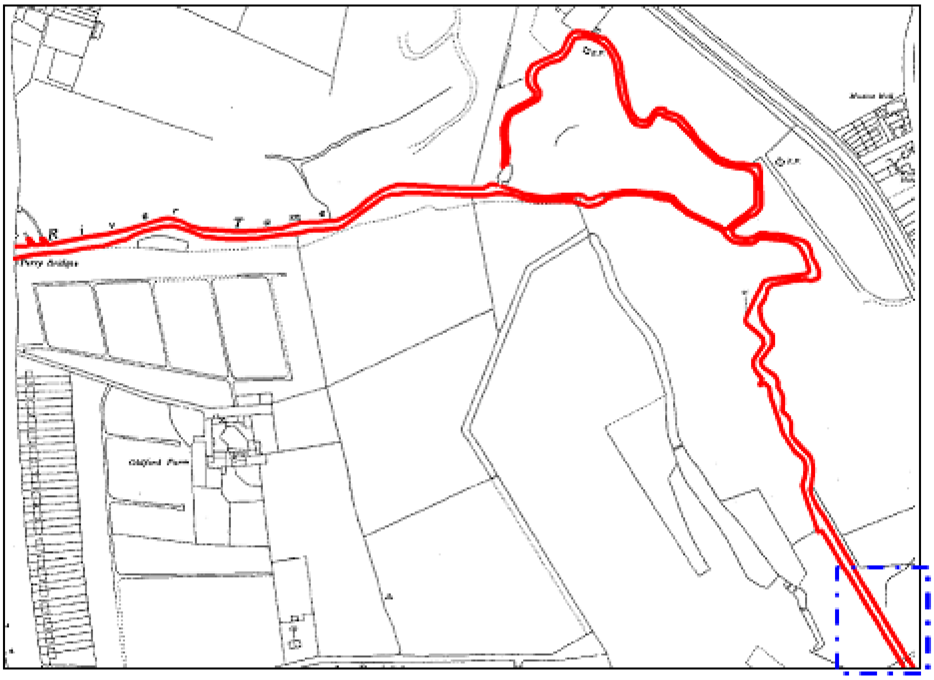

Figure 3.4: Digitized historic map of the River Tame published 1945; digitized red lines are the course of the River Tame, the -22m to +23m section of the SWITCH Site is highlighted by the blue dotted box. (www.edina.ac.uk/digimap, 2009).

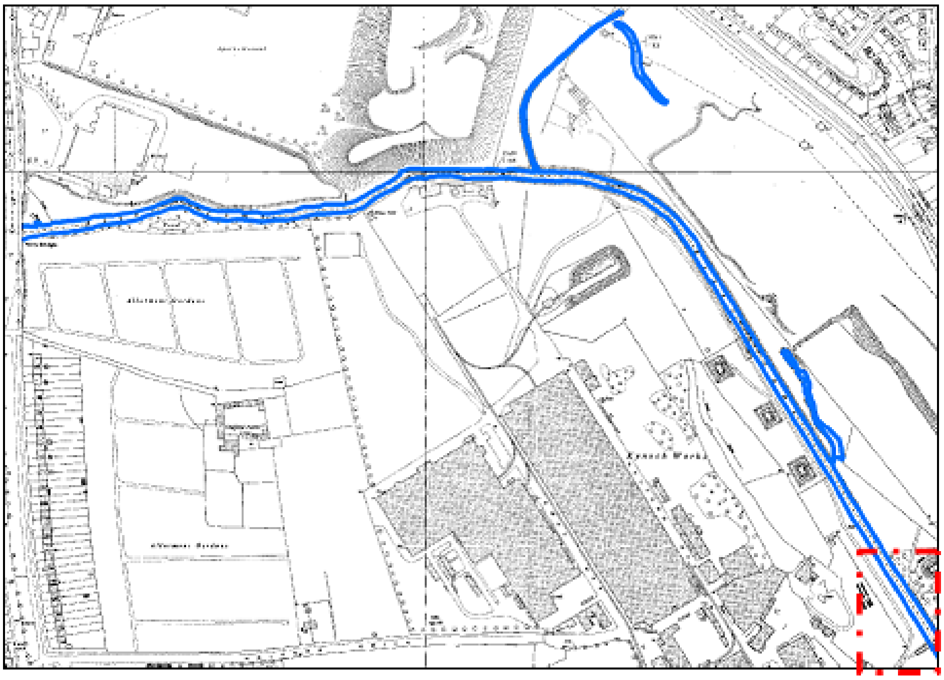

Figure 3.5: Digitized historic map of the River Tame published 1977; digitized blue lines are the course of the River Tame, the -22m to +23m section of the SWITCH Site is highlighted by the red dotted box. (www.edina.ac.uk/digimap, 2009).

There appears to be evidence of some of the natural meanders being cut off and thereby leading to the channelising of the river by the time of publication of the map in 1977 (Figure 3.5).

Channelising a river can significantly alter the flow regime and sediment transport of that river. In particular the heavily modified sections of the River Tame experience very high stream velocities during storm events (Brooker, 2003 cited in: Lawler *et al*. 2006).

3.6 SWITCH Programme

Figure 3.6 shows part of the SWITCH Urban Hyporheic Zone Test Site, located either side of a perpendicular line drawn from the borehole. There are four transect sections being focused upon in this study, -22m, -4m, +5m, and +23m. These transects are labelled in terms of their distance from the drawn line of the borehole; negative distances define a location upstream from the borehole, and positive distances indicate a location downstream from the borehole. At each of transect, there are various sets of piezometers which were installed in July 2007, ranging from depths from 0.15m to 1m. The different depths allow for the hydraulic and water quality conditions to be monitored.

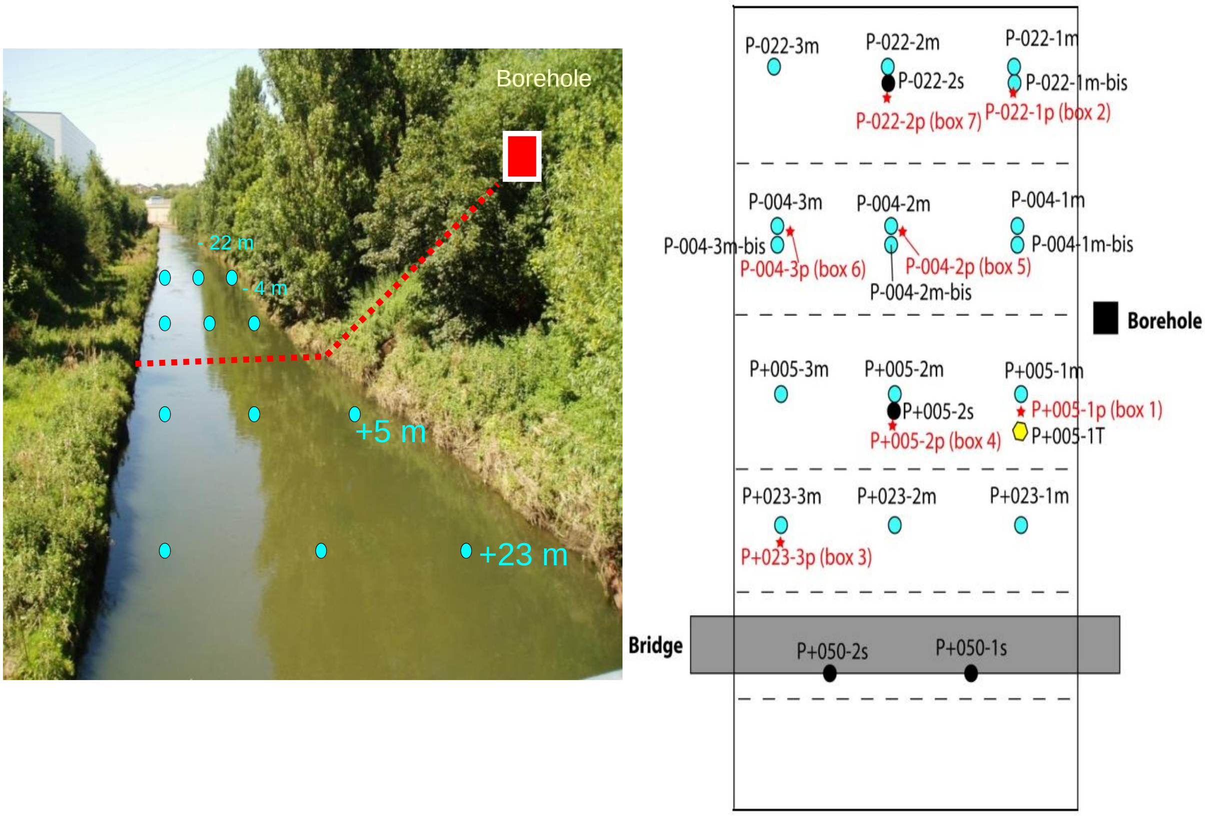

Figure 3.6: Photograph looking upstream at the -22m to +23m site, and a schematic diagram showing the positions of the piezometers.

The borehole was installed in 2007, to extract water and allow the assessment of altered hydraulic gradients and thereby assess different contaminant residence times within the nearby hyporheic zone (Cuthbert *et al*. in press).

The borehole is located 5m from the east bank of the River Tame, and was completed to a depth of 16.5m below the ground surface. The borehole log can be seen in Figure 3.7.

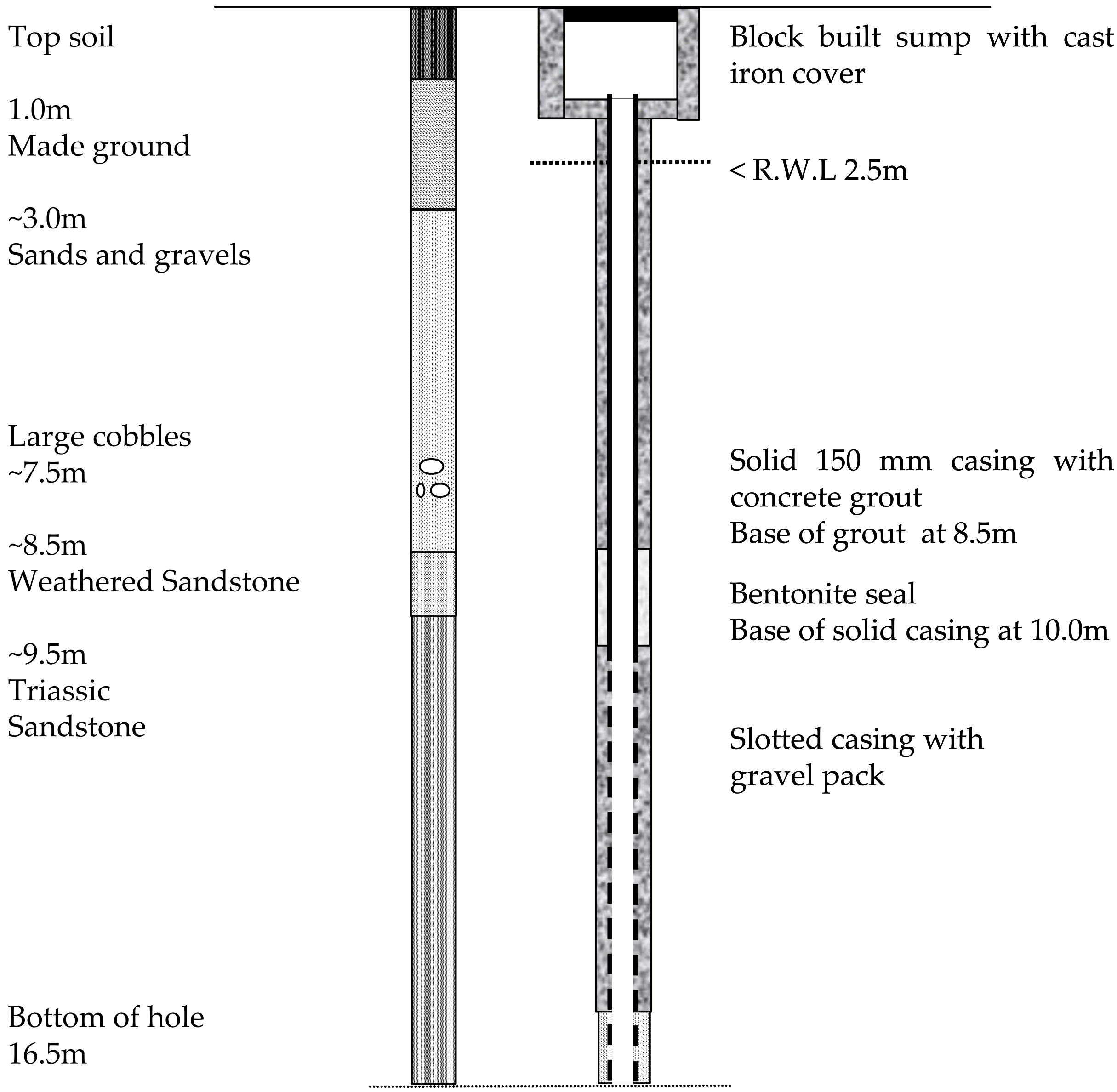

Figure 3.7: SWITCH Hyporheic Zone Test Site extraction borehole geological log. (Cuthbert *et al*. in press).

Chapter 4 Methodology

4.1 Introduction

The collection of material from the riverbed is critical, and thereby the method/methods chosen which abstract as much material as possible, whilst retaining most of the material are essential to answering the aim and objectives of this study. The details of data collection, analysis undertaken are provided in this section. The data for the study were collected during 27th May 2009 and 15th August 2009. Data collected and work undertaken within the River Tame was done so at periods when the weather was reasonable, and the flow within the river was not too high, and thereby not dangerous. The River Tame has a catchment size of approximately 408 km^2, and therefore any field work undertaken within the river was carried out after a period of dry weather, to ensure flow levels in the river were not safe. For any field work undertaken at or near the River Tame SWITCH test site, at least two people were present for safety reasons, and ease of undertaking field measurements.

4.2 Archive Data

The borehole log for the borehole situated at the River Tame SWITCH Urban Hyporheic Zone Test Site was compiled during the boreholes construction in July 2007. The log has been used to aid in the conceptualisation of the site, and is also compared to the geophysics survey for the same bank.

The chemistry data that will be used was collected during 27th September 2007 till 17th March 2009. The data was collected at various intervals throughout the time period and was not continuous, often during periods of stable flows; as mentioned above at periods when it was safe to work within the river. A whole range of chemicals were tested for. However, for this study, Chloride (CL^{-}) and Nitrate (NO^{3-}) levels will be preferably analysed, due to their general source being from surface water and groundwater respectively. Nitrate levels are most concentrated within groundwater sources, whereas chloride levels are mostly influenced by surface water. For this study the chemistry data is replotted so that they relate to specific piezometer locations and can therefore be compared to the freeze core and subsequent hydraulic conductivity data.

Falling head tests were also carried out on the set of piezometers within the SWITCH Hyporheic Zone Test Site during each chemical sampling campaign. Hydraulic conductivity values were calculated for certain piezometers. For this study the falling head tests for the -22m to +23m section will be used as a field based estimate for hydraulic conductivity to be compared to the lab estimates.

4.3 Hand Augering within the River / Auger Holes on the River Banks

To better understand and characterise the site, hand augering was carried out on the site. Auger holes were carried out on the river banks to provide understanding and help conceptualise the site and the processes that were likely to lead to the construction and deposition of the present material. Hand dug auger holes will be undertaken on both sides of the river bank, to compare whether the initial layers found are present in both banks.

Within the riverbed, hand augering was used subjectively to assess suitable locations for the freeze cores, and to aid in the conceptualisation of the site.

4.4 Freeze Coring

Previous University of Birmingham studies on the River Tame have used various coring and sampling methods to obtain material from the riverbed. Previous MSc projects such as Cleverly (2005) used hollow pipes that were hammered into sections of the riverbed, and to ensure that material was brought up, 'suction pads/tops' were attached to the top. The attached 'suction' top brought varying success, although the amount and quality of material collected was not ideal. Generally 25% of cores were successful with the recovery of material from these being 85% (Cleverly, 2005).

The technique of freeze coring was selected to provide more intact material from the site and thereby enable sediment and hydraulic conductivity analysis to be more accurate. A hollow metal core with a pointed shut off end is used. The hollow metal core is hammered into the riverbed as far as possible to facilitate as much material as possible being retained; to ensure the top of the corer does not become damaged, a metal sleeve cap is placed over the top. It is crucial that water does not enter the hollow metal core and thereby reduce the potential for

the liquid nitrogen to freeze the metal and subsequently for the material to stick to the metal surface.

Once the metal core was at the required depth, the liquid nitrogen was poured from the 25 litre dewar into the 2 litre flask, and then carefully transported to the location of the driven in metal corer. The liquid nitrogen is at first carefully poured into the metal corer, as the liquid nitrogen quickly evaporates (volatility) whilst temperatures first start to drop. As liquid nitrogen is denser than air it will stay at the bottom, evaporating in a condensed area. Therefore a ‘spoon’ was created from a copper metal pipe to help distribute the liquid nitrogen within the hollow metal corer and thereby freeze a greater length of the corer, retaining more material from the shallower depths.

Once the determined amount of liquid nitrogen had deemed to have evaporated, and frozen the core sufficiently, a winch was attached to the corer, and the core was pulled out using a triangular frame (Figure 4.1: Photograph of Freeze Core One being abstracted.Figure 4.1). The amount of time given for freezing started from the moment the first amount of liquid nitrogen was used, and after the first core was raised from twelve minutes to nearer twenty for freeze cores two to eight to improve sediment quantity and quality.

Ideally for freeze coring to provide substantial material, flows within the river need ideally to be as low and slow as possible. Lower flows will allow for the metal corer to penetrate the riverbed as far as possible whilst slower flows will help material closer to the surface of the riverbed to consolidate and stick to the metal surface.

Figure 4.1: Photograph of Freeze Core One being abstracted.

Once the core was taken it was quickly logged and photographed, as due to the high air temperatures at the time the freeze coring was undertaken, sediment sections with larger material, especially pebbles and cobbles, would soon become dislodged and separated from the core.

4.5 Samples from the Cores

After the core had been logged and photographed, samples were then taken; 58 samples in total.

For the material that would be analysed via grain size distribution, the core was separated and sectioned into different material bands. When there a large band of material present on a core, such as the orange brown uniform sand, this material would be separated, and grouped into different samples every 5 cm. The now sectioned materials were carefully labelled, and once

back in the lab, the samples were placed within a fridge to ensure no moisture was lost before weighing the wet weight of the samples before oven drying.

For the permeameter tests, plug samples were taken, where possible, both horizontally and vertically depending upon whether there was sufficient depth and thickness to the layers. By taking plugs samples directly from the cores, effectively taking undisturbed samples of the material and thereby reasonably accurate hydraulic conductivity measurements can be obtained in the horizontal and vertical directions.

4.6 Sediment Classification

For identifying the sediment samples, they will be identified using a standard identification scheme, and based upon their percentage of sand, clay, silt etc will be classified.

Figure 4.2 Figure 4.2: Shepard's Classification system Diagram Modified by Schlee (1973), (USGS, 2007).displays Shepard's (1954) triangular classification system which has been modified by Schlee (1973) with the addition of the second triangle classification for more gravelly material (USGS, 2007).

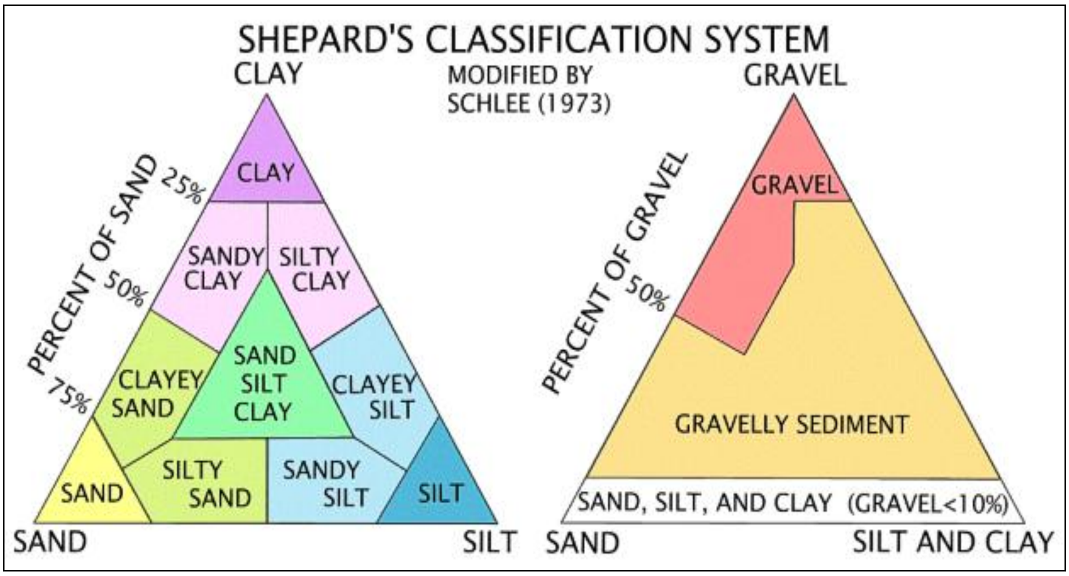

Figure 4.2: Shepard's Classification system Diagram Modified by Schlee (1973), (USGS, 2007).

4.7 Grain Size Distribution Method

The samples taken to be analysed for grain size distribution, required the metal tray first to be weighed, before the samples were weighed within the metal trays for their total wet weight, before being heated.

The bagged samples were dried for a period of at least 24 hours to 48 hours, on metal trays and dishes within a Gallenkemp oven baking at 65 degrees.

After the material had been taken out of the oven, it was weighed for its total dry weight, from which each sieve separated material weight would be compared to.

As the majority of the samples collected contained very little or no clay, dry sieving would be sufficient using an automatic shaker.

The sieve divides used for the grain size distribution are shown in Table 4.1.

16mm	Retain larger pebbles
4mm	Retain smaller pebbles
2mm	Retain granuales
1/2mm:	Retain coarse sand
1/4mm	Retain medium sand
1/16 mm	Retain very fine sand.
Rest	Retain silts and clays

Table 4.1: Sieve Divides for Grain Size Distribution.

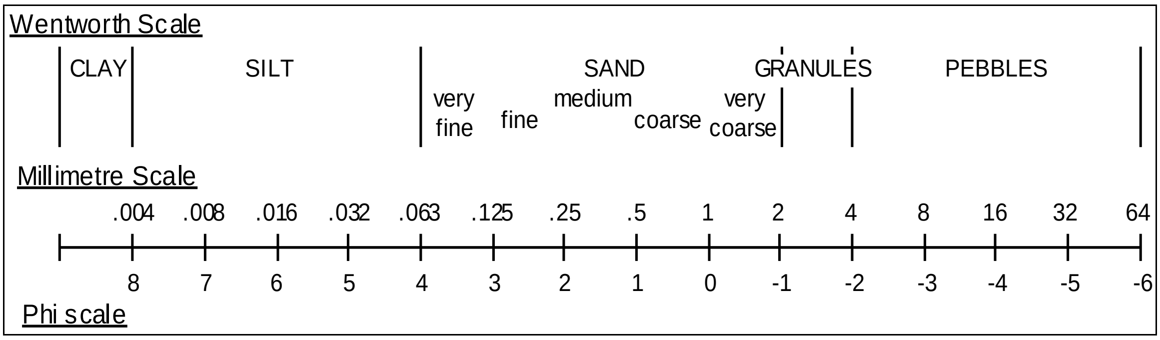

Figure 4.3: Millimetre, phi and Wentworth scales for sediment particle sizes.

Potentially one of the most important sieve divides, 0.063 mm, comes between the sand and silt sized material (Figure 4.3), and also is the same divide for sieve and pipette analysis (Gale & Hoare, 1991). Therefore, allowing a definite separation between sands and greater sized material, and the fines that potentially have a greater effect upon hydraulic conductivity.

Once the samples are dried, they are then separated by the various sieve sizes, each separated sample would then be individually weighed, and from the total dry weight, a percentage of that separated material would be calculated. As there were no finer sieves than the 0.063 mm sieve the fines retained at the bottom, will be classed as 0.01 mm for the purpose of graphing the results of the sieve analysis.

4.8 Hazen Analysis (1892)

The Hazen analysis of sandy material enables a value for the hydraulic conductivity to be produced. The method requires that the d_{10} of the material to be between the range of 0.1 and 3 mm, and also that the coefficient of heterogeneity (d_{10}/d_{60}) is between 1 and 5 (Wilson & Thornton, 2009). The d_{10} of a material refers to 10% of the samples weight passing through the set of sieves and is considered as the effective grain size for the Hazen analysis. **$K = C(d_{10})^2$** **Equation 1** is the relationship proposed by

Hazen to determine hydraulic conductivity from the grain size fraction produced via sediment size distribution for a particular sample.

$$\mathbf{K = C(d_{10})^2} \qquad \textbf{Equation 1}$$

K is the hydraulic conductivity in m/d, d_{10} is the effective particle size (mm), and C is a dimensionless coefficient which refers to the sediment type and sorting for an individual sample. The dimensionless coefficient C can be obtained via a set of values that were determined by Hazen, (Figure 4.4).

Sediment Character	**Coefficient C range (cm/s)**
Very fine sand, poorly sorted	40 – 80
Fine sand, high % fines	40 – 80
Medium sand, well sorted	80 – 120
Coarse sand, poorly sorted	80 - 120
Coarse sand, well sorted	120 - 150

Figure 4.4: Representative values for C (Hazen coefficient) for grain size and degree of sorting (Fetter, 2001).

Firstly the sorting and sediment types must be calculated by converting the sieve sizes to phi values (φ), where a phi value is the equivalent of $-\log_2$ (sieve size in mm). The phi values generated must then be plotted against the weight of material retained by each sieve for each sample. The mean particle size (M) and standard deviation are then calculated from the graph from Equation 2 and Equation 3 respectively.

$$\mathbf{M = \frac{\varphi 16 + \varphi 50 + \varphi 85}{3}} \qquad \textbf{Equation 2}$$

$$D = \frac{(\varphi 84 - \varphi 16)}{4} + \frac{(\varphi 9 - \varphi 5)}{6.6}$$ **Equation 3**

Once values are obtained for the mean particle size (M) and the standard deviation (D), they can then be compared to the following ranges (Table 4.2 and Table 4.3). Thereby determine sorting and size characteristics and therefore a value for C can be used in Equation 1.

Phi value (φ)	Sorting of the sample
0 – 0.35	Very well sorted
0.35 – 0.5	Well sorted
0.5 – 0.71	Moderately well sorted
0.71 - 1	Moderately sorted
1 – 2	Poorly sorted
2 – 4	Very poorly sorted
4 - ∞	Extremely poorly sorted

Table 4.2: Sediment Sorting Classes and Phi Values (φ)

Phi value (φ)	Sediment type
(-∞) – (- 1)	Gravel
(-1) – 0	Very coarse sand
0 – (+1)	Coarse sand
1 – 2	Medium sand
2 – 3	Fine sand
3 – 4	Very fine sand
4 - 8	Silt
8 - ∞	Clay

Table 4.3: Sediment Types and Phi Values (φ)

Once the values for C, d_{10} are used in Equation 1, a value for hydraulic conductivity is produced in (cm/s), which is easily converted to m/d for a more conventional value.

4.9 Alyamani & Sen (1993) Analysis

Alyamani & Sen (1993) commented that the majority of grain size analysis focuses upon a single representative value, such as a geometric mean, to relate to an estimated hydraulic conductivity for a sediment sample. Alyamani & Sen (1993) proposed a method for determining the hydraulic conductivity for a sediment sample by looking at the initial slope and intercept from a grain size distribution method (Sperry & Pierce, 1995).

Alyamani & Sen (1993) acknowledge the relatively fine sediment range of a sediment grain size distribution having the most effect upon hydraulic conductivity of a sediment sample. As a result of reasoning and empirically based studies, the approach to use the intercept and

difference of the average and effective grain sizes was deemed suitable (Alyamani & Sen, 1993).

To carry out the Alyamani & Sen (1993) analysis;

First the grain size distribution must be plotted upon a semi logarithmic graph with a smooth line being plotted through the points, typically creating a smooth sigmoid curve. Next the percentiles d_5 to d_{95} with every 5% increment must be calculated from the smooth curve, and then plotted against corresponding percentiles on an ordinary graph. A line of best fit must then be plotted for the initial slope generated by the percentiles. The intercept that this line produces must also be noted. The relationship proposed by Alyamani & Sen (1993) is presented in Equation 4.

$$\mathbf{K = A[\ I_o + 0.025\ (d_{50} - d_{10})\ ]^b} \qquad \textbf{Equation 4}$$

$$\mathbf{K = 1300[\ I_o + 0.025\ (d_{50} - d_{10})\ ]^2} \qquad \textbf{Equation 5}$$

Where K = hydraulic conductivity (m/d), Io = intercept created by the initial slope of the percentiles, d50 and d10 are the percentiles measured from the sigmoid curve of the grain size distribution. The A and b from equation … are two constants that were determined to be approximately 1300, and 2 (Equation 5). from the study of 32 samples from Saudi Arabia and Australia (Alyamani & Sen, 1993).

4.10 Constant Head Permeameter Tests for Repacked Material

The decision was made to further use the sediment that was collected by the freeze cores, and subject the material to constant head permeamaeter tests (Figure 4.5), once the material had been analysed via the grain size distribution tests.

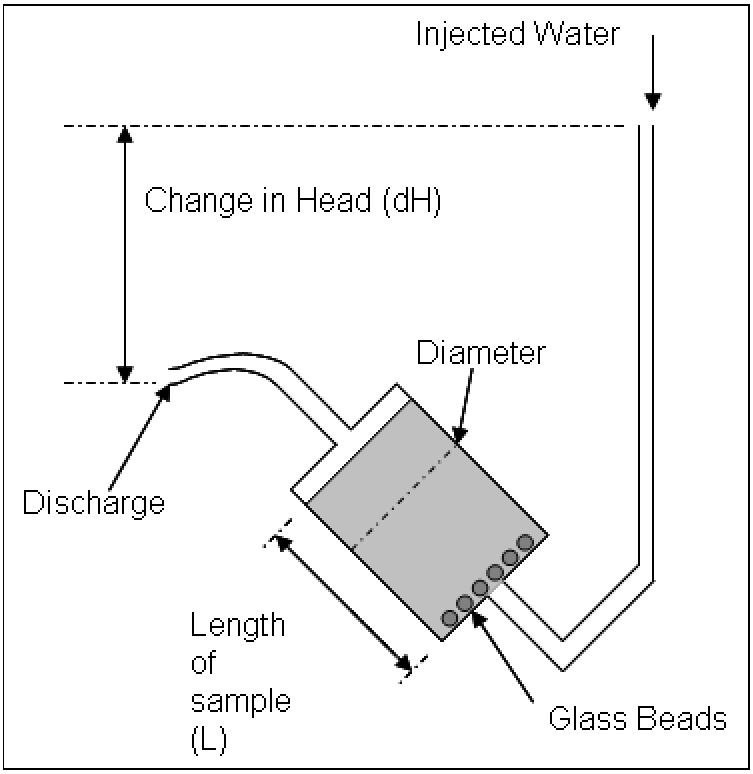

Figure 4.5: Schematic diagram of a constant head permeameter test.

After grain size distribution tests, material passing through the sieves becomes well sorted and graded, and as a result is unlikely to represent the situation in the field. Therefore the cone and quarter method was used to try and restore some representative sampling to the material, and provide as accurate a range of the material as possible. Once the material has been placed into a cone shape (Figure 4.6), a quarter of the material is then divided and used. The selected material is then packed into a cylinder tube, with both ends sealed by bungs which are connected to the equipment setup by small pipes (Figure 4.5).

Figure 4.6: Photograph of material ready to be quartered for the con and quarter method.

As the tube used to contain the material to be repacked has an approximate diameter of 5 cm, the larger cobble sized material greater than 16mm found within certain samples was excluded. For the purpose of these tests, including this material in the confined space of the tube would have created near impermeable sections, and would not generate an accurate hydraulic conductivity value. For factoring in the material that was removed, the hydraulic conductivity value produced was scaled down by multiplying the measurement by the percentage of material that was available to use from the total material weight of the sample.

A major issue with repacking material for use in constant head permeameter tests is that fines can create an impermeable layer at the bottom and thereby resulting in a lower permeability. To restrict the potential for this occurring, small glass beads were used as a packer layer, enabling the material to distribute evenly (Figure 4.5).

For permeability to be effectively measured, the repacked samples must be fully saturated. To ensure that the repacked samples are fully saturated, a combination of material and water must be added slowly in order to minimise disturbance of the material. In between adding amounts of water and material, the material within the column is compacted down using a pointy object such as a butter knife. Once fully saturated the repacked samples are then connected to the constant head permeameter equipment set (Figure 4.5).

Often for most studies with hard rock the quality of water becomes a big issue, especially with minerals in the water blocking pores thereby altering the permeability of the rock and thereby giving lower hydraulic conductivity to the material. For the time frame of the experiments, untreated tap water was deemed to be sufficient.

The Constant Head test works under the simple principle of Darcy's Law. Water within soils and rocks are able to move via interconnected pores, the hydraulic properties of a material govern its ability to store and transport water (Hiscock, 2005). Using a column of material is directly applicable to the studies Darcy carried out, who by subjecting columns of porous material to different head levels of water found a relationship to exist to total flow (Hiscock, 2005). Darcy's Law has many variants with parameters that can be interchanged and linked to other hydraulic properties. However, the Darcy's Law equation that will be used has been rearranged so that hydraulic conductivity (K) is the only unknown variant and is shown in Equation 6.

$$K = \frac{Q * L}{A * dH} \qquad \textbf{Equation 6}$$

Where K is the hydraulic conductivity of the material (m/d), L is the length of the sample within the column (m). A refers to the materials area within the column. dH refers to the

difference in water level between the container (which provides the constant head) and the end of the pipe running from the column of material (Figure 4.5).

Obviously the greater the head the quicker the flow rate will be. However, care must be taken that too high a flow is not pushed through the column, as this can unsettle fines and therefore make them mobile within the column. The movement of fines can either increase hydraulic conductivity by increasing void space within the packed material. Decreased hydraulic conductivity can also occur with the transport of fines, by creating an impermeable layer at either end of the column, within the pipes that connect the container to the column, or the opposite end that releases water into the measuring cylinder (Figure 4.5). Obviously either situation will alter the hydraulic conductivity, and also render any precautions for ensuring as accurate a measurement as possible, pointless. The use of a glass bead section at the bottom of the column (as mentioned previously) and ensuring that there is not too high a head placed upon the column, then the disturbance and subsequent movement of fines should be kept to a minimum.

4.11 Constant Head Permeameter Tests for Plug Samples

Plug samples were taken directly from freeze cores two, three, four and five so that these would provide relatively undisturbed samples for the hydraulic conductivities in the horizontal and vertical directions. The plugs consisted of cut syringes $10ml^3$, 0.02m length of sample for horizontal estimates, 0.04m length of sample for vertical estimates for hydraulic conductivity. The amount of sample collected in this manner was limited by the thickness of the freeze core, and samples could only be collected after the freeze core had partially defrosted.

For permeability to be effectively measured, the plug samples must be fully saturated, and must be done so at a slow rate in order to minimise disturbance of the collected material. The plug samples are placed into a container filled with water where a vacuum is created and released slowly to ensure that the water enters the samples at a slow rate. Once fully saturated the plug samples are then connected to a constant head permeameter setup.

4.12 Presenting the Hydraulic Conductivity Data

Once all the hydraulic conductivity data has been collected from the Hazen Analysis, Alyamani & Sen Analysis, and the constant head permeameter tests done on the plug samples and the repacked material. The material will be collated and presented on graphs representing each individual freeze core.

4.13 Geophysics – Resistivity Survey

A resistivity survey was carried out on the east bank to provide further information in the conceptualisation of the site, and also support the information previously collected, including the auger holes and the construction log for the borehole.

The Allied Tiger resistivity system was placed upstream from the borehole, approximately in the centre part of the SWITCH test site. Two cables with 32 electrodes each were placed into the ground upstream and downstream from centre, parallel to the river. Spacing between each individual electrode was 1m. The first electrode was placed at the furthest upstream point, with the last electrode being placed at the furthest point downstream, and thereby creating a geophysical cross-section looking towards the eastern bank. This spacing ensures that there is enough detail provided for the near surface depths, whilst the number of electrodes should

also providing sufficient penetration for assessment of materials at greater depths. The geophysical technique of resistivity has been proven many times to generate depictions of the broad geology of an area in a relatively short space of time.

A Wenner arrangement was used, with the on – off times cycling every second. The current used increased 0.5mA at the surface to 50mA at around a penetrative depth of 12m. Measurements would be repeated till a less than 1% error was achieved.

Chapter 5 Results

5.1 Auger Hole and Riverbed Augering Results

Hand augering was used as a rough guide to assess the difficulty of being able to penetrate the riverbed at various locations. Using this method alone highlighted the heterogeneity of the site; by moving the position of hand auger slightly, the amount of penetration could significantly change. There was considerable depth of bed armouring at certain positions, deep sections of sand that was very easy to penetrate often to a depth of 0.5m or greater. From hand augering the user could also distinguish the presence of a gravel layer in the downstream section of the -22m to +23m section of the Hyporheic Zone SWITCH Test Site. Freeze cores two, eight, and nine would suggest that the gravel layer starts around the +5m section of the site. The presence of this gravel layer became apparent with the hand auger just downstream from the +5m section of piezometers, approximately two or three meters. Figure 5.1 is a schematic representation of the difference between the presence of the sand and the gravel layers. The depth of the gravel appeared to increase the further downstream the user went from the +5m set of piezometers. The freeze cores from near the +23m set of piezometers backed this assumption. The hand augering also was able to pick out the presence of the sand layer up until the increasing thickness of the gravel layer became too great to be able to penetrate further.

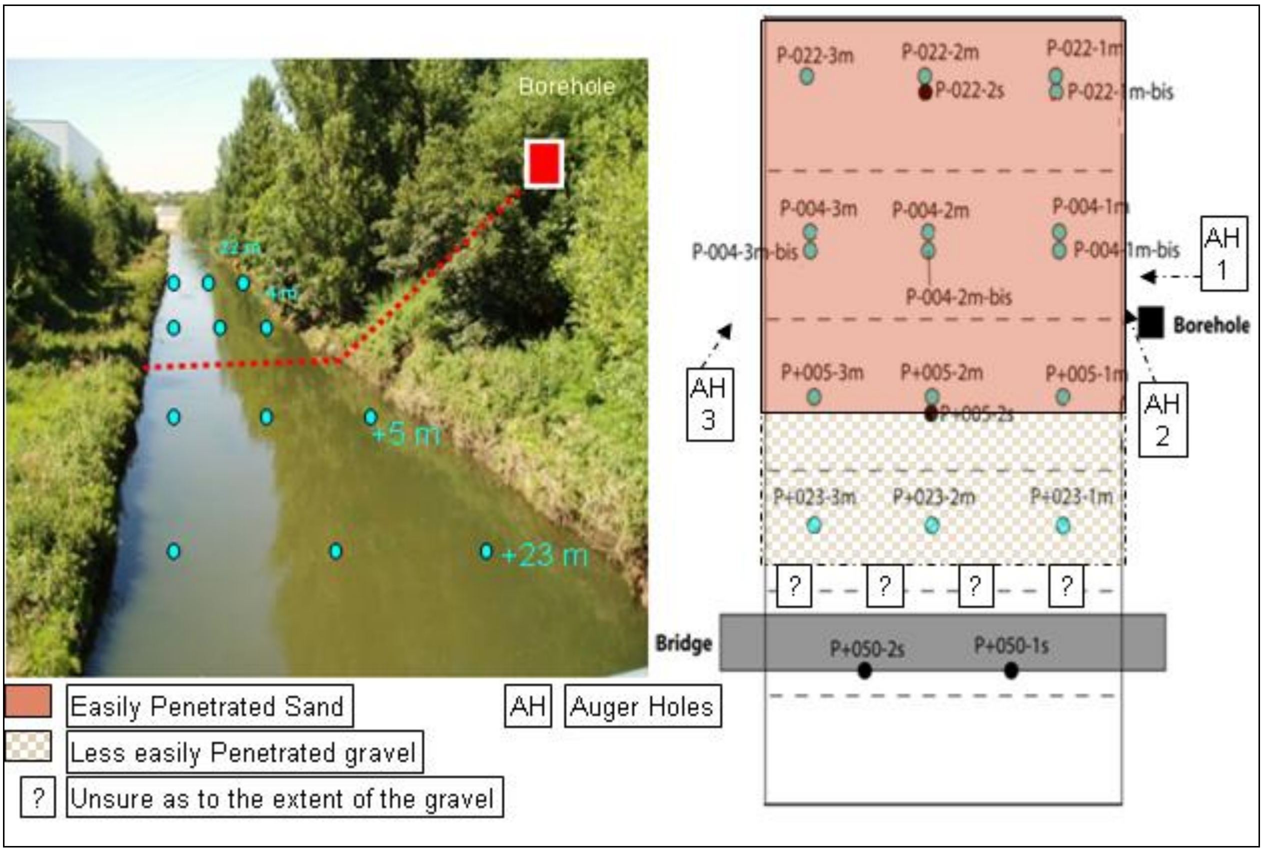

Figure 5.1: Photograph of the -22m to +23m Site, with a schematic diagram showing the positions of the dominant homogeneous sand and gravel layers. The positions of the Auger holes are also shown. Modified from (Cuthbert *et al*. in press).

The hand augering suggested that the heterogeneity of the gravel was great. Question marks are included in the schematic diagram, downstream of +23m, as this is at the end of the study area.

The hand augering also helped with determining the locations at which the freeze cores would be.

A number of auger holes were also carried out on the river banks, two on the east side (same side as the borehole), and one on the west bank (Figure 5.1). The auger holes all confirmed that the river banks had a high clay content of which there was a clay layer at approximately one meter depth at the east bank (Appendix 1). The auger holes were undertaken to aid with the characterisation of the site, especially with the visual assessment of material from an exposed section of bank further upstream from the -22m section of the study area (Figure

5.2). The exposed sections of bank, approximately 50m upstream from -22m appeared to show a poorly sorted mixture of smooth rounded pebbles and cobbles in layers, and layers of sediment. Figure 5.2 shows the River Tame's bank and the composition of the material likely to be found within the banks at the nearby SWITCH Hyporheic Zone Test Site. The apparent poor sorting of the material within the riverbank could suggest more of a glacial presence in the deposition of the material. However, the roundness and smoothness of the larger pebble and cobble sized material suggests more of a fluvial influence. However, the lack of a clear preferential orientation of the larger cobble sized material may rule out the deposition of the material solely by fluvial processes from the River Tame, and can be seen in the right-hand picture (Figure 5.2). Material deposited solely by a river tends to have an orientation that is similar to the direction downstream and the flow of the river.

Figure 5.2: Two photographs of the River Tame's banks, approximately 50m upstream from the -22m transect

5.2 Geophysics

One electrical resistivity survey was carried out, and due to a lack of time more surveys were not carried out. The survey carried out on the eastern bank (Figure 5.3), parallel to the river and passing the borehole seems to be successful and compliments the other techniques that have been used at the site.

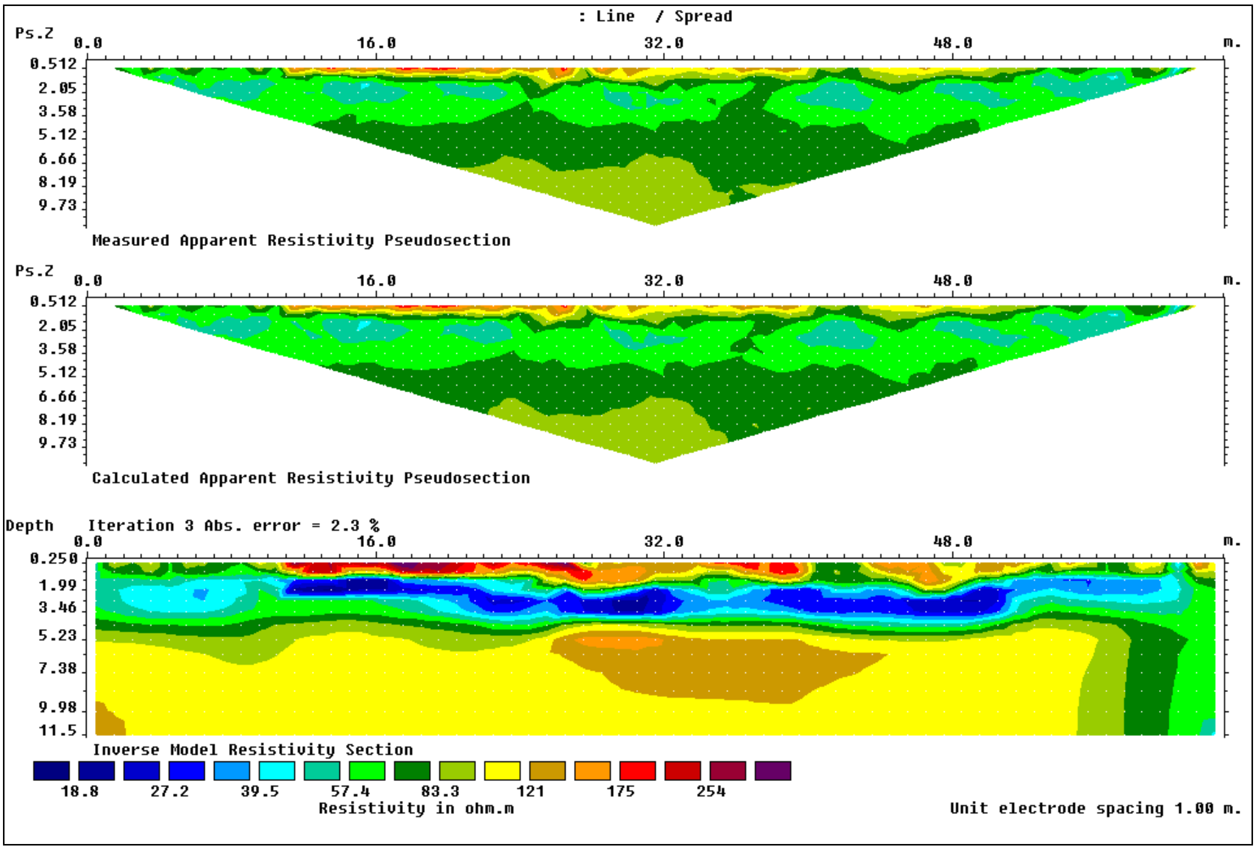

Figure 5.3: Pseudosection produced by RES2DINV of the Electrical Resistivity Survey at the Study Area.

The pseudosection images produced by RES2DINV (Figure 5.3) utilized a least squares optimisation approach which allows the true resistivity variations measured with depth to be shown (Loke and Barker, 1996 cited in; Gibson *et al*. 2004). The data presented in the bottom diagram (Figure 5.3) has been subjected to the reduce effects of side blocks option. This allows more emphasis to be given to the triangular readings, which the actual resistivity equipment measure (Figure 5.3). The bottom diagram shows a complete rectangle, which RES2DINV calculates from the triangular readings, providing an estimate of the materials resistances at the various depths and locations for the cross section beneath the resistivity equipment (Figure 5.3).

The RES2DINV plots show how the resistivity changes with depth and position.

The blue layer in the bottom image has been adjudged to be the clay layer that was found by the auger holes, due to the low resistivity values (18 - 40 Ωm) produced (Figure 5.3). The

yellow section in the pseudosection is assumed to be the Permo-Triassic Sandstone, picked up during the construction of the borehole; they both appear to correlate over the depth at which both are present and also the resistivity values (100 – 120 Ωm) suggest material with coarser texture than the blue layer (Figure 5.3). There is one anomaly found in the survey and that corresponds to the brown section, in the centre of the bottom image (Figure 5.3). The anomaly has a higher resistivity (approximately 120 – 170 Ωm) than the deemed sandstone, again suggesting coarse material. The anomaly could either refer to the gravel layer that was found within the riverbed, or it could also be injected concrete used to reinforce the borehole structure (pers comm. M. Cuthbert).

5.3 Freeze Cores

Figure 5.4 shows a photograph looking upstream at the -22m to +23m site and also a schematic diagram for the -22m to +23m River Tame Hyporheic Zone SWITCH Test Site. The schematic diagram has the approximate location of all the currently installed piezometers, and where the freeze cores abstracted material (Figure 5.4).

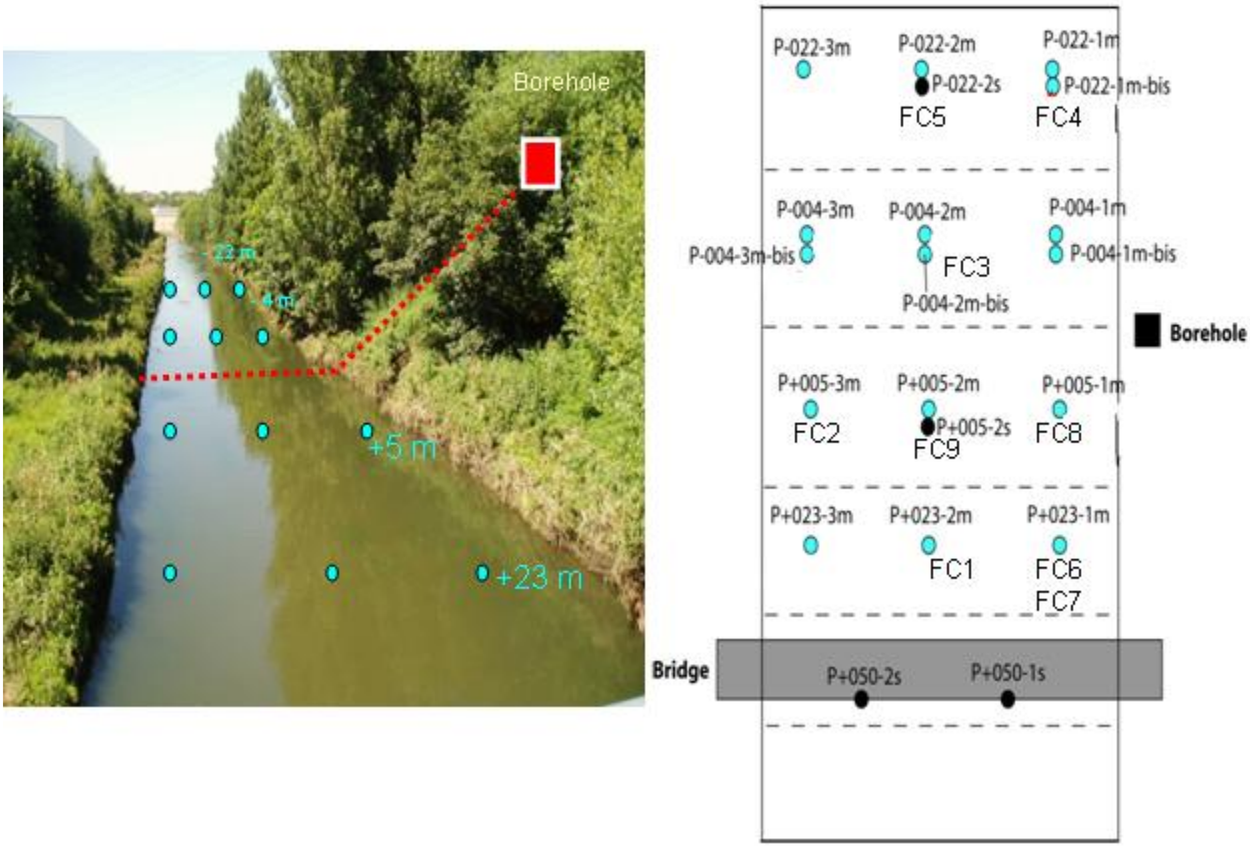

Figure 5.4: Photograph and schematic diagram of the study area, including piezometers and Freeze Core Locations. Modified (Cuthbert *et al*. in press).

The picture on the left is a photo taken from the bridge looking upstream; the diagram on the right shows the positions of the freeze cores in relation to the piezometers (Figure 5.4). Abstracting the material near to the piezometers helps to ensure that the material the piezometer is located in is accurately assessed. The safe distance from the piezometers that would ensure any future readings were undisturbed by the activity of freeze coring is unknown. It is likely that this safe distance would be approaching a meter, with the heterogeneity at the site meaning the material abstracted is likely to be completely different. Therefore a freeze core too far away from the piezometer would make the data and observations from the freeze core, irrelevant.

Freeze core one near piezometer +23m 2m was the worst core abstracted in terms of material lost, with approximately 0.21m of the sediment nearest the riverbed surface not picked up

(Figure 5.5). Freeze core one was the first one carried out, and therefore the decision was made to start with small amounts of liquid nitrogen, so as not to overexert the equipment, in particular the pulley and triangular frame. Approximately four litres of liquid nitrogen was used and twelve minutes of freezing allowed for the first freeze core. By increasing the amount of liquid nitrogen used and allowed time for freezing till an optimum amount and time were found, the equipment would not become damaged, and also ensured more sediment would be retained from the core sample.

The rest of the freeze cores excluding freeze core seven were given six to eight litres of liquid nitrogen, the time allowed for freezing was also increased to around 20 minutes, and this proved to be sufficient in obtaining a greater volume of sediment from the shallowest depths of the riverbed.

Two factors limited the depth to which feasible freeze cores could abstract; the first and probably the main factor being the length of the hollow coring tube, and the height of the water above the riverbed. The length of the hollow coring tube only became a factor when the water level was high enough that it could feasibly enter the hollow coring tube and thereby limit the effects of the liquid nitrogen.

As a result of carrying out a number of freeze core abstractions, a general bulb shape could be seen to be occurring from the abstracted material, Freeze core two (Figure 5.6), for example. The apparent explanation for this is that the bottom section of the corer is much more efficient at freezing sediments and thereby a fuller retention of material at greater depth is achieved. This could be as a result of the liquid nitrogen sitting at the bottom of the tube, despite efforts to distribute the liquid via the copper pipe spoon, and also greater insulation from the materials at greater depths, with little presence felt from the higher temperature of the surface water. The materials and geologic structure of the upstream sections (-22m and -4m) appeared to be much simpler and less varied than the down stream sections of the site

(+5m and +23m), proved by hand augering, and the freeze cores. This was the reason for less freeze cores being carried out at the sections with two at -22m, one at -4m, three at +5m, and three at +23m.

The +23m transect of the SWITCH Hyporheic Zone Test Site was suspected for a greater amount of larger material based upon freeze core six and one. A shallower core for freeze core seven was carried out, resulting in greater retention of larger material and material closer to the riverbed at that location near the piezometer +23m 1m (Figure 5.11).

Figure 5.5 to Figure 5.13 show three of the nine freeze cores to show the type of material being picked up. As can be seen from the freeze cores, a lot of the weathered Wildmoor Sandstone was being picked up, especially at the –22m, -4m, and to a slightly lesser extent the +5m transect. This certainly matches the information provided by the augering technique used within the riverbed. The increasing presence downstream of the gravelly material from +5m can be seen in freeze cores one (Figure 5.5), six (Figure 5.10), and seven (Figure 5.11) abstracted from +23m, further backing the findings suggested by the hand augering of the riverbed.

Freeze Core 1 +23m 2m	Top of layer, below riverbed (m)	Bottom of Layer, below riverbed (m)	
Amount sediment lost (cm)	0	0.21	
A	0.21	0.28	fine sand, uniform, orange
B	0.28	0.38	organic rich, sandy soil, some fauna
C	0.38	0.45	Sandy gravel, pebbles (non uniform) variation in size 5 mm to 3 cm
D	0.45	0.48	Sandy gravel, pebbles, rounded quartzite, some angular, poorly sorted

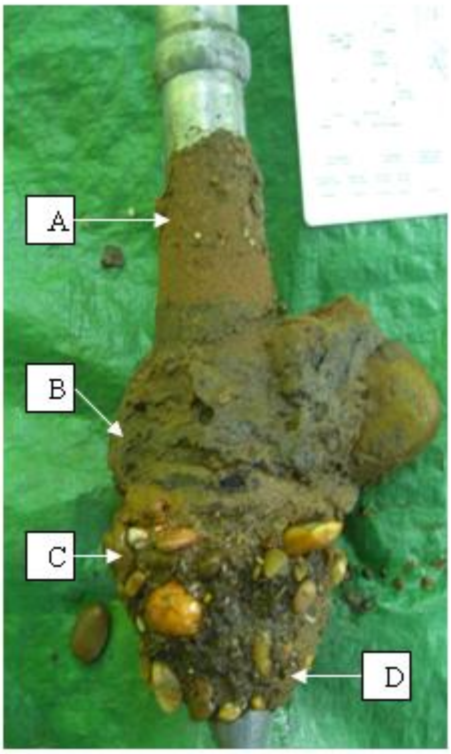

Figure 5.5: Freeze Core One and geology log.

Freeze Core 2 +5m 3m	Top of layer, below riverbed (cm)	Bottom of Layer, below riverbed (cm)	
Amount sediment lost (cm)	0	0.05	
H	0.05	0.19	Uniform dark brown, slightly grey organic soil, some black bands, well sorted.
G	0.19	0.24	Angular and rounded quartzite pebbles (possible armoured layer).
F	0.24	0.29	Orange-brown sand uniform, fine to medium, sub-rounded, quartz, mica. No distinguishable layering that should affect grain size distribution
E	0.29	0.34	
D	0.34	0.39	
C	0.39	0.44	
B	0.44	0.49	
A	0.49	0.54	

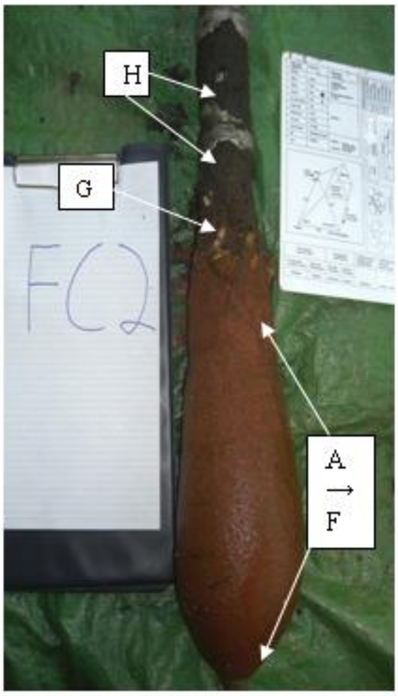

Figure 5.6: Freeze Core Two and geology log.

Freeze Core 3 - 4m 2mbis	Top of layer, below riverbed (cm)	Bottom of Layer, below riverbed (cm)	
Amount sediment lost (cm)	0	0.03	
H	0.03	0.05	Dark brown grey organic soil, some black bands, angular + rounded pebbles 3mm to 1cm
G	0.05	0.1	Orange brown clayey sand, no layering
F	0.1	0.13	Orange-brown sand uniform, fine to medium, sub-rounded, quartz, mica. No distinguishable layering that should affect grain size distribution
E	0.13	0.18	
D	0.18	0.23	
C	0.23	0.28	
B	0.28	0.33	
A	0.33	0.38	

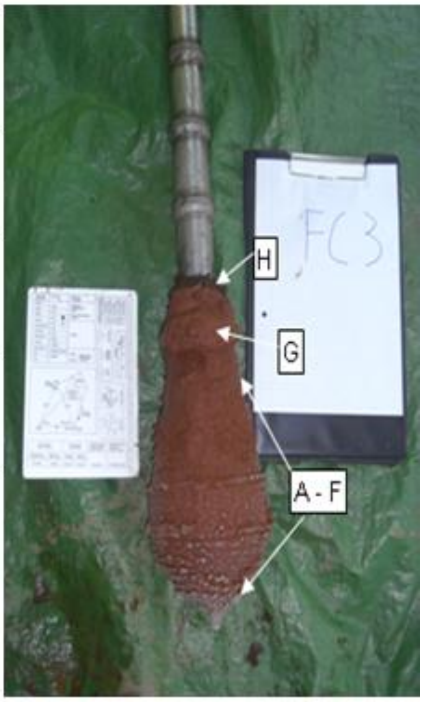

Figure 5.7: Freeze Core Three and geology log.

Freeze Core 4 -22m 1m	Top of layer, below riverbed (cm)	Bottom of Layer, below riverbed (cm)	
Amount sediment lost (cm)	0	0.04	
I	0.04	0.11	thin armoured layer, mixed with underneath layer, some angular hard to separate sample
H	0.11	0.16	similar orange brown sand as A-F, although appears disturbed, possibly by the technique
G	0.16	0.22	Different coloured banded section
F	0.22	0.27	orange-brown sand uniform, fine to medium, sub-rounded, quartz, mica. No distinguishable layering that should affect grain size distribution
E	0.27	0.32	
D	0.32	0.37	
C	0.37	0.42	
B	0.42	0.47	
A	0.47	0.52	

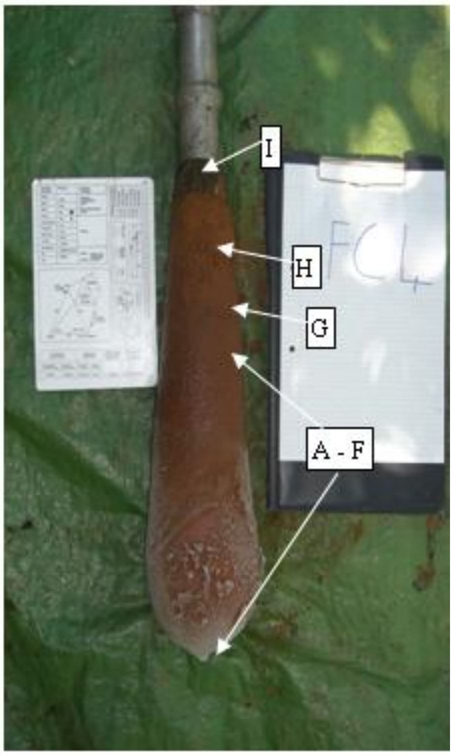

Figure 5.8: Freeze Core Four and geology log.

Freeze Core 5 -22m 2m	Top of layer, below riverbed (cm)	Bottom of Layer, below riverbed (cm)	
Amount sediment lost (cm)	0	0.04	
G	0.04	0.05	Top grey-brown organic soil, very thin and not sufficiently picked up
F	0.04	0.1	Orange-brown sand slight mixing with grey-brown organic top soil?
E	0.1	0.15	
D	0.15	0.20	Orange-brown sand uniform, fine to medium, sub-rounded, quartz, mica.
C	0.20	0.25	
B	0.25	0.30	
A	0.30	0.35	

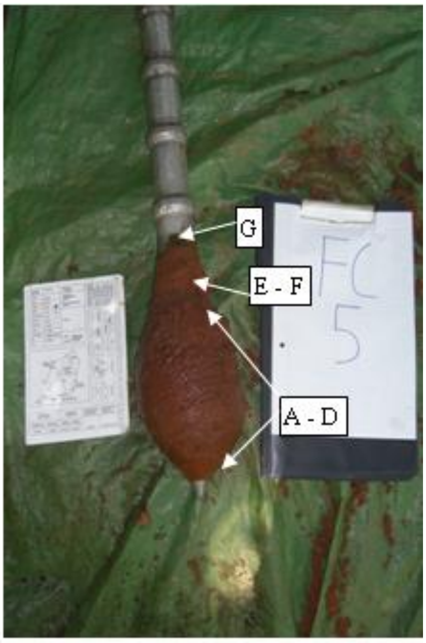

Figure 5.9: Freeze Core Five and geology log.

Freeze Core 6 +23m 1m	Top of layer, below riverbed (cm)	Bottom of Layer, below riverbed (cm)	
Amount sediment lost (cm)	0	0.15	
E	0.15	0.23	Dark brown organic soil, angular and rounded pebbles 3mm to 2cm
D	0.23	0.32	Brown slightly orange gravelly sand, quartz + mica, small pebbles 3mm to 2.5cm
C	0.32	0.42	Brown slightly orange gravelly sand, quartz + mica, pebbles and cobbles 3mm to 10cm. Cobbles angular and rounded
B	0.42	0.55	Orange-brown sand quartz, mica.
A	0.55	0.60	Orange brown sand, large cobbles angular and rounded 3mm to 10cm

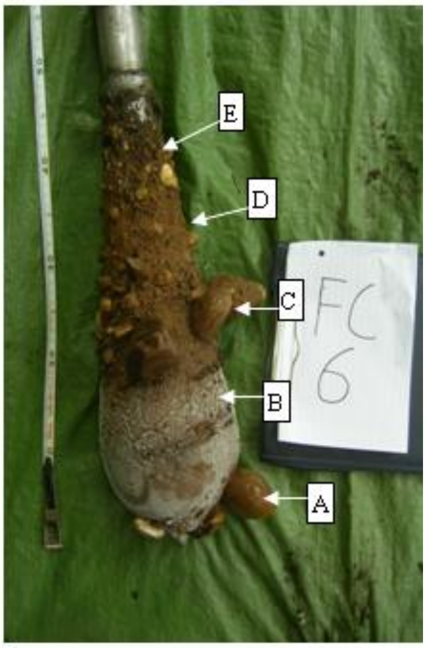

Figure 5.10: Freeze Core Six and geology log.

Freeze Core 7 +23m 1m	Top of layer, below riverbed (m)	Bottom of Layer, below riverbed (m)	
Amount sediment lost (cm)	0	0.02	
D	0.02	0.06	dark brown organic soil (some armouring) angular and rounded pebbles 3mm to 1 cm
C	0.06	0.14	brown slightly orange gravelly sand, quartz + mica. Angular and rounded pebbles + cobbles 3mm to 5cm
B	0.14	0.2	orange brown gravelly sand, high pebble content, angular + sub-rounded 2mm-1cm.
A	0.2	0.3	orange brown gravelly sand, high pebble content, angular + sub-rounded 2mm-3cm. Occasional large cobbles i.e. 12cm by 10cm

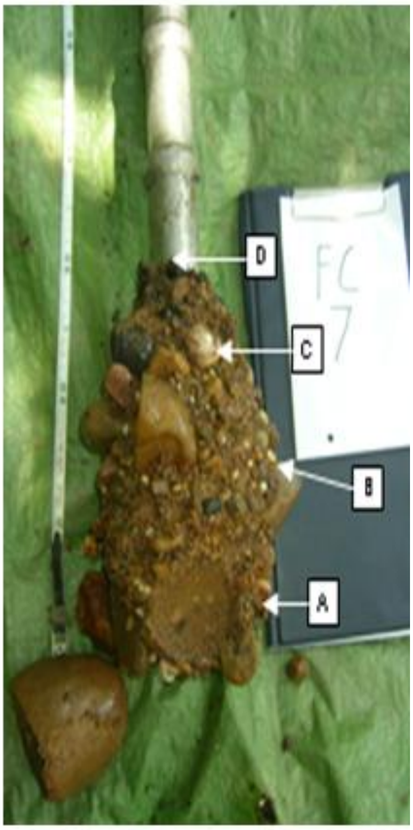

Figure 5.11: Freeze Core Seven and geology log.

Freeze Core 8 +5m 1p	Top of layer, below riverbed (cm)	Bottom of Layer, below riverbed (cm)	
Amount sediment lost (cm)	0	0.15	
G	0.15	0.17	Dark brown organic soil angular and rounded pebbles 3mm to 1cm
F	0.17	0.25	Grey brown clayey sand, small pebbles, sub-rounded 3mm to 1cm.
E	0.25	0.39	Grey brown clayey sand, pebbles and cobbles, 3mm to 7cm.
D	0.39	0.46	Orange-brown sand uniform, fine to medium, sub-rounded, quartz, mica.
C	0.46	0.51	
B	0.51	0.56	
A	0.56	0.61	

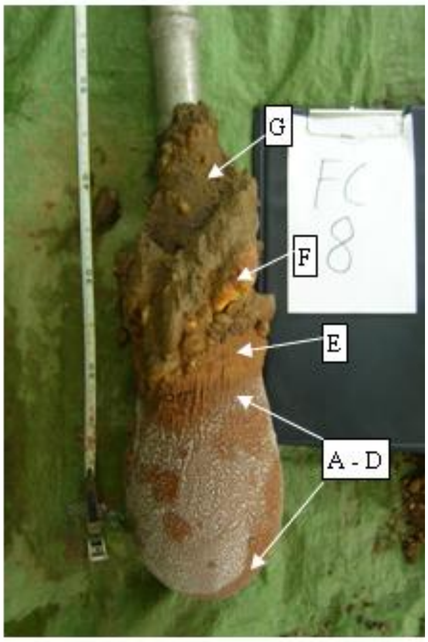

Figure 5.12: Freeze Core Eight and geology log.

Freeze Core 9 +5m 2s	Top of layer, below riverbed (cm)	Bottom of Layer, below riverbed (cm)	
Amount sediment lost (cm)	0	0.03	
E	0.13	0.18	Dark brown organic soil, angular and rounded pebbles 3mm to 1cm.
D	0.18	0.23	Orange-brown sand uniform, fine to medium, sub-rounded, quartz, mica.
C	0.23	0.28	
B	0.28	0.33	
A	0.33	0.38	

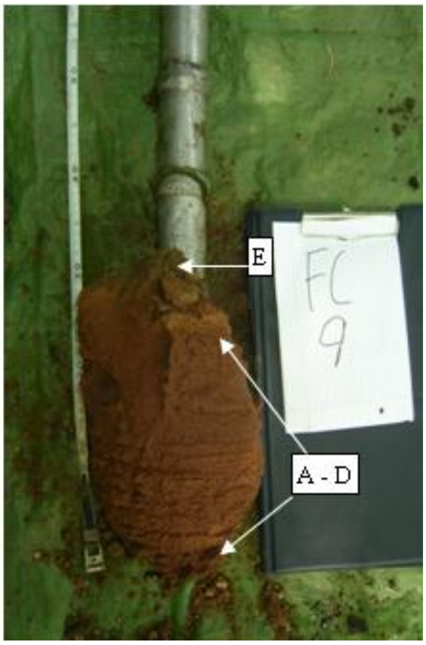

Figure 5.13: Freeze Core Nine and geology log.

5.4 Samples from the Cores

For the Hazen (1892), Alyamani and Sen (1993), and constant head permeameter analysis of the sediment samples grain size distribution curves were used (Figure 5.14), producing values for Hydraulic Conductivity. To generate values for Hydraulic Conductivity via repacking the sieved material into cores, the cone and quarter method was used to obtain as unbiased a range as possible for the material. Hydraulic Conductivity values were then produced for the repacked material samples via the use of Darcy's Law.

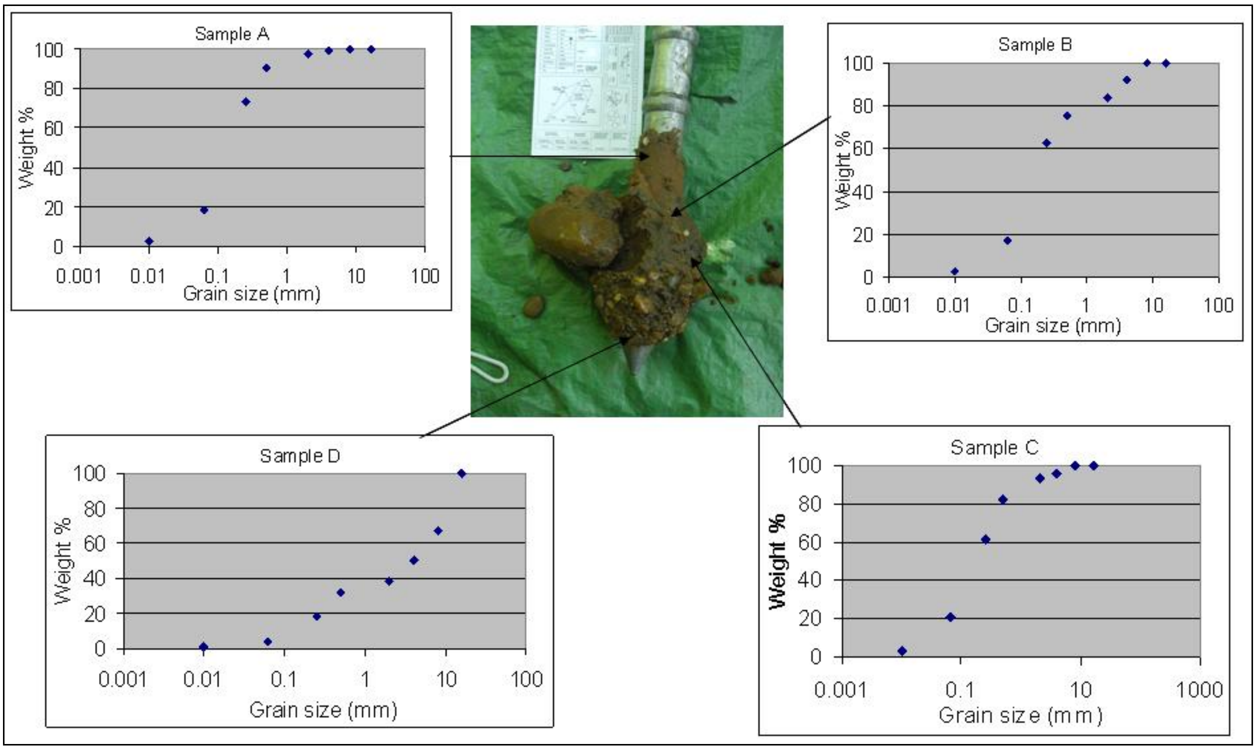

Figure 5.14: Grain size distributions produced for Freeze Core one via dry sieving

By using the percentages obtained for the various sediment types and comparing them to the Shepherd (1954) modified by Schlee (1973) classification triangles (Figure 4.2), the sediment samples could be classified into broad types. The majority of samples collected had high percentages of medium sand, especially the sand that was believed to be weathered Wildmoor Sandstone picked up by freeze cores two (Figure 5.6 Samples A to F), three (Figure 5.7), four (Figure 5.8), five(Figure 5.9), eight (Figure 5.12) and nine (Figure 5.13). Other samples contained high percentages of medium sand, but clearly displayed different visual characteristics such as colour and were therefore from another source, such as the organic sandy sediments, of which usually little amounts were picked up by the freeze cores. The assumed weathered sandstone displays an orange brown colour; the organic sandy sediments are black.

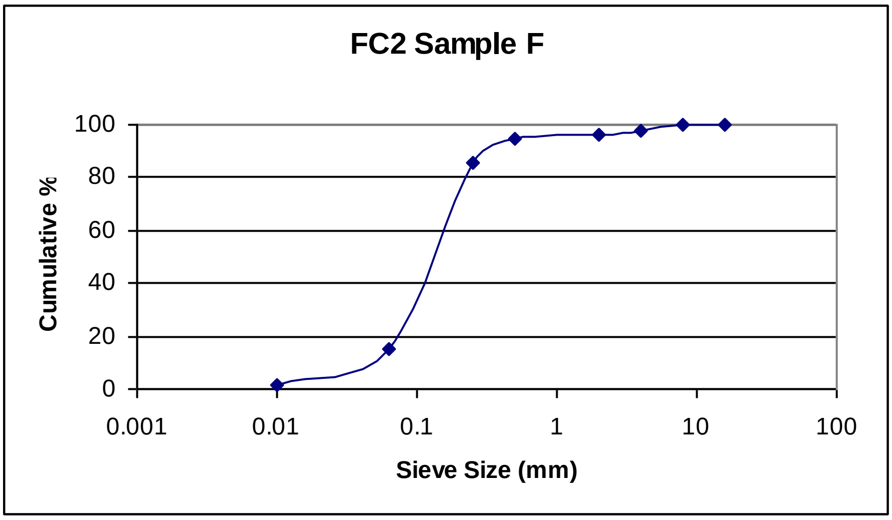

Figure 5.15: Grain Size Distribution for Freeze Core Two Sample F - homogeneous sand

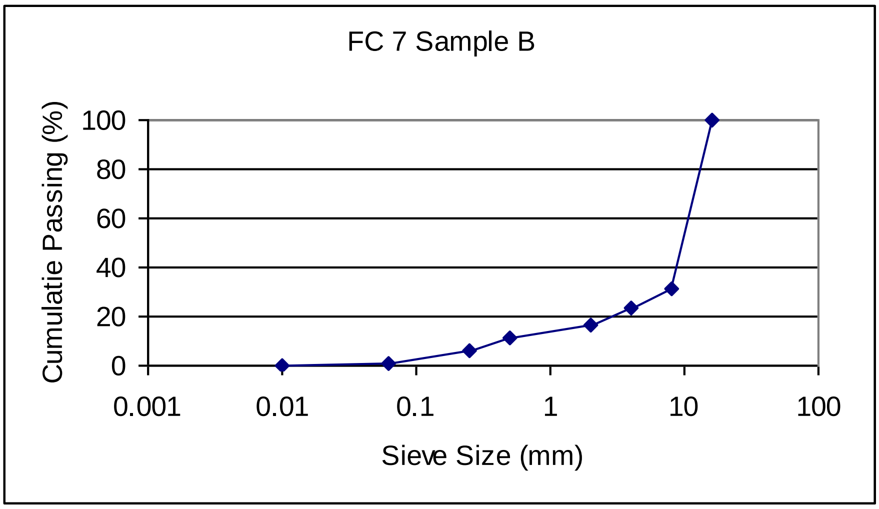

Figure 5.16: Grain Size Distribution for Freeze Core Seven Sample B - gravel

There are considerable differences in the grain size distributions between the homogeneous sand and the gravel material. Figure 5.15 displays the graph for freeze core two Sample F (Figure 5.6), showing that the homogeneous sand is reasonably well sorted. The gravel material of freeze core seven, sample B (Figure 5.11) however, is very poorly sorted (Figure 5.16).

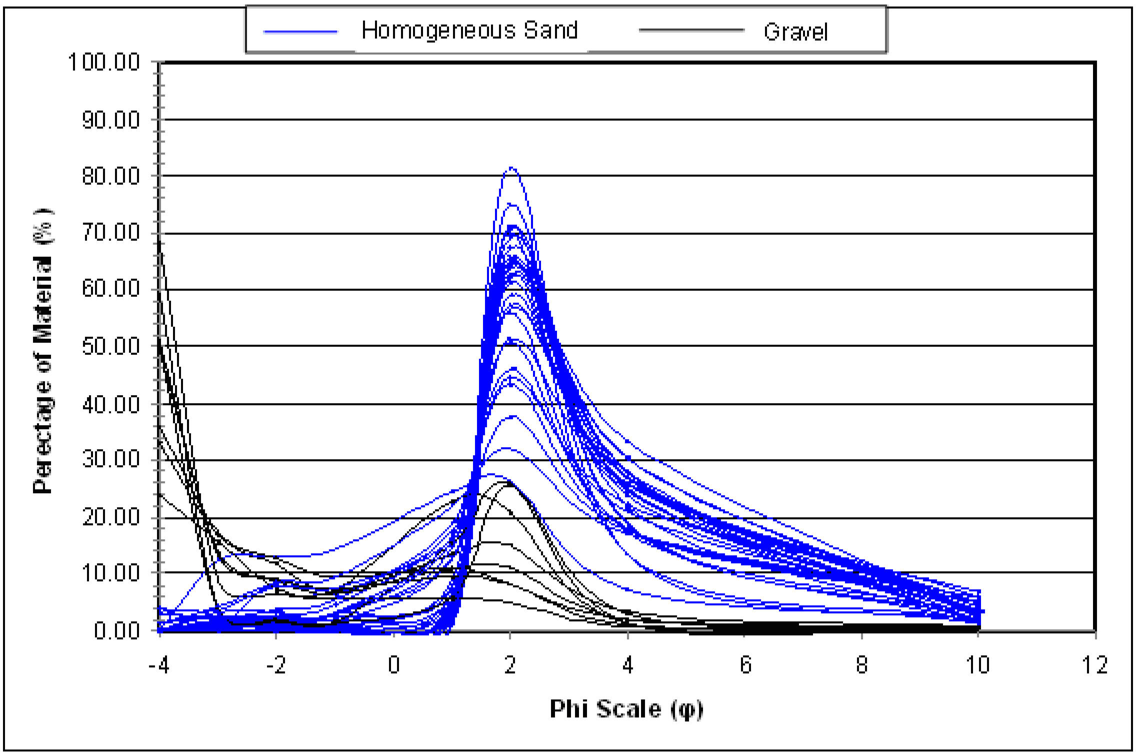

Figure 5.17: Percentage of Material Retained by Sieves for Homogeneous Sand and Gravel Samples

Figure 5.17 displays the percentage of material retained by the sieves for all of the sediment samples classified as either homogeneous sand (referring to the weathered sandstone), and the gravel collected by the freeze cores. There is a clear distinction between the two. The material classified as homogeneous sand peaks around the Phi value of 2, a sieve size value of 0.25 mm which retains fine sand. The homogeneous sand also has a much greater proportion of finer material rather than coarser. Whereas the Gravel material peaks at -4 on the Phi scale, this corresponds to gravels and larger material. The gravel material has a small second peak around the fine sand scale, Phi value of 2, further indicating the poor sorting of the material.

The homogeneous sand picked up by the majority of the freeze cores at the -22m, -4m, and +5m transects, is considered to be the weather Wildmoor Sandstone; the Wildmoor Sandstone Formation is the underlying bedrock. The grain size analysis carried out on the

samples of weathered Wildmoor Sandstone closely matches the grain size analyses carried out on the Wildmoor Sandstone Formation. Previously conducted analyses have found 40 to 60 % medium sand, 28 to 46 % fine sand, and less than 2% coarse sand (Powell, 2000). The majority of samples collected from the freeze cores showed similar ranges (Appendix 2). However, there were a few exceptions, especially those at shallower depths nearer to the riverbed, most notably sample G from freeze core three (Appendix 2).There is a wide spread of different sediment types, medium sand is 26.67%, fine sand 7.31%, and coarse sand is 24.48%.

5.5 Hydraulic Conductivity Data

The Hazen (1892) method requires that the d_{10} of the material to be between the range of 0.1 and 3 mm, and also that the coefficient of heterogeneity (d_{10}/d_{60}) is between 1 and 5 (Wilson and Thornton, 2009). With this in mind the majority of the homogeneous sand samples are not valid for the Hazen analysis, and the Alyamani and Sen (1993) analysis. The values generated from the sieving of the collected material and subsequent analysis by the various methods show a great range of values for hydraulic conductivity.

The Hazen (1892) analysis estimated that the lowest hydraulic conductivity of 0.075 (m/d) was for sample D from freeze core three (-4m 2mbis); part of the homogeneous orange to brown sand (Figure 5.7). The amount of fines contained within this section was particularly high compared to other samples; approximately 6.9% of material was less than 0.063mm in diameter. The Hazen (1892) method is particularly sensitive to the percentage of fines; due to this high percentage of fines, the d_{10} was 0.012mm, outside the valid range of 0.1mm to 3 mm. The highest hydraulic conductivity value Hazen (1892) produced was 138.24 (m/d), from freeze core seven (+23m 1m), sample B (Figure 5.11) the sediment comprised of orange

brown gravelly sand, with a high pebble content, angular and sub-rounded 2mm to 1cm. The amount of fines within this sample was particularly low, and as a result the d10 of the material was 0.4 (mm); within the 0.1mm to 3mm range.

The lowest value generated by Alyamani and Sen (1993) of 0.001 (m/d) came from freeze core eight (+5m 1p) Sample D (Figure 5.12), this was part of the homogeneous sand; there was a low percentage of fines within this sample just as for the lowest Hazen produced hydraulic conductivity.

The highest value Alyamani and Sen (1993) estimated 120.935 (m/d) from freeze core seven (+23m 1m) sample B (Figure 5.11). This was the same section of material that also produced the highest value for hydraulic conductivity as the Hazen analysis, with the low percentage of fines resulting in the high hydraulic conductivity value. Approximately 0.14% of the material was less than 0.063mm in diameter. Seeing as both the Hazen (1892) and Alyamani and Sen (1993) analyses are heavily based upon the amount of fines, therefore a very small percentage of fines will cause these analyses to produce a high hydraulic conductivity value.

As mentioned the repacking of disturbed material into cores for use in constant head permeameter tests is particularly susceptible to error in the values of hydraulic conductivity that the technique produces. For example the lowest hydraulic conductivity value of 0.24477 (m/d) is from freeze core eight (+5m 1p) Sample E (Figure 5.12). The material was adjudged to be clayey sand. However, the percentage of fines was 0.46%, which in terms of other samples is low. On the other hand the grain size distribution of sample e showed that the sample was poorly sorted. The other sample for this clayey sand showed better sorting, possibly leading to the higher hydraulic conductivity value of 1.4694 m/d, produced by the repacking of the sample.

The highest value for hydraulic conductivity estimated by the repacking of the disturbed material is 10.0629 (m/d) estimated from freeze core six (+23m 1m), Sample D (Figure 5.10).

Freeze core nine is displayed as an example to show the hydraulic conductivity values that were generated via the various methods (Table 5.1).

	Top of layer, below riverbed (m)	Bottom of Layer, below riverbed (m)	Hazen (1892) (m/d)	Alyamani and Sen (1993) (m/d)	Repacked Material (m/d)
Amount sediment lost (cm)	0	0.13	NA	NA	NA
E	0.13	0.18	0.677	0.184	3.78352
D	0.18	0.23	0.207	0.132	1.05594
C	0.23	0.28	0.207	0.329	4.06792
B	0.28	0.33	0.194	0.644	2.66541
A	0.33	0.38	0.221	0.728	1.01611

Table 5.1: Hydraulic Conductivity Results for Samples from Freeze Core Nine

Despite the known uncertainties of repacking material into a core, the method appears to have produced the most sensible hydraulic conductivity values.

With respect to the different geologic types; there is a relationship with hydraulic conductivity. For the repacked material the homogeneous sand has a lower hydraulic conductivity value range of 0.32208 to 4.06792 m/d. For the repacked material the gravel has a hydraulic conductivity value range of 2.00619 to 10.0629 m/d. (Appendix 3).

5.6 Plug Samples

The use of plug samples directly taken from the freeze cores and thereby providing an estimate for hydraulic conductivity that would be considered relatively undisturbed to the other methods, did not seem to provide reasonable values.

5.7 Conceptual Cross Sections

To aid in analysing the data from the SWITCH Hyporheic Zone Test Site,Figure **5.18 to Figure 5.22** were put together. The basis of the riverbed elevation came from measurements previously carried out upon the -22m to +23m River Tame SWITCH Site. The large diagram displays the interpreted geology cross section for the specific transects. The interpreted geology is a result of the freeze cores abstracted from the site, and the hand augering done in the riverbed. The chemical profiles for chloride and nitrate concentrations were included. A graph showing the hydraulic conductivity measurements from the techniques used for the various depths sampled was also included. The manual falling head tests done on the piezeometers were also included on the graph of hydraulic conductivity data, as a comparison between lab and field data. The down stream cross section was also constructed to conceptually characterise the profiles of the geologic materials, and comparing the elevation of the central section of the riverbed. It must be noted that the elevations are different for the downstream cross section and the cross sections for the different transects. Due to the number of different people working at the SWITCH Site, different elevations were used for individual studies. Unfortunately there was not enough time to correct these differences and produce one arbitrary datum for the elevation values. However, the relative differences within each cross section are accurate.

5.8 Chemical Results

The general patterns from the chemical data collected show that generally Nitrate levels increase with depth, whereas Chloride levels fall. Generally the chloride and nitrate patterns appear to be less complicated through the homogeneous sand, at the upstream section of the -22m to +23m study area. This is emphasised by the chloride and nitrate profiles for -22m

1mbis (Figure 5.18). The chloride profile for -22m 1mbis declines with depth, whereas the nitrate profile shows an increase with depth (Figure 5.18). The hydraulic conductivity data provided for this section by (Figure 5.18), show values that are fairly consistent with depth. The hydraulic conductivity values produced from the repacked material show an increase with depth from approximately 0.1m to 0.4m; any change in the chemical profiles is not reflected. There is a much sharper response from both chloride and nitrate profiles in 0.1m depth section of the riverbed for -22m 1mbis (Figure 5.18); from the augering and freeze core data the 0.1m depth consisted of what was deemed to be a mixture of organic sediments and armouring. The rest of the -22m and -4m chloride and nitrate profiles display similar profiles of a decrease and increase with depth respectively over the first 0.1m to 0.2m depth. After this initial change both chemical profiles rate of change of concentration with further depth decreases.

However, despite there being general trends. There is still considerable variation in the profiles at different locations and for different sampling dates, perhaps reflecting the heterogeneity of materials at the site and the responses they produce.

At the downstream transects, +5m (Figure 5.20) and +23m (Figure 5.21), a different pattern can be seen to the -22m (Figure 5.18) and -4m (Figure 5.19) transects; where the chloride and nitrate profiles have less variation with dept. This is typified by the chloride profile for +23m 3m (Figure 5.21), which shows little variation in both the chloride and nitrate concentrations with depth for the sampling dates. However, this little variation with changing depth occurs when there are substantial differences in the hydraulic conductivity measurements. Although the hydraulic conductivity measurements are generally higher at the +5m and +23m transects.

Figure 5.18: Cross - section one; -22m Transect looking upstream, and corresponding hydraulic conductivity and chemistry data.

Figure 5.19: Cross - section two; -4m Transect looking upstream, and corresponding hydraulic conductivity and chemistry data.

Figure 5.20: Cross - section three; +5m Transect looking upstream, and corresponding hydraulic conductivity and chemistry data.

Figure 5.21: Cross - section four; +23m Transect looking upstream, and corresponding hydraulic conductivity and chemistry data.

Figure 5.22: Cross - section five; downstream Transect looking east, and corresponding hydraulic conductivity and chemistry data.

Chapter 6 Techniques limitations

6.1 Freeze Core and Particle Size Analysis

As a result of carrying out a number of freeze core abstractions, a general bulb shape could be seen to be occurring from the abstracted material, freeze core four (Figure 5.8). The apparent explanation for this is that the bottom section of the freeze corer is much more efficient at freezing sediments and thereby a fuller retention of material at greater depth is achieved. This is likely a result of the liquid nitrogen sitting at the bottom of the tube, despite efforts to distribute the liquid with the use of the copper pipe spoon. Also the potentially greater insulation from the materials at greater depths, with little presence felt from the higher temperature of the surface water could contribute to the bulb shape.

For the homogeneous sand the majority of samples grain size analysis collected from the freeze cores showed similar ranges to those suggested by Powell (2000) (Appendix 2). However, there were a few exceptions, especially those at shallower depths nearer to the riverbed where the freeze core technique may have disturbed the sediment layers by introducing material from above, and can be seen from (Figure 6.1). Figure 6.1 shows that the top organic layer material has penetrated 0.22m into the core along the corers metal surface, effectively penetrating through four samples (I to F). Therefore this contamination affects their grain size distributions and subsequent hydraulic conductivities; all of the freeze cores are likely to have had this cross contamination to some extent.

Figure 6.1: Contamination extent of upper layers down centre of the sample

6.2 Plug Samples

The use of plug samples directly taken from the freeze cores was done to provide an estimate for hydraulic conductivity that would be considered relatively undisturbed to the other methods. However, the values produced seemed inaccurate. The plug samples were only able to be taken, once the freeze core had defrosted slightly and thereby the material had expanded slightly.

Another potential reason for their failing, may have been down to the method used to ensure the samples were fully saturated; a small vacuum container. Once the vacuum had been placed over the samples a small amount of fines and material was forced out of the samples containers, and thereby ultimately effecting the hydraulic conductivity of the materials.

6.3 Hydraulic Conductivity Values

In terms of particle size analysis, a much queried issue is over the amount of material mass for a sample that would be needed to produce a representative distribution of each size fraction present (Gale & Hoare, 1991). The suggested amount of material mass should be at least the largest material clast mass raised to the power of 2.75 (British Standards Institution (1985) cited in; Gale & Hoare, 1991). For the majority of the samples, the freeze coring technique seemed to be successful at collected sufficient amounts of material, with the exceptions of the shallower depth layers.

The grain size analyses was able to show the poor sorting of the gravels compared to the sand which is to be expected and therefore, it may be expected to reflect with lower hydraulic conductivity values. However this was not the case with the gravel sections of freeze cores one, six, and seven; from transect +23m, having the highest hydraulic conductivities according to the Hazen and Alyamani & Sen analyses. Freeze core seven, sample B (Figure 5.11) produced the highest hydraulic conductivity values from Hazen (1892) and Alyamani & Sen (1993), both over 120 m/d. However the repacked material (<16mm) and subsequent refactoring by mass for the larger sized material (>16mm), for the same sample produced a value of around 2m/d; a value which is not too dissimilar to other constant head permeameter tests done on some of the samples considered as the weathered sandstone. The Hazen (1892), Alyamani & Sen (1993) analyses almost consistently have lower hydraulic conductivity values for the samples of the weathered sandstone.

Song *et al*. (2009) state that the use of grain size distribution produced hydraulic conductivity values are inaccurate; with the Hazen analysis in particular producing some of the greatest overestimations.

Song *et al*. (2009) further discusses that there is great difference in opinion over the types of method used to assess hydraulic conductivity; some studies argue for the Hazen method to be disregarded, whereas others say it is just as reliable as other methods.

However, Song et al. (2009) successfully used a driven in tub with rubber cap; a similar method was used in previous MSc projects at the SWITCH Hyporheic Zone Test Site. However, using this technique on the SWITCH Test Site was not successful, possibly due to the materials being less cohesive.

6.4 Chemistry Data

There is some doubt over the validity of the data collected. In particular the there are some nitrate and chloride profile anomalies, the 15/10/08 sampling date for +23m 1m (Figure 5.21), in particular displays unusual fluctuating profiles.

Some of the chemical profiles such as those for the 15/10/08 date (Figure 5.21) are under scrutiny over their accuracy (pers comm M. Cuthbert 2009). This is also the case for the chloride and nitrate profiles for transect -4m piezometer 1mbis which appear as though they need to be raised 0.3m and thereby making them seem similar to the other profiles for the -22m and -4m transects.

Another issue over the accuracy of the chemical data is that the exact depths of the piezometer sampling points are unlikely to be as accurate as they are written down.

As the piezometers were hand driven, the depths to which they were pushed are not going to accurately known. The difference between actual and believed depths is unlikely to be great. However, it should be acknowledged that the chemistry data analysis is in terms of approximate depths.

Chapter 7 Discussion

7.1 Cross-Sections

Overall there seemed to be a small number of materials of different geologic types from the data available collected from the freeze cores and hand augering. Therefore the cross sections may appear over-simplified especially for the -22m and -4m transects (Figure 5.18 and Figure 5.19). However, the data provided by the freeze cores and the hand augering at these transects suggested that the underlying layer of sand was dominant. Small heterogeneities could be found with the hand augering, but were considered to be sporadic, and hard to accurately determine the extent of them. Therefore it was reasoned that at the -22m (Figure 5.18) and -4m (Figure 5.19) transects that the sand layer was the dominant geologic feature with no discernable differences picked up to be considered to have any affect on the hydraulic conductivity and consequently affect the chemical profiles.

Hence the seeming dominance of the sand was also the reason why only two freeze cores were abstracted at -22m and one at -4m; with the believe that little more valuable information would be provided.

The homogeneous sand picked up by the majority of the freeze cores at the -22m, -4m, and +5m transects, is considered to be the weather Wildmoor Sandstone; the Wildmoor Sandstone Formation is the underlying bedrock. The grain size analysis carried out on the samples of weathered Wildmoor Sandstone generally matched the data provided for the grain size analysis carried out on the Wildmoor Sandstone Formation (Powell, 2000).

For the +5m (Figure 5.20) and +23m (Figure 5.21) transects, a definite change appeared to this sole homogeneous sand section that was so apparent upstream from the +5m transect. As can be seen with the cross sections +5m (Figure 5.20) and +23m (Figure 5.21); a greater

variation to the homogeneous sand section, occurred through the presence of a gravel layer with increasing thickness downstream (Figure 5.22). This gravel layer appears to be picked up only very slightly from the three freeze cores (two, eight, and nine) at transect +5m (Figure 5.20), becoming quite significantly larger at the freeze cores (one, six, and seven) at transect +23m (Figure 5.21). The hand auger also confirmed this increasing gravel layer, with increasing depth needed to penetrate to the underlying sand layer. This increased variation in the geology at the +5m and +23m transects lead to the increased number of freeze cores taken at the downstream section of the -22m to +23m study area. Evidence of sand was found at the +23m transect for freeze core six (Figure 5.21), but was deduced to be a sand lens due to the colour difference to the assumed weathered Wildmoor Sandstone. Near the +23m transect, the position of the weathered Wildmoor Sandstone layer could not be located by either the freeze cores or the hand augering, but was assumed to continue, and likely be present at a slightly greater depth. Therefore the cross section of +23m (Figure 5.21) and the downstream cross section (Figure 5.22), have speculatively been included with the assumed location of the weathered sandstone, on the basis of the evidence provided by the freeze cores and hand augering.

Despite the inclusion of the gravel and variations such as the sand lens at +23m (Figure 5.21) or the higher clay content section at +5m (Figure 5.20); they are still both simplistic representations in the geologic sections that they represent. Whether the increased portrayal of heterogeneity at the sites would provide any further answers in terms of the chemical profiles included from the increased detail for hydraulic conductivity is debatable. However, for more complex systems including the presence of gravels that produce turbulent flows, scaling options can still produce different relationships for the variation of stream flows due to sedimentary types (Packman and Salehin, 2003).

7.2 Chemistry

The general patterns from the chemical data collected show that generally Nitrate levels increase with depth, whereas Chloride levels fall. There appears to be a general upstream and downstream pattern for chloride and nitrate profiles. At the upstream section of the site the -22m (Figure 5.18) and -4m (Figure 5.19) transects generally show chloride and nitrate concentrations, decreasing and increasing with depth respectively. However, the downstream sections of +5m (Figure 5.20) and +23m (Figure 5.21) show a general pattern for the chloride and nitrate which doesn't vary as much with depth, with the exceptions of the sampling dates which are under question.

The more varying nitrate and chloride profiles from -22m and -4m show that the interaction of groundwater and surface water continues to a depth of between 0.2m to 0.3m below the riverbed. Therefore mixing processes and subsequent alteration of the chloride concentrations varies across the study area. Despite there being positive flows from the aquifer to the river the chemical profiles indicate there is mixing taking place within the riverbed (Ellis *et al*. 2007).

7.3 Hydraulic Conductivity

Transects -22m (Figure 5.18) and -4 m (Figure 5.19) are dominated by the weathered Wildmoor Sandstone which generally produced lower hydraulic conductivity values. The +5m (Figure 5.20) and +23m (Figure 5.21) transects on the other hand were found to have a more varied riverbed sediment geology, with predominantly the inclusion of a gravel layer. The samples of the gravel layer from freeze cores one, two, six, seven, eight, and nine, were generally more poorly sorted than samples of the weathered sandstone. However, despite this poorer sorting; hydraulic conductivity values for the gravel samples were generally higher.

Therefore for transects +5m and +23m the higher hydraulic conductivity could be a factor for their being less variation found for the chemical profiles of the piezometers at these transects. The increased permeability of riverbed sediments, especially for a gaining section of river (Cuthbert *et al*. in press), can lead to the contaminants from groundwater (in this case nitrate) reaching the river with concentrations not having been significantly reduced (Conant, 2000). However, along these faster flow paths, the groundwater sourced contaminant can be reduced by other processes such as biodegradation (Conant, 2000); which may explain different sampling dates that show a reduction in nitrate with decreasing depth compared to other sampling dates that show little variation such as +23m 3m (Figure 5.21).

Generally the centre of the river channel appears to produce the less varied chemical profiles for the various sampling dates. Genereux *et al*. (2008) found hydraulic conductivity to be at its highest within the centre of the river channel due to the lower abundance of fines. The +5m section of the study area certainly shows a general higher hydraulic conductivity value within the centre of the channel (Figure 5.20), which may account for the generally straight chemical profiles.

7.4 Temporal Variation

Some nitrate profiles do exhibit variations for different sampling dates, with the controlling factor for the profile appearing to be the starting nitrate concentration at the deepest sampling point. Therefore the sampling dates discussed here would suggest that the groundwater flow varies causing nitrate pulses with varying concentrations. The varying inputs of nitrate concentrations into the River Tame Hyporheic Zone at the -22m and +23m SWITCH Test Site may be a result of varying groundwater level variations (Rivett *et al*. 2007). Also the lower concentrations at depth on the nitrate profiles maybe a result of attenuation within the

groundwater from the Permo-Triassic Sandstone, for which there is some evidence (Rivett et al. 2007). This potential attenuation occurs before the groundwater reaches the hyporheic zone thereby creating lower initial nitrate concentrations, and around a depth of approximately 0.2m to 0.3m on the profiles exhibiting a decline of nitrate levels with decreasing depth. Despite it not being concluded, there is some evidence for denitrification within the hyporheic zone of the -22m to +23m study area, with nitrite found to be present (pers comm. M. Cuthbert 2009).

The variation also experienced by the chloride profiles at different sampling dates may in part be due to temporal and annual differences. These differences include high flow events, that cause hydraulic fluxes to alter, as well as morphological changes of the riverbed including the removal of fine sediments which will alter the hydraulic conductivity of the riverbed (Keery *et al*. 2007). However, due to it being unsafe to work in the river at high flows, chemical sampling was often done at near stable river levels, which therefore meant that the likely effects caused by high flows on the chemical profiles can not be fully assessed.

However, the 30th - 31st /07/08 sample dates were done on the falling limb of a high flow event. Chloride concentrations generally appear to be diluted at lower depths for this date. Which is reasonable due to the chloride source being the surface water body (Ellis *et al*. 2007), and therefore a greater volume of water will dilute the chloride concentration.

7.5 Topography

Topography is also likely to be having a big influence on the flows experienced within the study area. The downstream cross section (Figure 5.22), shows that the upstream section -22m and -4m, and just before +5m experiences a slight decline in elevation. The downstream section, including +5m and +23m shows a slight rise in elevation, and combined with the

increasing thickness of the gravel layer may alter the chemical profiles of the downstream section. There have been numerous studies on how different morphologic features affect the exchanges present within the hyporheic zone (Kasahara and Wondzell, 2003; cited in Gooseff *et al*. 2006). The difference in elevation, and riverbed topography, along with the increased gravel section is likely to contribute to the much straighter nitrate and chloride profiles for transect +23m.

Chapter 8 Conclusions and Further Work

8.1 Conclusions

The aim of this project was to further develop understanding of how riverbed materials affect water quality variations within the Hyporheic Zone at the SWITCH Test Site. The results and discussion of the study are presented in Chapters 5, 6, and 7.

From the data collected, the major shallow riverbed materials likely to influence the hyporheic zone have been mapped out. This data along with auger holes and an electrical resistivity study on the river bank have contributed to characterising the site.

The hyporheic zone, which includes the zone for mixing and attenuation, has been shown to vary considerably across the small site, ranging from 0.2m to 0.3m.

Freeze coring was used to collect riverbed materials for characterising the site and for use in obtaining hydraulic conductivity values. The freeze coring technique was found to be effective, particularly compared to driven in cores used by previous studies on the River Tame.

The riverbed material was assessed by a variety of methods to produce hydraulic conductivity values. These included grain size distribution methods, and the constant head permeameter test of disturbed material, repacked into a core. These methods were discussed over their limitations and potential inaccuracies. The repacking of material, and subsequent hydraulic conductivity measurements provided from conducting a constant head permeameter test, was deemed to produce the best results.

Hydraulic conductivity data was compared to the various geologic type materials collected. The gravel layer present towards the downstream end of the site picked up at the +5m and +23m transects was found to generally have a higher hydraulic conductivity despite it being poorly sorted. Despite the profiles and results presented in this project being of a small

number of different materials, there is considerable heterogeneity at the site. The data and information provided from the various methods used only allow for a limited heterogeneity to be considered. Whether increased heterogeneity consideration for this study would make much difference in terms of the interpretation of the relationship between hydraulic controls and chemical profiles can be speculated.

However, despite uncertainties with the hydraulic conductivity data and heterogeneity at the site, the higher hydraulic conductivity of the downstream section along with the topography differences was adjudged to cause the nitrate and chloride profiles to become unvarying. The more homogeneous sand produced much more expected chloride and nitrate profiles with a decreasing and increasing concentration with depth respectively through the hyporheic zone.

8.2 Further Work

There is still a lot of potential for further work. Ideally given more time the project could be taken forward, especially in terms of modelling the results and data that have been collected with this study.

The use of modelling to assess mixing within the riverbed sediments for the various sets of piezometers may be advantageous. For the mixing model chloride and nitrate must be assumed to be conservative. However, within the River Tame Hyporheic Zone SWITCH Test Site there is the potential for nitrification taking place. Therefore the assumption of nitrate being conservative would not be valid.

Had more time been available further assessment as to the extent of the gravel would ideally have been undertaken, with the use of a further electrical resistivity study. Crook et al. (2008)

successfully carried out an electrical resistivity study of the streambed structure and materials. The further assessment of the gravel layer by use of an electrical resistivity survey would have included the depth and horizontal extent. The use of the electrical resistivity survey would also likely confirm the depth at which the homogenous sand layer could be found. The +23m transect freeze coring and hand augering found no evidence of the homogeneous weathered Wildmoor Sandstone Formation that was considerably present for the rest of the site.

Chapter 9 Reference List

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APPENDIX

Appendix files available on CD.