

**Nuclear Sciences & Technology Services**

**SCLS Phase 1 –  
Sellafield Groundwater  
Conceptual Model**



**Nuclear Sciences & Technology Services**

# **SCLS Groundwater Conceptual Model**

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**KEYWORDS:**

**Sellafield; SCLS; contaminated land; hydrogeology; groundwater conceptual model.**

## EXECUTIVE SUMMARY

A groundwater conceptual model is presented for the Sellafield Contaminated Land Study. This updated conceptualisation is based on previous conceptual models and recently acquired data in Phase I of the SCLS only. This conceptual model has been developed by the Site Characterisation task of the SCLS for use by the Continuum Modelling task. This document does not represent a source of all raw data collected during Phase I. Where possible, references have been made to other existing reports where more detailed descriptions and illustrations can be found.

Hydrogeological domains in the Sellafield area were proposed by McMillan et al. (2000) to facilitate the derivation of parameters for a regional scale groundwater model. Direct correlation of these domains with the local Quaternary stratigraphy identified at the Sellafield site has not been possible. This is due to the regional scale of the domains. However, identification of domains present on the Sellafield site has been attempted on the basis of the influence of deposits on migration pathways.

Brennan (2002) developed a hydrostratigraphic conceptual model for the Sellafield site. However, no conceptual model for contaminant transport in the drift and sandstone was presented.

The 2004 groundwater conceptual model provides a summary of parameters typically required for flow and transport modelling. The model also provides a brief description of contaminant distribution and contaminant transport mechanisms. Further work is required to develop the conceptual model and to reduce sources of uncertainty related to the water balance, the distribution of contaminants in the sandstone, retardation properties of the sandstone and detailed characteristics of the shallow groundwater in the Separation Area.

## **VERIFICATION STATEMENT**

This document has been verified and is fit for purpose. An auditable record has been made of the verification process. The scope of the verification was to confirm that : -

- The scope is accurate and represents the customer requirements
- The constraints are valid
- The assumptions are reasonable
- The document demonstrates that the project is using the latest company approved data
- The document is internally self consistent

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## 1. Introduction

### 1.1. Background

The overall objective of the Sellafield Contaminated Land Study (SCLS) is to produce an Integrated Contaminated Land Management Strategy (ICLMS) for the Sellafield site. The purpose of this is to allow BNFL to produce a strategy for each contaminated land source area that provides a recommended way forward for the management of the contaminated land. Options may include recommending a preferred remediation strategy or proposing a passive monitoring programme. It is not the role of the SCLS to implement the options only to provide sufficient information to inform decision makers within the company.

The SCLS follows on from a five-year programme known as the Sellafield Site Management Project (SSMP). The aim of this project was to determine if the company's reference strategy and estimate of the associated costs for eventual site closure were realistic and accurate. Part of this evaluation involved considering the company's contaminated land liabilities, in terms of estimating the inventory, investigating contaminated land at Sellafield and providing an assessment of the consequential financial liability. The SSMP did not specifically involve the collection of any new data relating to contaminated land. Hence, the position at the completion of the SSMP was derived solely from the available existing data. Consequently, during the assessment of the contaminated land, limitations were recognised with the available data and a number of recommendations for further data acquisition were made.

The SCLS consists of a number of work packages (Figure 1). The site characterisation work package is specifically charged with acquiring high quality, site-specific, geo-scientific data to allow the development of the conceptual and numerical models that will underpin the ICLMS at Sellafield. This requirement for further data acquisition principally follows on from the recommendations made by the SSMP.

The SCLS has been divided into two phases of work. Phase 1 commenced in 2002 and the second is due to commence in 2004. As a result of this phasing the acquisition of geo-scientific data by the SCLS was split. The first phase of site investigation commenced in the summer of 2002 and the programme is due to be completed in March 2004. The purpose of this phase was to collect data outside the Separation area. The investigation is principally located on-site although some data are also being acquired off-site. The second phase of site investigation (Phase 2) is programmed to commence in 2004 and this will be focussed towards data acquisition within the Separation area.

### 1.2. Hydrogeological Objectives

The hydrogeological objectives of the SCLS are summarised below.

- Characterisation of the site (primarily through the use of boreholes but also using other methods) to enable the construction of conceptual and numerical models of water

movement and contaminant transport. Information also needs to be collected and interpreted to support the calibration and validation of the numerical models.

- Investigation of the Sellafield site to identify and characterise subsurface contamination of solids and liquids.
- Identification and characterisation (in terms of quantity and quality) of groundwater entering the site.
- Identification and characterisation (in terms of quantity and quality) of groundwater leaving the site.
- Monitoring groundwater conditions to identify the movement of contaminants (plume development) towards the site perimeter.

### *1.3. Purpose of this document*

The purpose of this document is to present a groundwater conceptual model that defines the processes occurring within the system on a site-wide scale. This updated conceptualisation is based on previous conceptual models and recently acquired data in Phase I of the SCLS only. This conceptual model has been developed by the Site Characterisation task of the SCLS for use by the Continuum Modelling task. This document does not represent a source of all raw data collected during Phase I. Where possible, references have been made to other existing reports where more detailed descriptions and illustrations can be found.

### *1.4. Methodology*

This groundwater conceptual model has been developed in accordance with the Environment Agency's recent guidance on good practice in the development of conceptual models for contaminant fate and transport (Environment Agency, 2001). Where possible, the essential features of the real-world system have been captured and described in a simplified manner.

## 2. Previous investigations and conceptual models

The first hydrogeological conceptual model was developed by Holmes and Hall (1980). This model presented an aquifer system consisting of sandstone overlain by drift deposits. This main aquifer is divided into lower and upper components in certain areas of the site where silty sand and clay deposits are present. A buried valley was noted under the Separation Area running south-west across the site. However, there were insufficient data to provide a detailed description of the stratigraphy and provenance of the drift deposits. Groundwater elevations indicated that the flow direction in the drift was south-westwards towards the coast. Two groundwater mounds were observed that modify this hydraulic pattern, one within the Separation Area and the other in the vicinity of the B241 tank complex (Figure 2). A perched water system was suggested to be present due to clay bodies with limited areal extent. Homes and Hall (1980) identified groundwater discharge locations on the beach where significant levels of nitrate were detected. Tritium was also detected in the fresh water at this location.

Further work was undertaken by Stuart (1984) at the Sellafield site with a focus on the processes controlling interaction between the River Calder and the drift. Stuart (1984) concluded that water levels in the River Calder are generally higher than the adjacent groundwater levels in the upstream reaches of the river suggesting that the river recharges the groundwater at these locations. Stuart (1984) also suggested that perched water may discharge into the river at these locations.

Sears (1995) presented a similar conceptual model as Holmes and Hall (1980) for recharge to the river around the upstream reach of the River Calder. Sears (1995) constructed a plan of groundwater elevations in the deeper drift and observed a lowering of the hydraulic head in the “regional drift” aquifer under the Separation Area within the general vicinity of the buried valley. Sears (1995) noted increased hydraulic conductivity data in this area and suggested that groundwater was locally flowing to the west along the axis of the buried valley.

Wagstaff (1997) prepared a conceptualisation of Sellafield hydrogeology. The conceptual model presented suggested that the River Calder recharges the drift aquifer on-site. Wagstaff (1997) suggested that the River Ehen appears to receive groundwater as baseflow. During high tide conditions, bank storage conditions are created by surface water moving into the river bank. Bank storage is later released back into the river at low tide conditions. This mechanism contributes to river recharge.

Brennan (2002) presented a hydrostratigraphic interpretation of the hydrogeology at Sellafield. The hydrostratigraphic units were defined from the geological formations, hydraulic conductivity data, water strike and piezometric data. The definition of the hydrostratigraphic units revealed similar patterns in groundwater within each of the units over time. Perched groundwater within made ground and on shallow clay lenses within the drift was recognised. Contoured groundwater level plots based upon the identified groundwater patterns indicated the existence of an upper and a lower groundwater system. The contour plots showed that the upper groundwater unit is separate from the lower

groundwater beneath the Separation Area, but merges with the lower groundwater unit further down hydraulic gradient to the south-west.

### 3. Hydrogeologic setting

#### 3.1. Solid Geology

The Sellafield site and the local vicinity are underlain by strata of the Sherwood Sandstone Group (SSG) of Triassic age. Investigations performed by Nirex (1997b) have indicated that the SSG comprises two formations in the vicinity of Sellafield, the Calder Sandstone and the Ormskirk Sandstone (Figure 3). The Ormskirk formation overlies the Calder formation. The St. Bees Sandstone is located north of the site at greater depths than the Calder and Ormskirk formations.

These sandstone formations are of a predominantly aeolian origin and are reddish brown in colour. The sandstone that is at or near the surface has been subjected to substantial weathering. The effects of weathering decrease with depth and the sandstone becomes more integral in composition. Specific features such as clay/mudstone bands, bedding planes, fractures and fissures become increasingly evident with depth. The sandstone formations dip towards the south-west at an angle of approximately 23°.

The strata of the SSG beneath the Sellafield regional area ranges in thickness between 650m and 1150m, averaging at about 800m thickness (Nirex, 1993a).

#### 3.2. Quaternary deposits

The drift overlies the Sandstone at Sellafield. Cooper et al. (1999) have developed an events based lithostratigraphy which sub-divides the drift into four geological formations. Cooper et al. (1999) linked these formations to the established stratigraphy of west Cumbria (Akhurst et al. 1997) (Table 1). These formations are briefly summarised below.

**Lower Till Formation (LTF).** This formation is a till comprising clayey sand or sandy clay with numerous gravel and cobbles. It is confined to the flanks of the Buried Ehen Valley to the west of site and has very limited extent at Sellafield.

**Glacio-Fluvial Formation (GFF).** This formation overlies the LTF or lies directly on the Sandstone where the LTF is absent. It represents a glacial outwash sequence comprising gravels, sands and gravels and sands with occasional deposits of silts and clays. It shows a high degree of lateral and vertical variation.

**Oscillation Till Formation (OTF).** This formation overlies the GFF or lies directly on the Sandstone where the GFF is absent. It is present across most of the Sellafield Site. It shows a high degree of lateral and vertical variation. The formation contains two tills, referred to as the **Red Clayey Diamicton (RCD)** and the **Brown Clayey Diamicton (BCD)** by Cooper et al. (1999) both of which comprise stiff clays. The tills are separated by coarser granular deposits, which represent pro-glacial outwash and lacustrine deposits. A zone of possible glacio-tectonism has been identified within this formation.

**Post Glacial Formation (PGF).** This formation overlies the OTF and comprises fluvial, coastal and dune (wind blown) deposits. It occurs in a number of localised areas on the Sellafield and Calder Sites.

**Made Ground.** Made Ground is present across most of the Sellafield Site with a thickness that varies from 0.10 m to more than 5.00 m. In built-up areas of the site, it is common to encounter tarmac, limestone and concrete fragments within the made ground. In areas that have been backfilled, timber, bricks and concrete fragments are commonly encountered.

**Table 1 Drift Formations and Regional Quaternary Events (after Cooper et al. 1999)**

Stage / sub-stage	Events, Climato-stratigraphy	Key Events (Recognised in west Cumbria)	Study area Quaternary Formations
Flandrian 10 000 years BP to Present			
Late Devensian 26 000 – 10 000 years BP	Loch Lomond Stadial 11 000 – 10 000 years BP	Cold Period (Permafrost and corrie glacier expansion.)	PGF
	Windermere Interstadial 13 000 – 11 000 years BP		
	Dimlington Stadial 26 000 – 13 000 years BP	Scottish Readvance 14 000 years BP Gosforth Oscillation 16 000 years BP Main Late Devensian Glaciation 25 000 – 22 000 years BP	OTF (BCD?) (RCD?) GTF LTF
Mid-early Devensian 122 000 – 26 000 years BP	Interstadial Stadial		Not present
Ipswichian 128 000 – 122 000 years BP	Interglacial		Not present
Wolstonian 195 000 – 128 000 years BP	Stadial		Not present

### 3.3. *Regional Hydrology*

Sellafield is located within the surface water catchments of the rivers Calder and Ehen (Figure 5). The River Calder catchment has a total area of 55.5 km<sup>2</sup> which includes the Newmill Beck catchment. The River Ehen catchment has a total area of 156.6 km<sup>2</sup> (ESI, 2003).

The site is at the base of the River Calder catchment and covers an area of approximately 3.16 km<sup>2</sup>. The site slopes gently from the inland boundary towards the coast with a decrease in ground elevation from 40m AOD to 8m AOD.

An analysis of seasonal river flow hydrographs for the Rivers Ehen and Calder was performed by ESI (2003). Relatively rapid response to rainfall events was observed due to the steep topography and rapid surface runoff in the catchment headwaters. Consistent flow to the river channel from groundwater was observed throughout the year. Entec (1996a) reported that the baseflow indices increased between catchments as a function of the proportion of sandstone within that catchment.

The River Calder flows through the site between the Calder and Windscale sites in a south-south-westerly direction. The River Ehen flows in a south-south-easterly direction along the south-western site boundary.

### 3.4. *Sellafield regional hydrogeology*

The two geological units of interest that have been classified by the Environment Agency as aquifers in this region are the drift and sandstone. The deeper formations that exist in this area are beyond the scope of this report. The former has been classified as a minor aquifer and the latter as a major aquifer. Numerous licensed groundwater abstractions are located in the region and are summarised in detail in ESI (2003).

Nirex (Entec, 1996b) developed a groundwater flow model of the sandstone from just south of Egremont in the north-west (approximate NGR 301000 511000) to Muncaster Fell in the south-east (approximate NGR 309000 497000), extending inland as far as the contact between the Sherwood Sandstone and the (Borrowdale Volcanic Group) BVG at the Lake District Boundary Fault Zone and off-shore into the Irish Sea. It was reported that the model successfully reproduced observations of major river base flows in the model area and groundwater levels with reasonable accuracy. Modelled groundwater piezometric levels for the area surrounding the Sellafield site indicated that the regional groundwater flow direction is towards the south-west (Nirex, 1997b). Recharge occurs through the drift and groundwater flows towards the Irish Sea.

The model suggests a steeper hydraulic gradient exists inland to the north of the Sellafield Site in accordance with the slope of the ground surface. In this part of the model, the heads in the aquifer are higher than the heads in the River Calder, which indicates that some groundwater discharge into the river may occur, depending on the permeability of the river bed material.

In the coastal area, the model indicates that the hydraulic gradient decreases off in the vicinity of the Sellafield Site. In this area, the simulated contours do not bend as they cross the River Calder indicating that either the river level and groundwater level are similar or that the River is disconnected from the groundwater system.

The coastal discharge point of groundwater is largely defined by the location of the saline interface. This has been extensively modelled by Nirex (Heathcote et al., 1996). This work showed that the saline interface extends offshore about 500m from the coast, implying that most groundwater discharge will occur within that distance.

#### *3.4.1. The hydrogeology of the sandstone*

The Sherwood Sandstone Group (SSG) comprises three formations in the vicinity of Sellafield; the mainly fluvial St. Bees Sandstone Formation at the base, the aeolian Calder Sandstone Formation and the aeolian Ormskirk Sandstone Formation. The latter two formations have been observed at the Sellafield Site and are illustrated in Figure 3.

The sandstone is characterised by fissures and fractures or joints that play a significant role in groundwater flow. The layered nature of the sandstone aquifer as a whole contributes to the heterogeneity of groundwater flow characteristics. This heterogeneity has been observed both on a small scale as well as on the large scale between formations (Allen et al., 1997).

Recharge generally occurs in the east and flows through the sandstone to discharge in the west into streams, rivers and the Irish Sea. The St. Bees Sandstone Formation exhibits tidal influence for some distance inland (Allen et al., 1997).

Groundwater flow is subhorizontal when considered over a regional scale due to the low vertical permeability of the St. Bees Sandstone Formation. At locations that are distant from the recharge areas, upward hydraulic gradients have been observed within the sandstones (Nirex, 1993b). Groundwater flow occurs primarily in fractures.

The regional detail of interaction between the drift deposits overlying the sandstone is not well-documented. However, local studies have demonstrated that low permeability deposits such as Lodgement Till are present in depressions in the sandstone surface and may exert some control on vertical flow (BNFL, 1997; Nirex, 1997b).

#### *3.4.2. The hydrogeology of the drift*

The hydrogeology of the Quaternary sediments at Sellafield has been studied in detail by Nirex. A total of seven hydrogeological domains were identified by McMillan et al. (2000) on the basis of geological domains.

Sellafield lies within a number of hydrogeological domains including: Alluvial Flood Plain Deposits, Multi Till Lacustrine, Till and Clay, Buried Channel and Bedrock at or near surface. A description of these domains is provided below.

**Alluvial Domain (Alluvial Floodplain and Estuarine Deposits).** This domain shares the same footprint as the Alluvium (silt, sand and gravel) and the River Terrace Deposits (sand

and gravel) shown on the 1:50 000 geological map of the area. McMillan et al. (2000) divide this domain into two sub-domains, the Alluvial Floodplain and the Estuarine deposits. The majority of the Sellafield Site shown on the map is covered by coarse-grained alluvial deposits, except for a small area at the mouth of the River Calder. However, much of this material is composed on made ground due to the development of the site since 1945.

McMillan et al. (2000) state that the Alluvial hydrogeological domain is recharged by leakage from the rivers Calder and Ehen and by rainfall. The Alluvial domain is generally underlain by the Multi Till Lacustrine hydrogeological domain. As this latter domain is discontinuous, McMillan et al. (2000) state that, in places, the Alluvial hydrogeological domain may be in hydraulic contact with underlying sequences.

**Multi Till Lacustrine Domain.** This hydrogeological domain is characteristic of the Glacially Over-Ridden geological terrain and consists of an alternating succession of inter-bedded diamicton and lacustrine sand and silts with gravel layers. The thickest successions exceed 50m in thickness. Locally, coarser grained, very heterogeneous sediments with intercalations of gravel and diamictons are associated with the Gosforth Oscillation. The profile consists of interlayered aquitards (diamictons) and sand and gravel aquifers. The presence of peat within this domain supports the idea that the upper till unit is poorly permeable. However, peat deposits have not been identified at the Sellafield site. It is anticipated that the overlying sands and gravels will locally perch water on the upper till. Within the profile, in the coarser lacustrine sediments, flow will be predominantly horizontal, flow between them possibly occurring where the diamictons are thin or laterally discontinuous, and perched water tables occurring on more continuous layers of till.

**Buried Channel Domain.** This domain comprises buried valleys or channels, infilled with generally coarse-grained meltwater deposits and concealed beneath the products of later ice readvances. These concealed valleys and their infill are believed to exercise a major control on groundwater movement. The deposits that constitute this domain are not present at the surface at the Sellafield site.

One buried channel has been identified at the Sellafield Site referred to herein as the Ehen buried channel. This channel has a north-south trend in the area west of the site. A branch of this main channel extends to the east within the site boundaries and beneath the Separation Area (Figure 2).

**Till and Clay Domain.** The southern and eastern parts of the Sellafield Site are covered by this hydrogeological domain. This domain is characterised by profiles consisting mostly of till and clay with variable amounts of silt and very fine sand. It extends on either side of the buried channel. Locally the upper unit of sandy and clayey silt is penetrated by closely spaced sub-vertical to vertical fissures. Pebbly, silty, sandy diamicton has been observed to occur as folded and contorted shears cutting through the fissures. Leakage through these sediments is expected to be small and the hydrogeological domain probably behaves as an aquitard with limited flow in the vertical direction along fissures.

McMillan et al. (2000) report that Sellafield is typical of hydrogeological conditions in the area, with the Drift deposits providing little impediment to recharge to the underlying sandstone, except in localised areas where downward movement of water is impeded by clayey material.

#### 3.4.3. Hydrostratigraphy of the Sellafield Site

The sandstone and drift aquifers have been divided into seven hydrostratigraphic units by Brennan (2002) based on analysis of the available lithological, hydraulic conductivity, groundwater hydrograph, vertical head gradients and water strike data collected during drilling. The seven hydrostratigraphic units and their relationship to lithological units and the two aquifers are displayed in Table 2.

**Table 2. Relationship between aquifers, hydrostratigraphic units and lithological units at the Sellafield Site (Brennan, 2002)**

<b>Aquifer</b>	<b>Hydrostratigraphic Unit</b>	<b>Lithological Unit</b>
Drift aquifer	Made Ground Perched Unit	Made Ground upper Post Glacial Formation and Oscillation Till Formation
	Post Glacial Formation Unit (PGF)	Post Glacial Formation
	Upper Oscillation Till Unit (OTF)	Oscillation Till Formation above Brown clayey diamicton/Red clayey diamicton
	Clayey Diamictons Unit (CDU)	Brown clayey diamicton and Red clayey diamicton
	Lower Oscillation Till Unit (LOU)	Oscillation Till Formation below Brown clayey diamicton/Red clayey diamicton
	Glacio-Fluvial Unit (GFU)	Glacio-Fluvial Formation, Oscillation Till Formation and Lower Till Formation
Sandstone aquifer	Sherwood Sandstone	Bedrock

The concept of hydrogeological domains has been adopted for the approach to the development of the Sellafield groundwater conceptual model. The hydrostratigraphic units described above are not essential for the conceptual model. On the other hand, the domains approach describes the aquifer in terms of the influence of these deposits on large-scale groundwater flow. The hydrostratigraphic model has not been abandoned. However, to simplify the hydrogeological conceptual model, the relationship between the hydrostratigraphic units and the hydrogeologic domains has been examined. A coarse correlation between the units and the domains has been developed and is presented in Table 3 and Figure 4 below.

**Table 3. Correlation between hydrogeological domains and hydrostratigraphy**

<b>Hydrogeologic Domains</b>	<b>Hydrostratigraphic Units</b>
Alluvial deposits	Post Glacial Formation Unit (PGF) Upper Oscillation Till Unit (OTF)
Till and clay	Upper Oscillation Till Unit (OTF) Lower Oscillation Till Unit (LOU)
Buried channel	Glacio-Fluvial Unit (GFU)

## 4. Water Balance

A preliminary groundwater balance for the Sellafield Site was prepared by ESI (2003) and is presented in Table 4. Due to the considerable uncertainty associated with many aspects of this water balance, a range of values has been applied for many of the input parameters to evaluate a minimum and a maximum plausible value of flow. A most likely flow has then been estimated.

### 4.1. Inputs

Rainfall recharge has been calculated using the values of precipitation, potential evapotranspiration and actual evapotranspiration provided in ESI (2003). Rainfall recharge is greatest in grassed areas and the most likely estimate developed by ESI (2003) was  $5,430 \text{ m}^3 \text{ d}^{-1}$ .

Enhanced recharge from factory process losses were quantified by Sears (1995) over a portion of the Separation Area. This recharge was attributed to the presence of the oldest buildings and storage facilities on site in the Separation Area and it is considered that these are most likely to contribute to process losses. The most likely value for this recharge was estimated to be  $188 \text{ m}^3 \text{ d}^{-1}$ .

Steam emitted from the cooling towers will condense and contribute to rainfall over the surrounding areas, although no quantification of this process has been carried out. The contribution to rainfall across the area of the control rectangle is not known and the maximum bound and most likely values have been estimated as 1% of the maximum and most likely recharge.

Losses from the River Calder to groundwater were estimated and presented in ESI (2003). Details of the river bed sediments are not available and a large range of river bed hydraulic conductivity values has been applied. For the maximum flux, it is assumed that water can leak out of the river banks as well as the bed and flow laterally for some distance. The regional water table lies below the base of the river. The uncertainty in this component is high. Given the geological complexity in this area, as suggested by Stuart (1984), a more detailed conceptual understanding of these processes must be developed in order to reduce uncertainty in the water balance.

Upwards flows within the Sandstone at depth form an input to the water balance. Upwards flow in the Sandstone is relatively well constrained by environmental head data and vertical hydraulic conductivity data available from the Nirex programme. Table 4 shows that this flux is a small component of the overall site water balance.

### 4.2. Outputs

The most significant discharges of groundwater from the control rectangle are discharges across the south-western boundary to sea and to the River Calder. The contribution of

groundwater discharge to the River Calder has been calculated over a series of reaches defined by the average head difference between river stage and groundwater elevation. There is no river flow measurement at the downstream end of the site on the River Calder. This prevents flow comparison with the upstream station at Calder Hall and also calculations of flow loss or gain along the reaches adjacent to the site. In addition, the profile of river stage and river bottom for both rivers is poorly known and there is no information on the river bed material. The remaining groundwater outflow, abstraction, is a small component of the water balance.

Overall, there is large uncertainty in most of the significant water balance components. As a result the total input and output fluxes are poorly constrained.

**Table 4. Preliminary long-term average groundwater balance for the Sellafield Site**

<b>Input/Output</b>	<b>Minimum flow (m<sup>3</sup> d<sup>-1</sup>)</b>	<b>Most Likely (m<sup>3</sup> d<sup>-1</sup>)</b>	<b>Maximum flow (m<sup>3</sup> d<sup>-1</sup>)</b>	<b>Uncertainty/Comments</b>
<b>Inputs</b>				
Groundwater inflow	2852	3993	17111	Constrained by range in values from pumping tests.
Rainfall recharge	3701	5430	7415	Relatively well constrained. Recharge dominated by grassed areas
Process losses	0	188	188	Small component of total water balance
Condensate from cooling towers	0	54	74	Estimated value
Upwards flow in Sandstone	3	29	292	Minimum and maximum bounds defined as an order of magnitude higher and lower than most likely
Losses from River Calder	263	368	5519	Wide range of values, no validation data.
<b>Total Inputs</b>	<b>6819</b>	<b>10061</b>	<b>30599</b>	
<b>Outputs</b>				
Groundwater discharge to sea / sandspit	2694	5532	18119	Order of magnitude variation in Drift hydraulic conductivity give wide range in flux
Baseflow to River Calder	2683	4507	30599	Wide range of values, no validation data. Most likely value adjusted to balance inflows and outflows
Abstractions	37	37	37	Relatively well constrained
<b>Total Outputs</b>	<b>5413</b>	<b>10075</b>	<b>48754</b>	
<b>Balance (In-Out)</b>	<b>1406</b>	<b>-14</b>	<b>-18155</b>	
<b>Balance as a percentage of inflows</b>	<b>20.62%</b>	<b>0.13%</b>	<b>59.33%</b>	

The water balance in Table 4 shows the dominant groundwater components. Groundwater inflow across the north-east of the control rectangle is slightly lower than groundwater outflow to the south-west. This is because there is a net gain from rainfall recharge.

## 5. Unsaturated Zone Conceptual Model

The purpose of this section of the report is to provide a description of the unsaturated zone at the Sellafield site with a focus on the key contaminant source areas.

The unsaturated zone extends from the land surface to the water table. Areas of the unsaturated zone above the capillary fringe may temporarily be saturated due to surface ponding of water or because of the development of perched water tables above relatively low permeability soil layers. Unsaturated zone hydrology is different from saturated zone hydrology because of the presence of air in the pore space. The relative proportion of air and water in the pores can vary, and with it can vary the hydraulic properties of the porous media (Fetter, 1999). Fetter (1999) describes three types of preferential flowpaths in the unsaturated zone: short circuiting, fingering and funneling. The influence of unsaturated zone materials on preferential flowpaths at Sellafield is described below.

The unsaturated zone at the Sellafield site consists mainly of made ground and drift deposits of varying nature according to the location on-site. In the south-eastern part of the site adjacent to the River Calder, the unsaturated zone is characterised by Recent Deposits overlying Glacio-fluvial deposits. The unsaturated zone in northern areas of the Sellafield site comprises the shallow sandstone.

The following sub-sections cover the primary contaminant source areas at the Sellafield site.

### 5.1. *Unsaturated zone beneath the Separation Area*

The unsaturated zone beneath the Separation Area is characterised by a combination of made ground and OTF deposits comprising clayey sand and gravel with occasional thin layers of clay (maximum thickness of 2m). Perched water levels have been observed at several locations and have been correlated to these poorly permeable clay layers within the unsaturated zone.

Two groundwater mounds have been observed and recorded in the literature (Holmes and Hall, 1980). The OTF consists of up to 10m of very clayey gravels interspersed with firm to stiff sandy clays. Groundwater levels have been measured in the area underlying the Separation Area in the vicinity of borehole (BH) BH785 and are consistently elevated (up to 5m above the static water level in surrounding wells). Pumping test data interpretations from Holmes and Hall (1980) suggest that various silty sand lenses are in poor hydraulic continuity with each other and with the underlying more permeable GFF. The elevated groundwater levels are likely to be due to the less-permeable nature of the deposits underlying the Separation Area. Static water level readings have been recorded at a depth of approximately 9m bgl.

The influence of made ground deposits on unsaturated zone contaminant transport is described in Towler et al., (2004). Preferential pathways in the made ground deposits beneath the Magnox Silo base slab were attributed to the heterogeneity of the deposits. This

behaviour was described as fingering, which occurs when a uniformly infiltrating solute front is split into downward-reaching “fingers” due to instability caused by variations in the permeability of the made ground.

Radionuclide activities in the unsaturated zone resulting from the Magnox Silo leak were monitored with blind tubes. An analysis of the data was described in Towler (2004). The results of this study were used to describe vertical and horizontal movement of water from leaks in the silo and are summarised below.

- lateral migration of contamination within the unsaturated zone was driven by the leak;
- subsequent unsaturated zone contamination migration has generally been downwards, towards the water table;
- water table fluctuations enhance leaching from the unsaturated zone; and
- it is likely that unsaturated zone migration is currently being reduced by the concrete ground cover. If this were removed, or degraded, it is expected that the rate of unsaturated zone migration would increase.

### 5.2. *Hydrologic properties*

Laboratory testing of remoulded soil samples from the unsaturated zone at Sellafield has been performed as part of the SCLS Phase I investigation. Hydraulic conductivity values are available for constant head and falling head (triaxial cell) tests. These data have not been analysed and documented.

Site specific data to define the soil moisture characteristic curves for unsaturated deposits are not available for the Sellafield site. Therefore, generic characteristic curves have been used for groundwater modelling work at the Sellafield site (Bond, 2003b).

### 5.3. *Contamination in the unsaturated zone*

Unsaturated zone contamination in the Separation Area is primarily the result of leaks from buildings. Numerous leaks of radioactive liquors to ground are known to have occurred from several plant buildings, vaults and disposal trenches within and around the Separation area over the period of the last 40 to 50 years. The leaks that are considered to be most significant occurred from the Magnox Silo, the Caesium Extraction Plant, the Magnox Reprocessing Pump House, the Sludge Storage Tanks, the Burial Pits and the Medium Active Evaporation and Thermal Denitration Plant, although minor spills and leaks from other buildings, as well as pipelines, drains and the lagoon are likely to have contributed to the inventory of below-ground radioactivity. Soil sampling records from boreholes and other excavations undertaken during three decades of site engineering and construction work has demonstrated that radioactively contaminated ground exists beneath and, occasionally, outside of the Separation area. Intermittent monitoring of groundwater quality from several hundred wells, both temporary and permanent, installed throughout the site, has also demonstrated that radioactive contamination is present in the groundwater. Monitoring of

groundwater quality has also demonstrated that radioactive contamination has migrated towards the south-western site boundary, in accordance with the local groundwater flow direction.

#### *5.4. The influence of sub-surface engineering features on contaminant migration*

The influence of sub-surface engineered features on contaminant migration in the Separation Area at the Sellafield site has previously been described in Towler (2003). The drains and building foundations are located within the unsaturated zone. Preferential pathways, such as the gravel drain along the east wall of the Caesium Extraction Plant, were identified.

## 6. 2004 conceptual model for the Quaternary deposits

### 6.1. Approach

The characterisation of highly heterogeneous glacial deposits for the development of hydrogeological conceptual models has been performed by Fleming (1998) and Stanford & Ashley (1998), among others. Fleming (1998) identified the importance of facies variation in determining the relationships between deposits of contrasting hydraulic properties. The approach adopted by McMillan et al. (2000) also highlighted the role of laterally extensive deposits of low permeability.

Given the heterogeneous nature of the Quaternary deposits at Sellafield, the characterisation of groundwater flow within the Quaternary deposits has been developed using the above approach. The movement of groundwater within the Quaternary deposits is controlled by hydraulic conductivity, which is controlled by the sediment texture. In turn, the sediment texture is controlled by the environment of deposition. Direct correlation of the hydrogeological domains suggested by McMillan et al. (2000) with the Quaternary deposits identified at the Sellafield site has not been possible. However, where possible, the following section provides a description of the sediments in the hydrogeological domains and the primary geologic features in the subsurface at the Sellafield site that control groundwater flow.

Due to their thickness, lateral extent and heterogeneous nature, the GFF and OTF are considered the most hydrogeologically significant formations in the drift aquifer at the Sellafield site. Much attention has therefore been afforded to these deposits.

Frequent references are made in this report to 'p1' and 'p2' monitoring wells. Across the Sellafield site a number of monitoring wells have been installed at more than one depth using nested wells in a common borehole. The monitoring points have been assigned the suffix 'p1' for the deepest monitoring level, 'p2' for intermediate levels and 'p3' for the most shallow monitoring level (where applicable) at each location.

The existing groundwater monitoring wells at the Sellafield site are a miscellaneous collection of structures that have been installed for a variety of purposes at different times during the last 30 years. The original design and the current condition of these wells varies from good to poor and consequently the quality and value of the historical data derived from them is also variable. These wells have been reviewed and those of sufficient quality for inclusion in a groundwater monitoring network were identified (Firth & Cunningham, 2001). Brennan (2002) took the quality criteria into consideration while developing the hydrostratigraphic model described above in section 3. A complete description of the groundwater monitoring network at the Sellafield site is presented in Henderson and Hunter (2004).

## 6.2. *Buried Channel Domain*

A deep, steep sided trough feature was described by Cooper et al. (1999) towards the central area of the Sellafield site, directly beneath the northern half of the Separation Area. This feature is a well defined buried channel extending westwards across the site (Figure 2). The channel has a thickness of over 35m beneath the Separation Area on-site and thickens towards the west beyond the site boundary to a depth of approximately 55m. Hydraulic contact with the sandstone is assumed since water levels in the two units are nearly identical.

The deposits within the buried channel generally consist of gravels and sands with occasional deposits of silts and clays. Many of the coarser deposits are highly mixed, but broad fining upward sequences from gravels to sands have been noted. These deposits were defined as being part of the Glacio-Fluvial Formation (GFF) described in Brennan (2002) and represent a postglacial outwash sequence. In addition, extensive fine silty sand up to 30 m in thickness appear to have filled the sandstone channel towards the beach west of the site. Silty sands have also been proven to be extensive (up to 15 m thick) beneath the Separation Area.

## 6.3. *Till and Clay Domain and Multi-Till Lacustrine Domain*

The map presented by McMillan et al. (2002) suggests that the former domain is present in the southern and north-eastern parts of the site while the latter is only found in small areas in the south. It has not been possible to differentiate between these two domains at the Sellafield site.

The stratigraphic formation that is considered to be most significant to groundwater flow and therefore was considered to resemble the deposits within both of these hydrogeological domains is the OTF. The most extensive deposits are stiff clayey diamictons, which contain varying amounts of sand and silt as well as clasts ranging from fine gravels to boulders. These form a highly complex sequence of stiff clays, which were identified in Cooper et al. (1999). These deposits influence the distribution of groundwater head as described below.

## 6.4. *Alluvial Flood Plain Domain*

According to the map presented in McMillan et al. (2000), these deposits exist across the majority of the site and comprise primarily clean gravels, sands and gravels and sands, with occasional silts and soft clays. Local data collected at the Sellafield site indicate that these deposits have been removed and replaced by made ground material during the site's redevelopment. This hydrogeological domain has not been recognised at the site and is not considered important to the 2004 groundwater conceptual model.

## 6.5. *Glacio-tectonic deformation of the drift deposits*

Glacio-tectonic deformation occurs when either the compressional or extensional stresses transferred by an ice body exceed the strength of the material in front (proglacial) or below the ice (subglacial). This deformation can be brittle or ductile and is expressed in physical form as thrusts, folds and faults on a variety of scales.

Evidence of glacio-tectonic deformation of deposits has been discussed in Arthurton (1977), Wiggett and Eaton (1991), Richards (1992) and Nirex (1997c). Steep inclined beds and changes in inclination were observed by Arthurton (1977) in or around the Separation Area and also to the south of the site. Various features underlying the Separation Area such as single and multiple clay layers, clay-free areas and duplication of strata were attributed to thrust faulting.

## *6.6. Distribution and significance of low-permeability bodies*

### *6.6.1. Site-wide*

The Sellafield drift aquifer system contains a variety of low-permeability units that are of great importance to the hydraulic behaviour of the system. Cooper et al. (1999) provide a detailed description of the composition and depositional nature of the drift formations. The most extensive formation with the most heterogeneous and complex nature at the Sellafield site is the Oscillation Till Formation (OTF). The formation consists of clays, sands, gravels and silts. The most extensive deposits are stiff clayey diamictons containing varying amounts of sand and silt as well as clasts ranging from fine gravel to boulders.

The influence of these deposits on groundwater flow was demonstrated by Holmes and Hall (1980). Pumping tests indicated that the silty sand lenses (identified as OTF deposits by Cooper et al., 1999) are in poor hydraulic continuity with each other and with the lower part of the aquifer in the north-eastern corner of the Separation Area. Holmes and Hall (1980) identified upper and lower units in this part of the site. Recent piezometric data to demonstrate piezometric head differences in this area of the site are not available.

Figure 6 also illustrates the presence of elevated head values in the upper drift immediately to the south of the Separation Area and extending south towards the site boundary. Lithologic data obtained during Phase I of the SCLS indicate the presence of stiff clay, fine sands and silty deposits. The two units eventually merge due to the absence of low permeability deposits. This upper unit was observed in all investigations performed at the Sellafield site.

Pronounced head differences to suggest the presence of upper and lower units within the drift deposits in the area west of the site were not observed. This may be due to a greater degree of hydraulic continuity between the deposits in this area. The drift aquifer in this area comprises deposits from the Buried Channel Domain (primarily GFF) characterised by the absence of clay and the presence of relatively thick layers of sand and sand and gravel (up to 50m).

### *6.6.2. Separation Area*

Two groundwater mounds were observed within the Separation Area by Holmes and Hall (1980). Brennan (2002) was not able to differentiate between an upper unit and isolated perched water bodies in the Separation Area.

The presence of perched water within the made ground and shallow drift deposits is likely, given the presence of low-permeability deposits in the unsaturated zone. Interpretation of the lithologic and groundwater elevation data presented in Brennan (2002) indicates that an upper unit is present within the OTF deposits at several locations within the Separation Area. There are no recent groundwater elevation data from the Phase I investigation to clarify this for the 2004 conceptual model.

The characteristics of the upper groundwater unit within the Separation Area are directly relevant to contaminant migration on a local scale only. Groundwater contamination in the north-eastern corner of the Separation Area is localised (described in Henderson & Hunter (2004) and briefly in section 8 of this report). Elevated groundwater levels were observed during previous investigations in this area. The groundwater elevation data obtained during Phase I of the SCLS and presented in this report do not indicate that groundwater flows towards the River Calder to the east. However, piezometric and groundwater quality data between the Separation Area and the river are required to clarify these observations.

### *6.7. Aquifer conditions*

Holmes & Hall (1980) suggested that the Quaternary deposits comprise a main aquifer observed to be in hydraulic continuity with the underlying sandstone formations. Holmes & Hall (1980) also suggested that the main Quaternary aquifer was unconfined at most locations. This main aquifer is divided into lower and upper components (referred to as units in this document) in certain areas of the site where silty sand and clay deposits are present. Recent piezometric data collected in December 2003 for Phase I also indicate the presence of upper and lower units within the drift aquifer.

Perched water bodies were also observed by Holmes & Hall (1980) at several locations where low-permeability clay horizons exist. However, it is important to differentiate in this conceptual model between a discontinuous perched water table and the surface of the upper unit within the drift aquifer. The upper unit within the drift aquifer is laterally extensive across the Sellafield site, is not temporary (as may occur in perched water tables) and contributes to the lateral migration of contaminants.

### *6.8. Aquifer properties*

#### *6.8.1. Hydraulic conductivity*

Hydraulic property data for the drift deposits at the Sellafield site are available from pumping tests, injection tests and slug tests. Based on these data, a range of hydraulic conductivity for the drift deposits at the Sellafield site of between 1 and 90 m/d is considered representative of the measured range. This wide range of hydraulic conductivity, spanning nearly two orders of magnitude, reflects the highly heterogeneous nature of the drift deposits in this area.

Although limited data exist for the geology underlying the Separation Area, calculations of hydraulic conductivity in this area tend towards the higher ranging values.

The values of drift hydraulic conductivity vary with no readily distinguishable pattern. An area in the central-southern part of the site shows consistently high values of hydraulic conductivity and may be attributable to the high permeability sediments associated with the original course of the River Calder. The hydraulic properties of the drift deposits beneath the Separation Area are poorly sampled and therefore not well constrained.

A statistical analysis of hydraulic conductivity data was performed by Brennan (2002) and is presented in Table 5 below.

**Table 5. Statistical analysis of hydraulic conductivity values (m/d)**

<b>Formation</b>	<b>PGF</b>	<b>OTF</b>	<b>GFF</b>	<b>LTF</b>
Max	8	87	10	6.85
Min	0.6	0.015	0.05	0.29
Number of values	10	28	6	5
Mean	2.91	17.85	2.98	1.78
Geometric Mean	1.85	2.7	0.72	0.81

The above data suggest that the OTF is characterised by the greatest range of hydraulic conductivity values. The highest values are for the sand and gravel deposits within the OTF. This broad range of values reflects the complex deposits that comprise clays, silts, sand and gravel.

However, the data for the GFF in Table 3 are not representative of the GFF due to the small number of values available. The GFF is characterised by thick deposits (up to 50m) of generally coarse-grained deposits (cobbles, sandy gravel, sand and gravel and silty sand) representing a de-glacial sequence from to glacio-fluvial to glacial outwash to fluvial. Greater values for the hydraulic conductivity of these deposits are anticipated given their grain size and texture. The permeable nature of these deposits is indicated by the localised decrease in groundwater elevations across the buried channel on-site.

Recent data from variable-head tests performed during the Phase I SCLS drilling work have not been interpreted. The results from these tests should be added to the above data set.

#### 6.8.2. Porosity

Values in the range of 15% - 20% have been used in the past for total porosity of the drift deposits at Sellafield (Wagstaff, 1997). Towler (2003) discusses appropriate porosity values for different rock types described in Towler & Bond (2003). These are detailed in Table 6.

**Table 6. Rock porosity values**

<b>Lithology</b>	<b>Total porosity</b>	<b>Effective porosity</b>
<b>Sandy drift</b>	0.3	0.2
<b>Clayey drift</b>	0.5	0.1
<b>Sandstone</b>	0.15	0.085

### 6.8.3. *Storativity*

Values for storativity for the drift aquifer were presented in Holmes and Hall (1980). The values range from 0.00007 to 0.28.

### 6.8.4. *Dispersion and diffusion*

Solute transport in heterogeneous glacial and fluvial deposits occurs primarily by advection in the high-permeability zones, but primarily by molecular diffusion in the low-permeability zones (Zheng & Bennett, 2002). Within the clays and silts, velocities may be so low that molecular diffusion dominates solute transport mechanisms, while advection may dominate in the sand or gravel.

In systems of this sort, diffusion of solute into the low-permeability zones reduces the mass of solute moving advectively in the high-permeability intervals. The result is a more uniform solute distribution and a slower solute advance than would be expected with only advective movement in the high-permeability features. This process is commonly referred to as advective-diffusive transport in heterogeneous unconsolidated deposits (e.g., Gillham and Cherry, 1982).

### 6.8.5. *Hydraulic gradient*

A hydraulic gradient of 0.02 within the lower drift and sandstone aquifer (contoured in Figure 6) was calculated for the north-eastern part of the site. The distribution of groundwater contours in the central part of the site reflects a smaller hydraulic gradient estimated to be approximately 0.005. Groundwater abstraction may exert an influence on the gradient in the eastern part of the Separation Area. However, current groundwater elevation data in the Separation Area are not available.

## 6.9. *Groundwater abstractions*

Groundwater is abstracted in the eastern part of the Separation Area (Figure 2) for building basement de-watering purposes. The boreholes all pump at different rates when used. Borehole 768 pumps continuously at 2m<sup>3</sup>/hr and discharges to the Low Active Drain (which in turn discharges to the Sea Tanks). Boreholes 1 and 2 also pump to the Low Active Drain. Borehole 1 pumps on automatic mode, which is triggered by the level in the borehole, at 10 m<sup>3</sup>/hr. Borehole 2 does not pump as frequently, but also pumps at 10m<sup>3</sup>/hr. Boreholes 764, 765, 766, 768 & B212 are only pumped for sampling purposes.

Based on daily abstraction returns between 1979 to 1983, Sears (1995) estimated that approximately 36.5 m<sup>3</sup>/d is pumped from these de-watering wells.

## 6.10. *Seasonal variations in groundwater levels*

Local Sellafield groundwater levels have been monitored since 1989. Wagstaff (1997) noted that monitoring wells located in the northern area of the site demonstrated a greater range of

fluctuation than those located nearer the coast. Wagstaff (1997) also noted that groundwater level peaks occurred during the winter/spring months.

#### *6.10.1. Tidal fluctuations*

The influence of tidal loading on groundwater levels has been observed by Holmes and Hall (1980) at monitoring wells along the beach and the River Ehen (e.g. 701 - 703, 723, 725, 745) with variations of up to 0.3m.

#### *6.11. River Ehen interaction*

The conceptual model proposed by Wagstaff (1997) suggests that the local groundwater system is influenced by the tidal state of the River Ehen and is diurnally cyclic. The surface water level of the River Ehen rises above the local groundwater levels in the area of Sellafield Banks and the sandspit in response to the tidal state. Under these conditions, the river recharges the aquifer as bank storage. During low tide conditions, the surface water level in the river is lower than groundwater levels and groundwater is released from bank storage into the river. Deeper, regional groundwater at the base of the drift and sandstone will continue to flow beneath the river, even under high tide conditions.

#### *6.12. River Calder interaction*

Stuart (1984) concluded that, in the upstream reaches of the River Calder at Sellafield, water levels within the River Calder are generally higher than the adjacent groundwater levels, indicating that there is potential for river water to recharge the groundwater system. However, Stuart (1984) also discusses the possibility that perched water may discharge into the river in this area. Sears (1995) presents a similar conceptual model to Stuart (1984) for the same area of the River Calder. However, the profile of the River Calder used by Sears (1995) was based on a suspect data set.

The above description of River Calder interaction is consistent with the interpretation of river levels and groundwater levels presented in ESI (2003) for upper river reaches (north of northing 503500).

ESI (2003) suggest that the river gains flow from groundwater in the lower reaches of the river (south of northing 503500). However, no river flow measurement at the downstream end of the site on the River Calder is available. The profile of the river stage and base of the river is poorly described. The uncertainty in this component of the water balance is high.

#### *6.13. Groundwater flow*

The groundwater contours presented in Figure 7 indicate that the groundwater flow direction within the lower drift and sandstone aquifer is from north-east to south-west. A similar distribution of groundwater elevations was demonstrated by Brennan (2002) and ESI (2003). The regional hydraulic gradient becomes steeper towards the coast.

Intergranular flow is the primary groundwater flow mechanism in the drift deposits. Preferential flowpaths within the coarse sand and gravel strata are likely to influence groundwater migration within both the saturated upper and lower drift deposits.

#### *6.14. Recharge*

Estimates for both natural and artificial recharge were made by ESI (2003). Hydrologically effective rainfall values were calculated for the various land use types at the Sellafield Site. Estimates were also made for flow into groundwater from the River Calder. Factory process losses were also estimated as a source of recharge to groundwater.

Rainfall recharge forms the largest water input to the groundwater balance and is dominated by recharge to grassed areas.

#### *6.15. Flow system boundaries*

The natural physical boundaries of the Sellafield groundwater system are defined as follows:

- The upper boundary of the unconfined aquifer is the water table, which changes over time;
- The bottom model boundary is located in the sandstone at a depth of 200 m below the upper boundary (suggested by Nirex (1997e) where the hydraulic conductivity of the sandstone is significantly reduced;
- The Irish Sea to the south-west and down-hydraulic gradient; and
- Northern boundary defined by the faulted contact between the Sherwood Sandstone Group and the Borrowdale Volcanic Group (up-hydraulic gradient).

The model boundaries proposed for the first iteration of the site wide model constructed within phase 1 of the SCLS (Towler and Bond, 2003) agree with the physical boundaries listed above with the exception of the east and west model boundaries. These boundaries are orientated perpendicular to the general regional groundwater flow direction and are set as no flow boundaries. The model results indicate that flooding is particularly great in the eastern corner of the model (Gosforth village area) due to the flow direction being out of the model domain rather than parallel to the long axis of the model. Since this model boundary is a no flow boundary, groundwater is not able to leave the model domain, and substantial flooding occurs. This is a preliminary groundwater flow model and further work will be performed to refine the model.

## 7. 2004 conceptual model for the sandstone

### 7.1. Introduction

A recent description of the characteristics of groundwater flow in the sandstone aquifer is provided in Bond (2003a).

### 7.2. Aquifer conditions

The water table is usually above the base of the drift except in certain areas at the northern end of the site where the sandstone is unsaturated. The permeability of the drift is variable, but generally it does not effectively confine the Sherwood Sandstone Group aquifer (Allen *et al.*, 1997).

### 7.3. Groundwater flow

The matrix hydraulic properties of the various members of the Sherwood Sandstone Group have been well documented at numerous sites in the UK (Allen *et al.*, 1997) and some site specific data is available for the Calder and Ormskirk formations at the Sellafield site (Brennan, 2002), at the Drigg site (BNFL, 2002) and through previous Nirex investigations (e.g. Nirex, 1997b). It is therefore anticipated that hydraulic parameterisation of the sandstone matrix will be possible with a well-constrained degree of uncertainty due to geologic heterogeneity at various length scales.

Groundwater flow in the Calder Sandstone Formation is driven by recharge in areas of higher topography inland to the east (Nirex, 1993b). On a local scale groundwater flow occurs mainly in fractures. The spatial distribution of fracturing has been examined in detail in a number of locations (Nirex, 1997c; Allen *et al.*, 1997) and tends to follow a similar pattern. Large sub-horizontal fractures occurring parallel to or concurrent with bedding planes and have been observed to be in excess of 30 m in length at outcrop. Cross-cutting these large sub-horizontal fractures are typically 2 sets of sub-vertical joints/fractures, with mean strikes approximately at right angles to each other. These smaller fractures are significantly smaller, being in the order of 1-2 m in length and more closely spaced than the bedding fractures (Jeffcoat, 2001, Wealthall *et al.*, 2001).

Several features that have the potential to affect groundwater flow and hence groundwater contaminant migration were examined by Bond (2003a). Only the most basic of groundwater migration mechanisms *i.e.* the migration of groundwater through rock matrix, is certain to operate. There is a high degree of likelihood that open fractures will significantly contribute to groundwater migration at a local scale (10 s of metres), however there is not sufficient evidence to suggest that these networks definitely operate over the scale of 100 s to 1000 s of metres. The other mechanisms may be present in the system, but at the current level of understanding there is not enough data to support their inclusion or to parameterise the physical processes associated with them.

The importance and complexity of fracture flow over short distances in the Triassic sandstone was demonstrated by Streetly et al. (2002). Tracer tests performed at Haskayne in south Lancashire provided data to demonstrate the complexity of intergranular flow routes, and that different retardation factors can be associated with different pathways.

For both the drift and the sandstone, contaminant interaction with the saline interface is also expected. Final outflow is expected through the beach face into the sea or through the saline interface. Faults within the sandstone may form preferential flow paths along fault planes and/or may act as hydraulic boundaries to flow normal to the fault plane

#### 7.4. Hydraulic properties

##### 7.4.1. Hydraulic conductivity

A variety of laboratory and field measurements of hydraulic property data have been performed to characterise the Sandstone. Small scale hydraulic properties data (laboratory core analyses and results of field testing) are available for the Sherwood Sandstone from the Nirex Geosciences Database.

Pumping tests were performed by the Institute for Geological Sciences (IGS) and were reported in Homes and Hall (1980). The average hydraulic conductivity value from these data was calculated at 3.2 m/d. The lowest value of 0.4 m/d was recorded for borehole 704 drilled in the Ormskirk sandstone formation. The remaining data were recorded at locations drilled in the Calder sandstone formation and ranged from 1.5 m/d to 20 m/d.

In total, six constant head, nine falling head and two rising head tests were carried out within the Sandstone formation. These data were summarised in Brennan (2002) and a statistical summary of the results is given in ESI (2003) and reproduced below.

**Table 7. Statistical summary of hydraulic conductivity values ( $\text{m d}^{-1}$ ) of the Sandstone obtained from falling, rising and constant head tests**

Number of samples	17
Maximum Value	1.296
Minimum Value	0.069
Arithmetic Mean	0.573
Geometric Mean	0.436
Harmonic Mean	0.291

Entec (1996b) reports that results of pumping tests carried out in 1983/84 in the Calder Hall and Brow Top areas were re-analysed using radial flow modelling. These tests show that hydraulic conductivity is between 0.5 and 3 m/d. Regional groundwater flow modelling undertaken by Entec (1996b) used these data as an initial input. The final value used in the

model was 0.7 m/d. The modelled anisotropy ratio ( $K_h:K_v$ ) was in the range of 2 to 40, with the most probable average value of 20, reflecting the dominant role of bedding plane flows.

#### 7.4.2. *Storativity*

Storativity data obtained from pumping tests performed by Holmes and Hall (1980) were found to be between  $2 \times 10^{-3}$  and 0.28. No values have been reported in the literature for storativity of the Calder or Ormskirk sandstone formations.

Specific yield values have also been estimated from the pumping tests that were mentioned above. Of the 15 results given, four were very low (around 0.05%) which represents a storage coefficient similar to the values estimated in the same report for confined storage. If these low values are ignored, since the sandstone appears to be behaving as a confined aquifer for these tests, the average of the remaining 11 results is 8.5%. Experience has shown that often the specific yield determined from pumping tests is an underestimate and it is considered that the specific yield of the sandstone is likely to be between 10 and 15%.

#### 7.4.3. *Porosity*

The mean total porosity of the Calder and Ormskirk sandstones (Nirex, 1997b) were found to be approximately 20%. The mean total porosity of the St Bees Sandstone is lower at 12%. The effective porosity of the Sandstone is expected to be lower than the total porosity with values expected to be between 5 and 10%.

### 7.5. *Contaminant migration*

The following sections address contaminant transport within the sandstone aquifer. The objective of this section is to present a conceptual model for contaminant transport at the Sellafield site. Site-specific data for these aspects of contaminant transport are not available. Therefore, laboratory or field results from research performed on sandstones from other formations in north-west England have been presented.

#### 7.5.1. *Dispersion*

Diffusion of radionuclides in groundwater in porous rock acts to smooth concentration gradients by the mass transfer from regions of high concentration to regions of low concentration. Diffusion also permits the transfer of radionuclides across a region of porous medium under no flow conditions.

Dual porosity flow mechanisms were examined in laboratory scale experiments on Triassic sandstone samples from north-west England by Bashar (1997). These experiments demonstrated the role of mobile/immobile zones within the sandstones and their influence on solute transport.

### 7.5.2. *Ion exchange*

Ion exchange is a major process controlling natural and contaminated groundwater chemistry in the Permo-Triassic (P-T) sandstones of the UK. The sedimentary materials in P-T sandstones of north-west England (Gillespie, 1987) that are known to have a role in adsorption are clay minerals, organic matter and oxide or hydroxide content. Clay minerals include illite, kaolinite and smectite. Cation exchange capacity values and exchange constants for an ion exchange model of laboratory-scale samples of the Triassic sandstone were developed by El-Ghonemy (1998).

Technetium-99 is most commonly present in groundwater in the form of the pertechnetate ion and technetium dioxide. The high solubility of pertechnetate allows it to move quite rapidly in groundwater systems. The migration rate of pertechnetate is expected to be very close to the velocity of groundwater unless it is reduced to a less soluble form.

The cationic radionuclides Cs-137 and Sr-90 may be subjected to ion exchange and other processes that sorb the radionuclides onto mineral or organic surfaces in the sandstone. These radionuclides undergo cation exchange in a fashion similar to other exchangeable cations, such as  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  (Fetter, 1999).

Tritium substitutes readily for ordinary hydrogen in water, and thus becomes part of the hydrological cycle. Through sandy soils, migration of tritium takes place at the same velocity as groundwater. However, the migration of tritium in clay soils may be slower due to a small number of tritium atoms exchanging with ordinary hydrogen atoms in water molecules bound with the clay.

## 8. Source-pathway-receptor linkages

A more detailed description of the distribution of groundwater contamination at the Sellafield site is provided in Henderson and Hunter (2004). The following is a brief description of the sources, migration pathways and receptors.

### 8.1. Contamination sources

There are a number of known source buildings and structures at Sellafield that have contributed to the current inventory of radioactive contamination contained in both soils and groundwater beneath the site. In some cases the contamination has escaped to ground as a consequence of documented individual incidents or spills, while other sources may have been responsible for slow, prolonged, unmonitored leaks over a period of several years. The list of major contamination sources is described in various reports and includes significant buildings such as the Magnox Silo, the Caesium Extraction Plant, the Magnox Reprocessing Pump House, the Sludge Storage Tanks, the Burial Pits and the Medium Active Evaporation and Thermal Denitration Plant as well as the burial trenches.

In addition to these primary sources, there is a separate group of known smaller sources and also a further group of suspected and potential sources. Included amongst the latter are the South and Calder Landfills and a network of buried drains for 'active' fluids which can also act as contaminant migration pathways. All of the known, suspected and potential sources will be described in greater detail in a number of separate reports and databases to be produced by the SCLS Risk Assessment work package and will not be discussed further in this document.

### 8.2. Distribution of groundwater contamination

The distribution of contaminants in groundwater is illustrated in Figure 8. This figure illustrates contamination within groundwater detected in monitoring wells screened in the 0m to 10m AOD elevation only. Contamination detected at other elevations is discussed and illustrated in Henderson and Hunter (2004). This figure is included in this section to demonstrate the lateral extent of contamination and the contaminants detected.

The presence of Tc-99 in shallow groundwater is illustrated in Figure 8. The distribution of contaminants in the Quaternary deposits indicates migration within upper (detected by p2 wells) and lower (p1) units south-west of sources in the Separation Area. Tritium (H-3) contamination was also detected in upper units of the Quaternary deposits, although the impact to groundwater does not appear to be as extensive as that from Tc-99.

Localised areas within the Separation Area are impacted by caesium (Cs-137) and total beta from strontium-90.

Deeper contamination (Tc-99, H-3, total beta) was detected south-west of the Separation Area.

### 8.3. *Groundwater migration pathways*

The limited number of generic pathways depicted in the pre-SCLS conceptual model (Hunter and Crompton, 2002) have been refined during Phase 1 of the SCLS project into a larger set of specific model pathways with defined spatial extents. These individually numbered pathways, or ‘compartments’, are shown in plan view on Figure 8 and are described in more detail in Hunter (2004). Each pathway compartment encloses separate primary sources, distinctive geology and, in some cases, known migrating contamination. Some of the pathways are likely to have more complicated, multiple migration routes in the vertical dimension. Deeper migration pathways will probably enter the sandstone, where regions of enhanced fracture porosity associated with faults could influence groundwater flow directions and complicate the simplified conceptualisation of contaminant migration parallel to the regional hydraulic gradient.

The network of buried active drains, including abandoned drains, could constitute fast, shallow, horizontal migration pathways. Similarly, monitoring boreholes that have been destroyed or improperly abandoned could provide vertical cross-contamination pathways. Buried solid engineering structures, including temporary construction facilities such as sheet piling, could behave as obstacles to shallow groundwater flow, causing diversion of flowpaths around certain buildings. All of these features contribute to the uncertainty in the current understanding of the contaminant transport conceptual model.

### 8.4. *Receptors*

Current SCLS risk assessment modelling considers the aquatic biosphere as a series of inter-related compartments which include features such as the Calder and Ehen rivers, the beach environment and the local coastal and deeper waters of the Irish Sea. A number of specific receptor exposure groups, both floral and faunal, have been identified and allocated to these compartments. The primary human receptor groups include farmers, fishermen, bait diggers and construction workers. Most of the migration pathway compartments shown in Figure 8 have been delineated to incorporate the spatial locations of sources, known patterns of contamination and conceptual receptors, of which the first are usually within the Separation Area and the last are the rivers, springs on the beach and the Irish Sea.

## 9. Uncertainty in the 2004 conceptual model

Uncertainty in the conceptual hydrogeological model could arise from two areas:

- Model uncertainty or the possibility that the conceptual model is not appropriate (e.g. it has assumed inappropriate processes such as degradation of contaminants during transport, or that there is no vertical groundwater flow into the sandstones) for the objectives and approach of the SCLS;
- Parameter uncertainty related to hydraulic parameters, transport parameters, boundary conditions and hydrogeologic features which are not known in all locations covered by the conceptual model.

### 9.1. *Model uncertainty*

Primary topics of conceptual model uncertainty include:

- Interaction between the River Calder and groundwater;
- Influence of the buried channel on contamination migration rates;
- Vertical extent of contamination within the sandstone;
- Lateral extent of contaminant distribution in the sandstone; and
- Apparently isolated zones of groundwater contamination that have not been linked to identified sources (e.g. beta contamination south of the Separation Area and tritium beneath the Ehen spit).

### 9.2. *Parameter uncertainty*

Primary topics of parameter uncertainty include:

- Hydraulic conductivity values for the Quaternary deposits (range of values);
- Distribution coefficient values for numerical modelling of transport.

### 9.3. Recommendations

The following recommendations have been made to address areas of uncertainty identified in this conceptual model. Recommendations made as a result of the water balance prepared by ESI (2003) have also been reviewed.

#### 9.3.1. Contaminant transport

The following tasks are suggested to improve the 2004 conceptual model for contaminant transport:

- Review contaminant distribution to ascertain whether the Phase I data present an adequate representation of groundwater quality for development of the 2004 contaminant transport conceptual model;
- Evaluate the influence of local groundwater flow gradients within the Separation Area that may represent migration pathways to the River Calder;
- Evaluate the influence of low permeability deposits below primary contaminant sources on the migration of contaminants on a local scale;
- Develop a conceptual model for contaminant transport in the sandstone aquifer to identify:
  - the role of ion exchange and dual porosity on retardation and implications for remedial work; and
  - the depth of contamination.
- Interpret geotechnical data collected in the Phase I investigation to obtain parameters for use in quantitative risk assessment models; and
- Interpret well test data from the Phase investigation to improve the current hydraulic conductivity data set.

#### 9.3.2. Water balance

The recommendations made to improve the current preliminary water balance are presented in ESI (2003).

#### 9.3.3. Groundwater modelling

Further work is required to refine the Sellafield site-wide groundwater flow model. Specific tasks for the second model iteration recommended include expanding the model area, simulating transient conditions and refinement of the model using the complete dataset acquired during the Phase I investigation.

## **10. Summary of the 2004 Sellafield site groundwater conceptual model**

This 2004 groundwater conceptual model has been developed for the Sellafield Contaminated Land Study. The conceptual model represents the current understanding of physical and chemical hydrogeology at the Sellafield site. This conceptual model has been prepared to meet the requirements of groundwater modellers for risk assessment and continuum modelling tasks. Sources of uncertainty and poorly defined characteristics of the groundwater system have been described as clearly as possible to avoid misinterpretation and ambiguity.

The Quaternary aquifer at the Sellafield site comprise lower and upper units separated by less permeable sediments. These low-permeability deposits have been identified in both previous and current investigations. Recharge occurs through the Quaternary deposits. The heterogeneity of the Quaternary deposits is reflected by the large range in hydraulic conductivity values obtained by field hydraulic tests. Groundwater flow within these deposits is intergranular and is towards the coast. Preferential flow within the Quaternary aquifer is likely to occur through coarse sand and gravel deposits. Vertical flow of groundwater occurs within the Quaternary deposits and into the deeper sandstone aquifer.

Groundwater flow within the sandstone aquifer occurs within the rock matrix and is also likely to occur through fractures. The natural and contaminated chemistry of groundwater within the sandstone is likely to be influenced by ion exchange and dispersion.

The primary sources of groundwater contamination at the Sellafield site are radioactive materials stored in the Separation Area. Radionuclides in groundwater have been detected from these sources within the drift and extend as far as the River Ehen at the coast. Less extensive contamination has also been detected within the sandstone.

Several groundwater migration pathways have been identified to demonstrate a source-pathway-receptor linkage for risk assessment modelling.

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## Figures

**Figure 1. Task interaction**

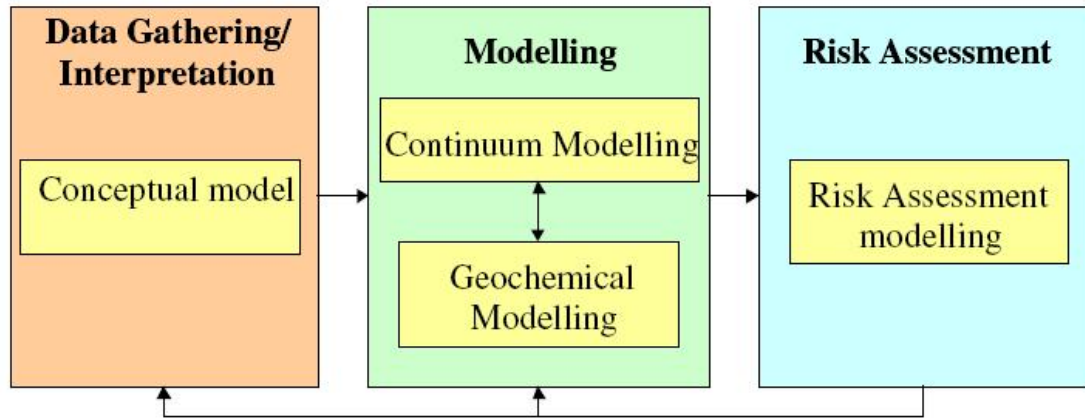
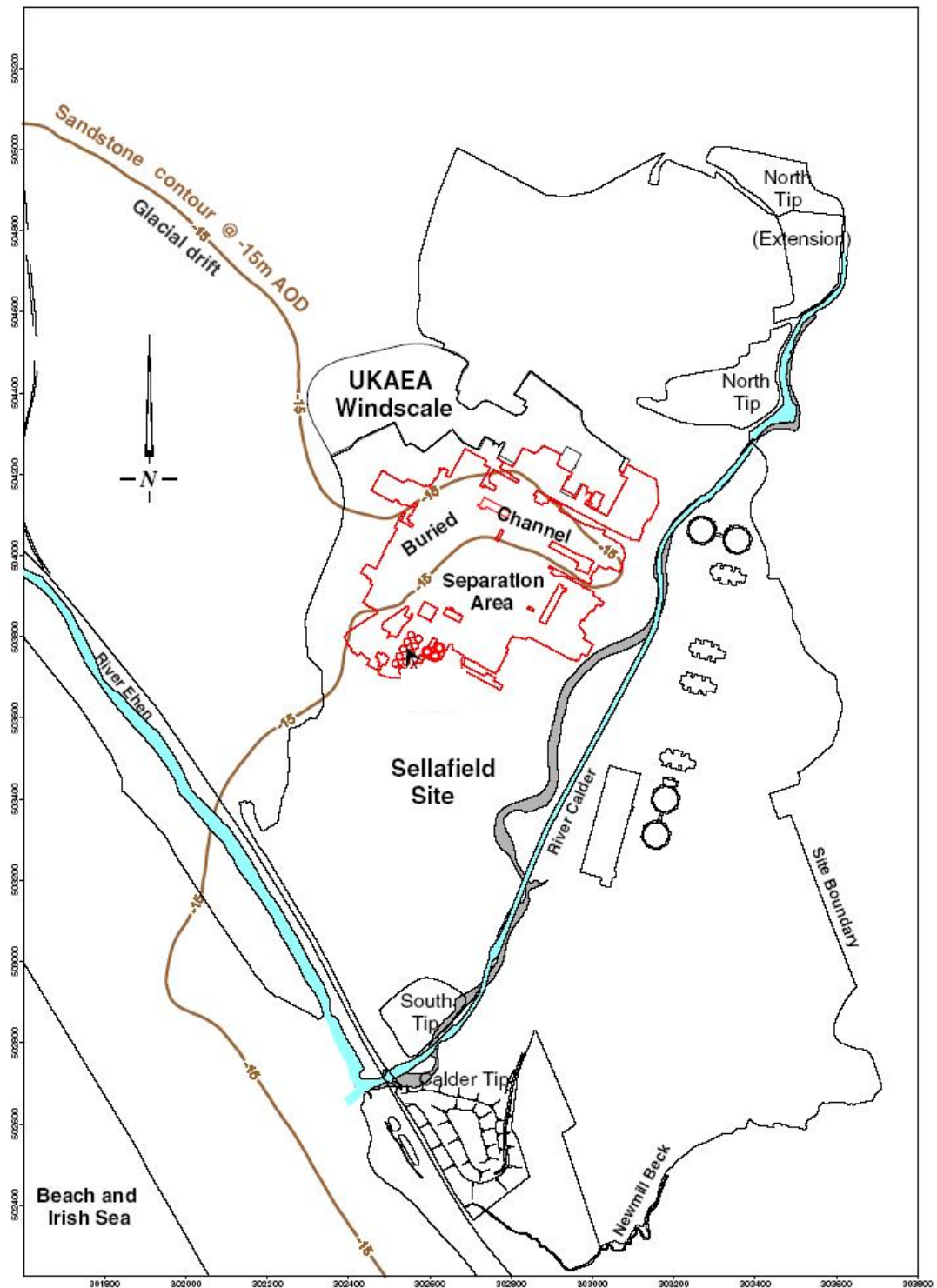


Figure 2. Site plan



**Figure 3. Location of the Calder and Ormskirk sandstone formations in the study area.**

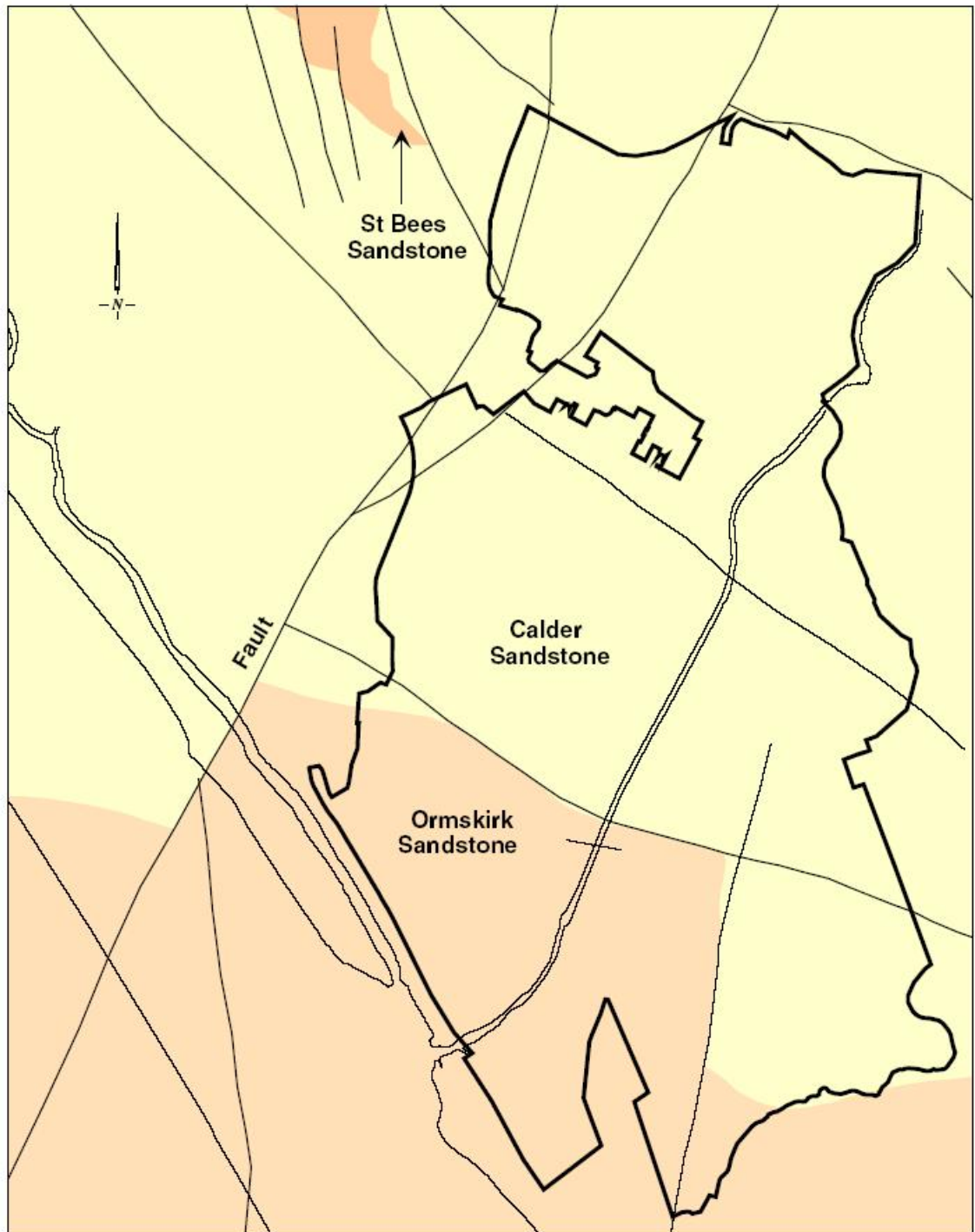


Figure 4. Nirex Quaternary Hydrogeological Domains

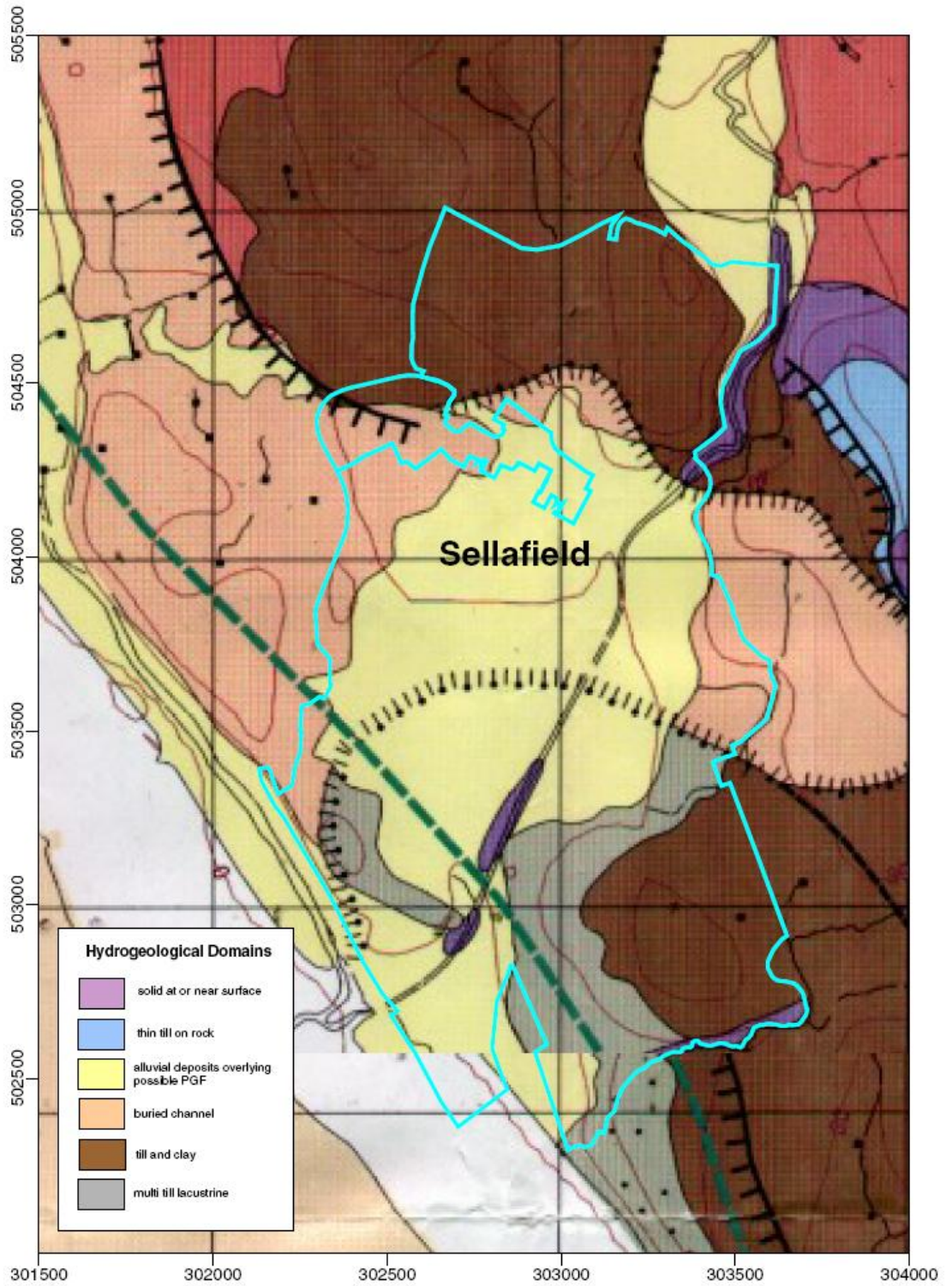




Figure 5. Proposed hydrogeological domains for the Sellafield site

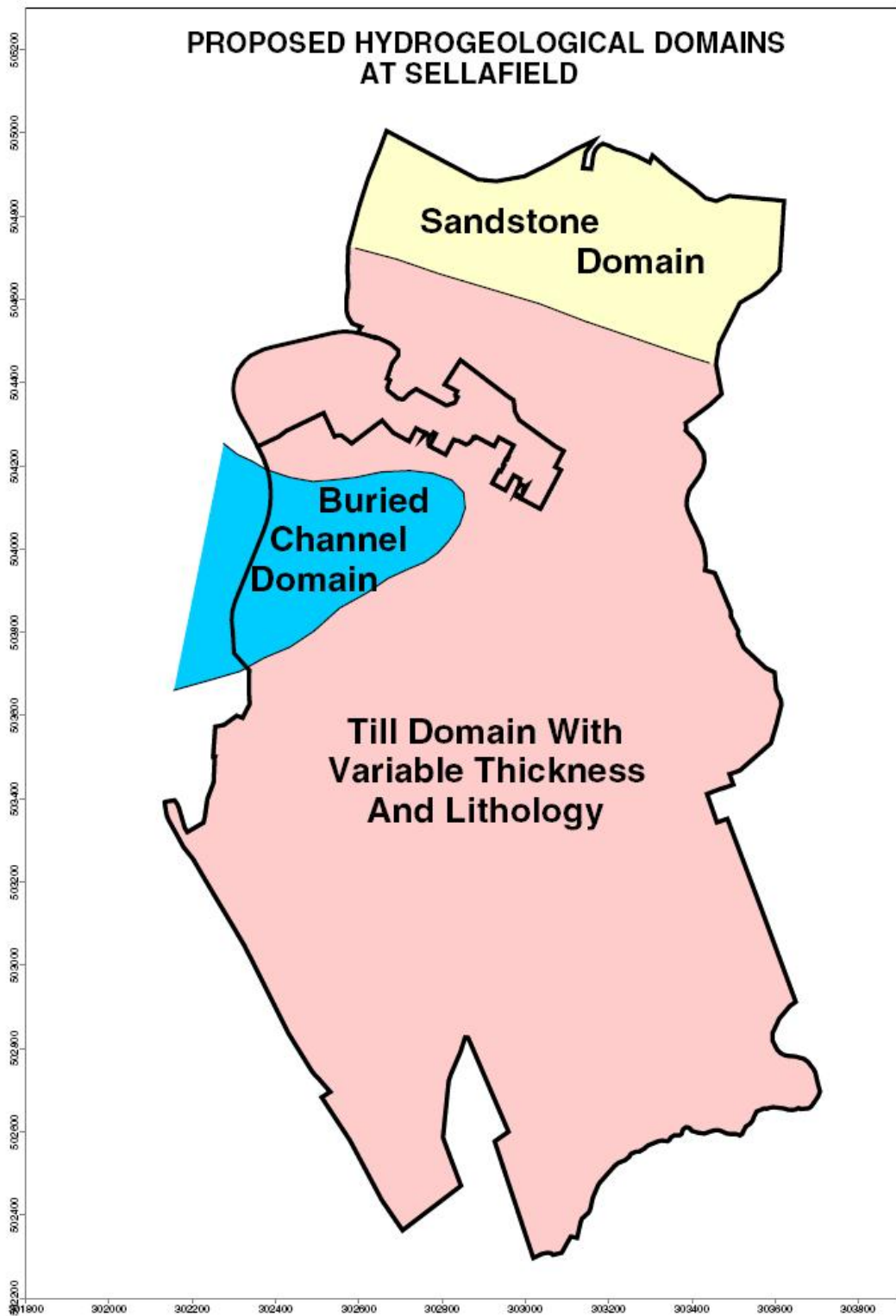
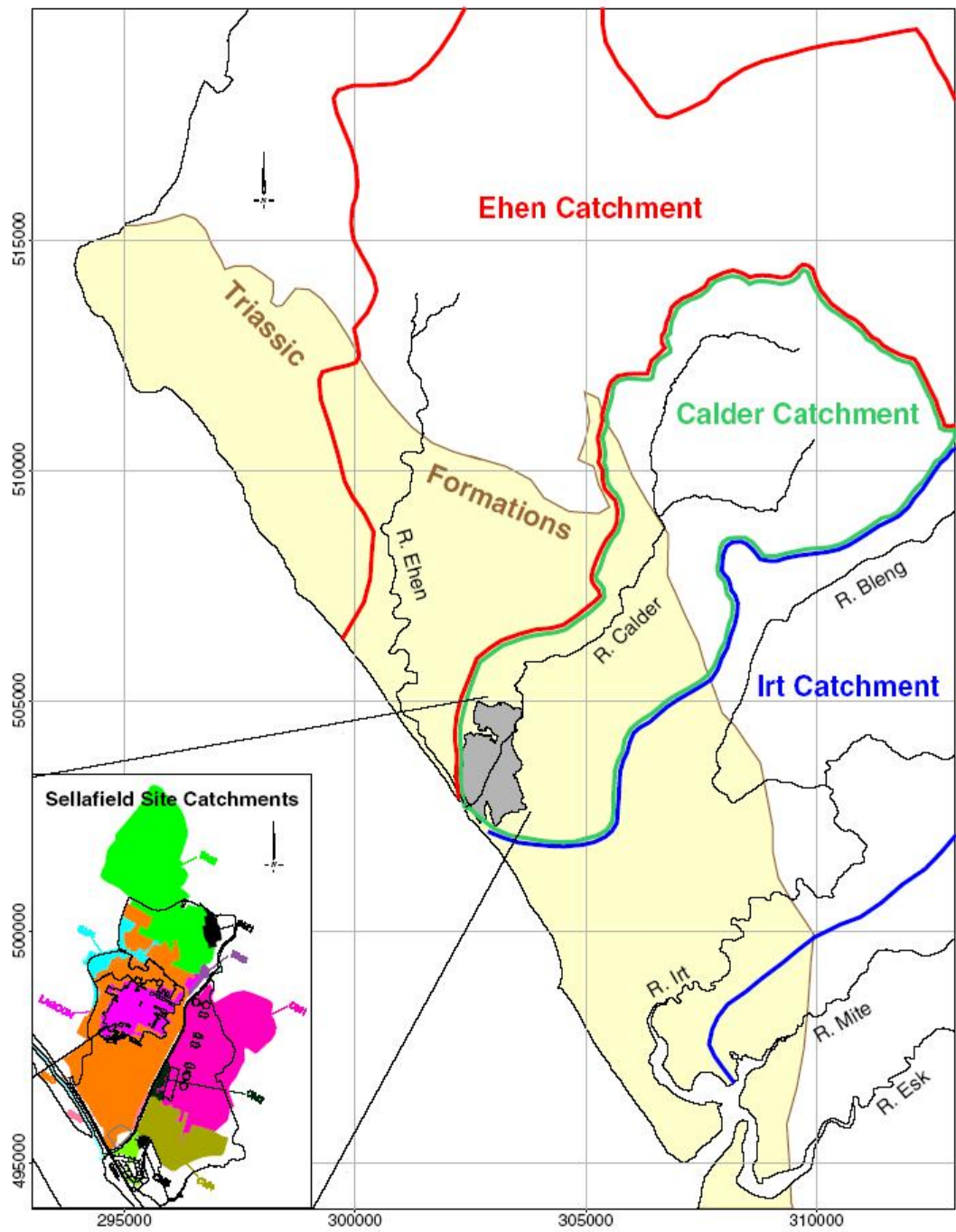


Figure 6. Surface water catchments



**Figure 7. Differences in elevation of groundwater levels between “p2” and “p1” monitoring wells (red circles indicate areas where a difference of >0.5m was observed)**

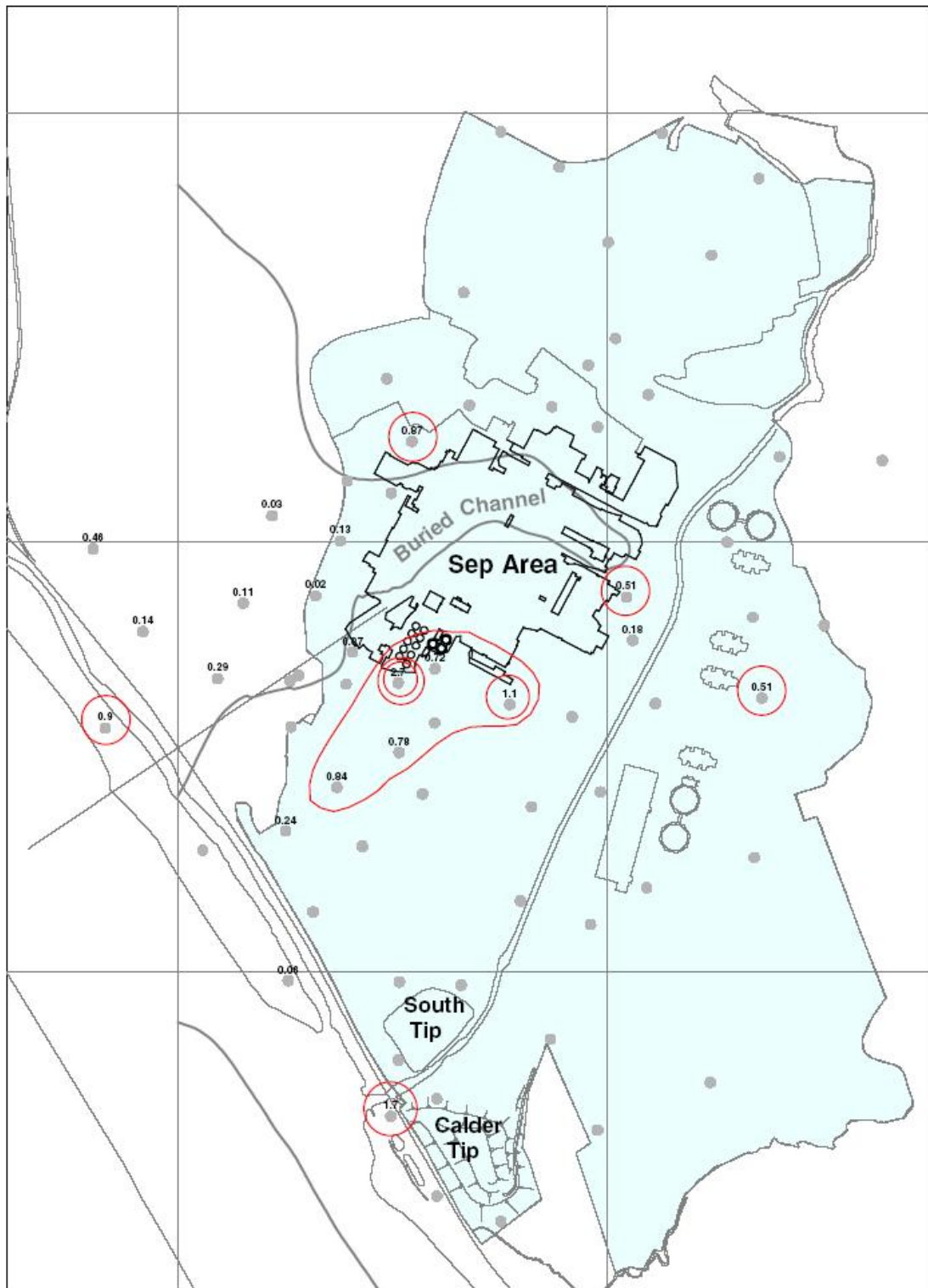




Figure 9. Groundwater contamination and migration pathways (from Henderson and Hunter, 2004)

