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Recharge through Till: Developing a methodology for estimating groundwater recharge with examples from two case studies in East Anglia

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Recharge through Till: Developing a methodology for estimating groundwater recharge with examples from two case studies in East Anglia

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Key words

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Groundwater sampling at investigation borehole CLR1.

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Summary

This report describes the results of a desk study to investigate recharge in an area of discontinuous low permeability till in the Waveney catchment. Within the study area the till is absent in the valley of the River Waveney and also in the lower parts of some of the tributary valleys. The study develops a methodology to identify the main recharge areas and make initial estimates of recharge in such hydrogeologically complex areas. Following earlier work on Chalk recharge through till this combined study area was selected to include both the Chalk and the Crag aquifers. It was thought that the difference between these two aquifers may shed further light on the recharge mechanisms through the overlying till.

The main outcomes of the study have been:

1. A recharge estimate methodology is devised based on the effective rainfall, the till thickness, estimates of runoff from the till sheet and delimiting the main recharge areas where the till is thin or absent.
2. The infiltration through thick till (>10 m) is low and as a consequence, runoff from the till sheet is large and is potentially a significant component of recharge at the margins of the till sheet. Estimating the quantity of water that may runoff the till sheet is essential when attempting to assess the amount and distribution of groundwater recharge.
3. An important issue, when considering catchment water balances, is the relative proportion of runoff that infiltrates to groundwater at the margins of the till sheet, compared with that which flows directly into the river. It has not been possible in this study to devise a methodology to split these two components. More catchment scale studies are required to evaluate how catchment characteristics influence the infiltration rates.
4. The time-lag between rain falling at the soil surface and recharge arriving at the water table will be relatively short at the margins of the till sheet where the water table is generally shallow. This has important implications for water quality, as widespread changes in land-use are likely to be observed more rapidly in groundwaters at the edge of the sheet than in areas of extensive Chalk-Crag outcrop.

1 Introduction

The Chalk Group and the Crag Group are important aquifers in East Anglia where they outcrop and subcrop over a large area (Figure 1.1). The Upper Cretaceous Chalk Group is a very productive aquifer and many public water-supply boreholes are located in the main river valleys where aquifer transmissivity is typically in the range 500-1500 m^2/d. Away from the valleys, the Chalk transmissivity decreases rapidly to less than 50 m^2/d and sometimes it can be as low as 2 m^2/d.

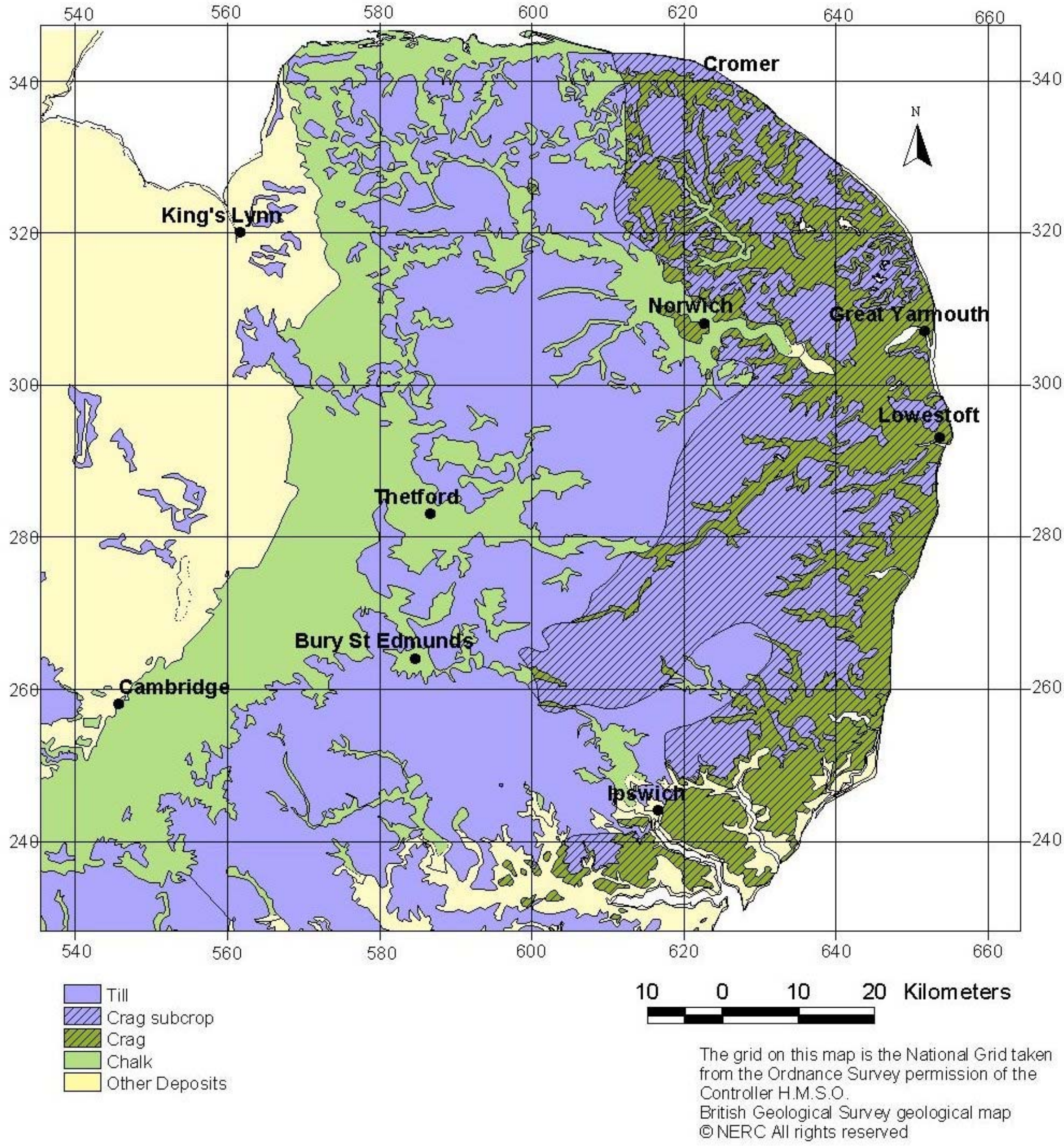

Figure 1.1 Geological map of East Anglia showing the Chalk and Crag aquifers and the overlying till.

The Crag Group, which is a partly consolidated sandstone of Plio-Pleistocene age, stores and transmits considerable volumes of groundwater. Aquifer transmissivity is very variable and ranges from 10-4000 m^2/d, although 100-600 m^2/d is more typical. The Crag is less important as an aquifer than the Chalk because of problems with well construction (due to lack of cementation and wide grain-size distribution) and the high iron content of the groundwater. Many boreholes are drilled down to the underlying Chalk although most of the water pumped may be derived indirectly from the Crag.

Both aquifers are overlain by thick drift deposits of glacial till and glacio-fluvial sand and gravel over extensive areas. The till sheet can be more than 30 m thick on the interfluves but is usually absent in the main river valleys. The till exerts an important influence on the hydrogeology of the underlying aquifer system by (a) reducing infiltration to the aquifer, (b) reducing aquifer vulnerability to pollution, and (c) by routing potential recharge to the edge of the till sheet (Figure 1.2). For these reasons it is important to understand the processes controlling both recharge through, and runoff from, the till, if the groundwater resources in the underlying aquifer are to be quantified. Recharge rates and mechanisms can also have important implications for groundwater quality.

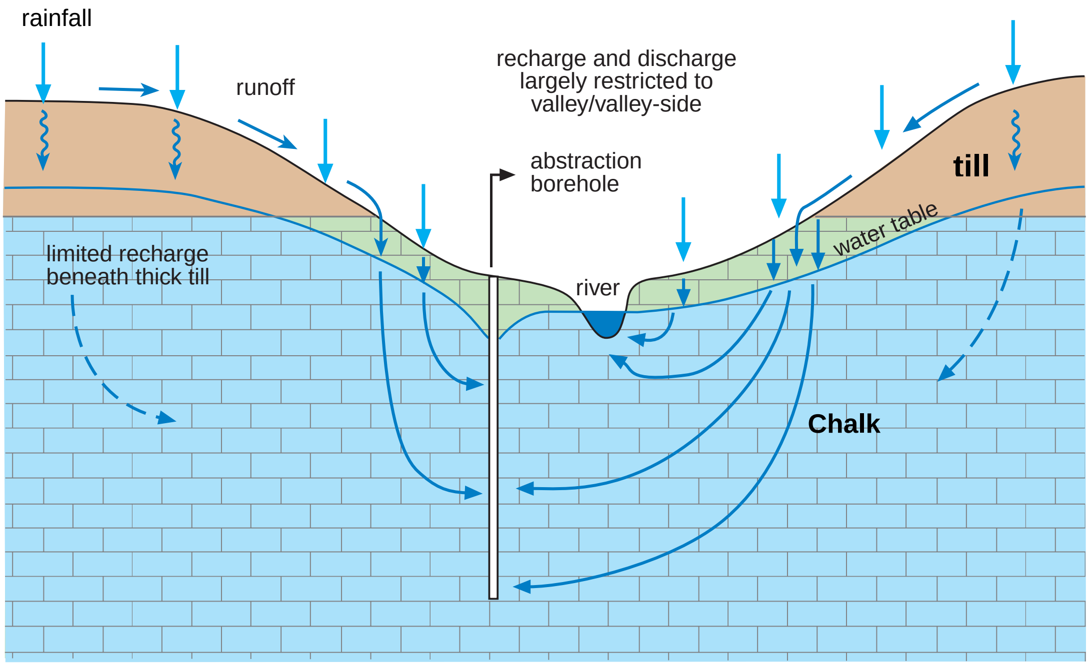

Figure 1.2 The influence of the till sheet on the groundwater flow system in the Chalk aquifer

This report discusses the controls on recharge to the Chalk and Crag aquifers in areas that include extensive till cover. A methodology is developed to help both identify the main recharge areas and estimate the potential recharge available. Two case studies are presented in areas, which drain to the River Waveney. In one study area the catchment is underlain by the Chalk aquifer only and in the other by both the Crag and Chalk aquifers.

2 Quaternary history of eastern East Anglia

The early Quaternary history of the region is dominated by gradual subsidence and marine transgression, with the laying down of the Crag Group deposits in a shallow marine environment (Table 2.1). These Crag deposits are shelly sands of Plio-Pleistocene age, which lie unconformably upon the underlying Chalk Group.

Table 2.1 Quaternary history of East Anglia (after Rose et al. 2004: Rose et al. 2002:Rose 1989 and Ehlers et al. 1991)

Period/event	Time (BP)	Processes	Deposits
Holocene	Present – 10,000	Cliff retreat Incision of rivers Marine transgression	Extensive fenland development Estuarine and shallow marine Organic accumulation
Devensian	10,000 – 122,000	Extensive fluvial aggradation Ice impinges on north Norfolk coast Severe periglacial conditions develop	Re-mobilisation of earlier deposits Till (north Norfolk) and outwash deposits Ice wedges, pingos, and patterned ground formed
Ipswichian	122,000 – 132,000	Incision of rivers Marine transgression	Terrace flights Organic accumulation
"Wolstonian"	132,000 – 352,000	Various periods of intense periglacial conditions	Ice wedges, pingos, and patterned ground formed Re-mobilisation of earlier deposits
Hoxnian	352,000 – 428,000	Extensive fluvial systems develop and incise Warm conditions prevail.	Terrace flights Organic accumulation
Anglian	428,000 – 480,000	Retreat of ice sheet; intense periglacial conditions persisted Ice sheet extends to North London Severe periglacial conditions develop	New drainage pattern developed as ice retreated Lowestoft Till deposited, infilled previous drainage pattern Re-mobilisation of earlier deposits
Cromerian	480,000 – 810,000	Extensive fluvial systems develop and incise Warm conditions prevail.	River terraces deposited Extensive forest development
Early to Early-Middle Pleistocene	c.640,000	Pre-Cromerian (Happisburgh) glaciation Gradual uplift and emergence of Crag	Till and outwash deposits Deposition of Wroxham Crag
Plio-Pleistocene	c.2.0 My	Subsidence and marine transgression	Deposition of shallow marine Crag formations

Later, throughout the early Middle Pleistocene, gradual uplift resulted in shallowing of the seas and the sand and gravel of the Wroxham Crag were deposited in a coastal environment.

The sand and gravel of the Wroxham Crag were derived from large rivers (the Thames, Bytham and Ancaster Rivers), which flowed eastwards into the southern North Sea (Rose et al., 2001).

Subsequent emergence resulted in the dissection of the Crag by these rivers and the deposition of river terrace sequences (the Beccles Beds and Kesgrave Sand and Gravel). In the coastal regions, successive marine transgressions and regressions, controlled by eustatic and neotectonioc changes, laid down distal fluvial and estuarine deposits such as the Cromer Forest Beds.

The Anglian Glaciation had a major effect upon the topography of East Anglia. Even before the ice covered the area, severe periglacial conditions had developed, as evidenced by ice wedge casts in the Barham Soil, a palaeosol that underlies the deposits of the Anglian ice sheet (Rose et al., 1985 a,b). The Anglian was the most extensive glaciation recorded in terrestrial deposits in the UK and the ice sheet reached as far south as Finchley, in North London, diverting the Thames river into its current valley. The ice sheet deposited a thick till (the Lowestoft Till), which blocked and infilled the previous drainage patterns across east Anglia, and fundamentally altered the landscape and depositional style of lowland Britain and the adjacent North Sea Basin (Rose et al., 1985a).

Following ice sheet retreat, new drainage patterns were established which initially reworked the glacio-fluvial outwash. These deposits were subsequently incised during the following Hoxnian Interglacial.

East Anglia, apart from the north coast of Norfolk, was probably largely ice-free during the remaining Pleistocene glaciations. However, during these subsequent cold periods the new rivers aggraded and the region was again subjected to intensely cold periglacial conditions, as proven by ice wedge casts in deposits overlying Hoxnian Interglacial deposits (Gladfelter, 1975). Head derived from the Anglian glacial deposits was mobilised down slopes, and patterned ground and ice wedge casts developed on flat till surfaces.

Ipswichian Interglacial deposits have been identified in Ipswich and at Wretton in Norfolk, where they are overlain by Devensian fluvial sand and gravel of a braided river system (West et al., 1974). These sands and gravels form part of the terrace flight of the River Wissey, and exhibit abundant evidence of a periglacial tundra environment, with ice wedge casts, ground-ice depressions and blown coversands, indicative of a paucity of vegetation. By the Late Glacial Maximum (the Dimlington Stadial) ice had impinged on the north Norfolk coast, whilst beyond the ice limit, the exposed land surface was subjected to wind erosion, glacio-fluvial reworking and the development of pingos and other periglacial phenomenon such as patterned ground.

Following deglaciation, rapid warming during the Windermere Interstadial resulted in the development of grasslands and open woods as temperature climbed to approximately present-day values. However, this warm period was short-lived, and the climate deteriorated again into the Loch Lomond Stadial. Whilst glacier ice reformed in the uplands of Scotland, the Lake District and Wales, in East Anglia it was marked largely by a degradation in the vegetation, with sparse grasses and sedges in open tundra.

During the Holocene, the end-glacial marine transgression flooded much of the coastal northern East Anglia resulting in extensive fenland development (the Broads), whilst in central East Anglia woodlands quickly became established. Subsequently, human influence has reclaimed much of the low-lying fenland, although rising sea-levels have resulted in the abandonment of some of the more marginal coastal fields, whilst the till cliffs of Suffolk are particularly prone to marine erosion and have retreated tens of metres over the last few centuries.

3 The Anglian till and its influence on recharge to aquifers

3.1 DESCRIPTION OF TILL

The till, also known as the 'Chalky Boulder Clay', is an over-consolidated chalky, bluish-grey to brown clay of variable sand and silt content containing clasts of Chalk, flint and some Jurassic mudstones. Perin et al., (1979) described the mineralogy of the till and reported that calcium carbonate accounts for 40% of the matrix and over half of the clast grade material. The clay fraction consists of mica, kaolinite and variable amounts of smectite. The till can reach thicknesses in excess of 30 m on the interfluve, but is usually absent in river valleys where Chalk-Crag, glacio-fluvial and fluvial deposits are exposed. The till sheet forms a gently undulating plateau, which is drained by intermittent streams, which flow off of the till sheet and into the main river valleys.

Since the mid 20th century an extensive land drainage system has been introduced to prevent water logging of the soils on the till sheet and this allows cereal cropping. This has had the effect of both increasing the quantity of water draining off the till sheet and reducing the lag time between rainfall and the subsequent runoff arriving at the edge of the till sheet

A schematic geological section from valley to interfluve is shown in Figure 3.1.

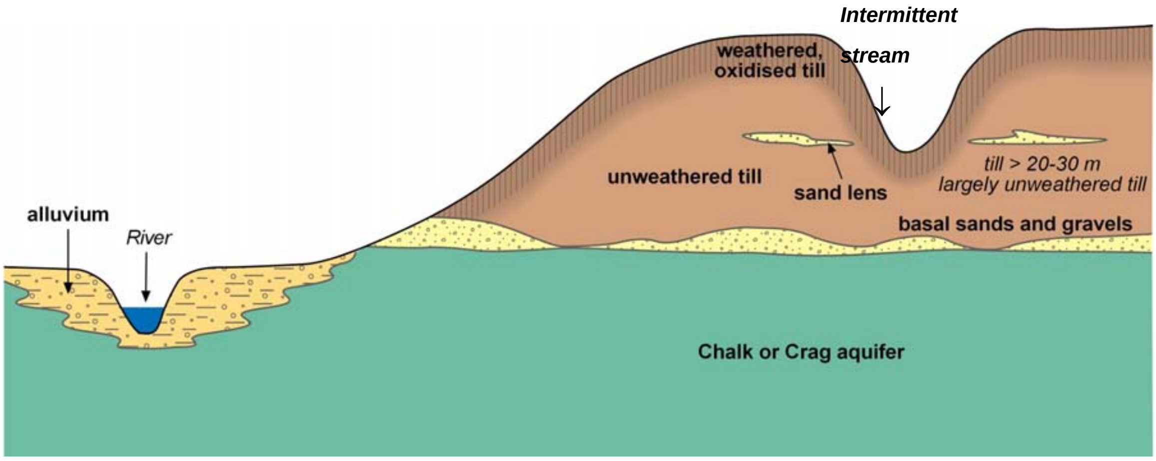

Figure 3.1 Schematic geological section from valley to interfluve.

Recharge through the till to the underlying aquifer will be controlled by several factors:

- lithology of the till
- weathering of the till and overlying deposits
- fracturing
- thickness of the till sheet
- till sheet runoff

These factors, which are inter-related, are discussed below:

3.2 LITHOLOGY

The till is a fine-grained silt or clay-grade deposit although glacio-fluvial sand and gravel layers may also be present. These sands and gravels are usually sub-horizontal, discontinuous, lensoid bodies within the till sequence. A glacio-fluvial sand and gravel bed is commonly present beneath the till. All these sand and gravel layers have a varied lithology and thickness and are commonly poorly sorted (Pattison et al., 1993). The sand and gravel lenses can be several metres thick and, the basal sand and gravel layer can be extensive. All these layers will have considerably higher permeability than the surrounding clay-rich till but, unless interconnected, these sand and gravel lenses are unlikely to significantly increase recharge (Cox, 2003), although they will act as reservoirs for feeding water to any fractures that extend through the full till thickness.

The permeability of the till matrix is low, hydraulic conductivities of 1.1-1.8 x 10^{-10} m/s were obtained for the till from East Anglia (Marks et al., 2004), which are similar to hydraulic conductivities obtained for till deposits elsewhere (Hossain 1992; Klink et al 1996). Rates of downward movement through the matrix are, therefore, very low and probably less than 1 mm/a (Marks et al., 2004). A travel time of many hundreds of years can be anticipated for infiltration to migrate through a 20 m thick till, assuming intergranular flow and an average moisture content of about 0.2. The implications are that if all recharge occurred by intergranular flow then beneath thick till deposits on the interfluve (a) recharge to the Chalk would be very limited (<1 mm/a) and (b) no modern (post 1960) water should be observed.

3.3 WEATHERED TILL AND OVERLYING DEPOSITS

A weathered zone, typically 2-4 m deep, is widely developed on the till surface. This zone is usually yellow-brown in colour in contrast to the underlying grey (unoxidised) till. Whilst the oxidised and unoxidised zones of the till have similar matrix hydraulic conductivities, the bulk permeability of the oxidised zone can be significantly enhanced both by fracturing (due to weathering) and by the development of root channels (Klint and Gravesen, 1999). Thus, there is potential for an appreciable component of the residual rainfall to infiltrate the weathered zone of the till. As mentioned earlier a network of land-drains are commonly installed beneath agricultural soils to prevent water logging and these may increase infiltration rates within the upper 1-2 m (by preventing any shallow water table surfacing). Infiltration rates of 30–40 mm/a have been suggested for oxidized till (Klink et al 1996). However, since the unweathered zone of the till is believed to be generally less intensively fractured (and, therefore, have a lower bulk permeability) infiltration rates are likely to decrease with increasing depth.

Where thin permeable drift overlies the till these deposits can act as a reservoir for recharge through underlying till. However, where they are shallow (and do not extend beyond the depth of the land drains) their value may be limited.

3.4 FRACTURING

Although fractures have not been observed by the authors in cored samples of deep (>5 m) till in East Anglia, they are undoubtably present at shallow depths in most clay rich tills (Hossain 1992, Klink et al., 1996, Klink and Gravesen, 1999).

Gerber et al. (2001) suggest that some fractures may extend to considerable depths in tills and that these could account for the component of modern water observed in some tills in North America. Likewise, Marks et al. (2004) considered that fractures are likely to be the principal route for modern (post 1960) water to reach the Chalk aquifer beneath thick till deposits on the interfluve. However, Marks et al. (2004) suggested that, although the fracture flow component of recharge through thick till was much higher than the intergranular component, recharge rates were still low (<10 mm/a).

3.5 TILL THICKNESS

Till thickness clearly has an important control on recharge rates. From the above discussion it is evident that till thickness needs to be considered relative to the depth of both weathering and intensive fracturing. Thus thin tills, where the zone of weathering (and more intensive fracturing) may account for much of the till layer, are likely to permit higher infiltration rates than where a considerable thickness of unoxidised till exists.

Results of core drilling in the till of East Anglia showed that the 'front' of modern (post 1960s) water had only penetrated a few metres below the weathered zone and indicated an average infiltration rate of 20-40 mm/a (Marks et al., 2004). Such a rate confirms that water movement is through fractures with solutes being retarded by diffusion exchange with the surrounding till matrix. This compares with infiltration rates of less than 10 mm/a (and possibly as low as 5 mm/a) where the till is thicker and where the zone of weathering and intensive fracturing comprises a relatively small fraction of the total till thickness. While it is not possible to equate thickness of drift with a specific recharge rate, a semi-quantitative estimate is proposed (Table 3.1). Within the scheme, till thickness incorporates the factors of weathering and fracturing.

Table 3.1 Estimated recharge rates through till deposits.

Till thickness (m)	**Recharge rate (mm/a)**	**Description**
Absent	High At potential rate	Commonly permeable Drift overly the aquifer providing high infiltration rates.
<5 m	Moderate – high Could be up to potential rate	Till likely to be largely weathered throughout; pathways for high infiltration rates are provided by root openings and fractures.
5 – 10 m	Moderate 20 – 40 mm/a	Till will include several metres of weathered till; some fractures may extend to 10 m but fracturing probably less intense than at shallower depths.
>10 m	Low <20 mm/a (and maybe as low as 5 mm/a)	Considerable thickness of unweathered till; fractures may provide pathways for some recharge, but rates are low.

3.6 TILL SHEET RUNOFF

Given that recharge through thick till is low (less than 20 mm/a and possibly as low as 5 mm/a), a considerable fraction of the effective rainfall (effective rainfall in this part of East Anglia is about 160 mm/a) will runoff from the till sheet. This runoff may however, infiltrate to groundwater where it encounters permeable ground at the till sheet margins on the valley sides. Thus, areas where the till is absent, or less than 5 m thick, can be considered as potential zones of high recharge (main recharge areas) and could receive additional recharge (in excess of the effective rainfall) as runoff from adjacent areas where the till sheet is much thicker. How much of the available recharge will infiltrate to groundwater will depend on the lithology of the surface deposits, the slope of the ground surface, the depth to water table and the area available for this infiltration to occur.

It is important to consider (i) the slope of the land surface across the areas of main recharge (gentler slopes may permit greater infiltration) and (ii) the surface catchment area draining to these recharge zones as this will permit an estimate to be made of the maximum potential recharge available.

4 Hydrogeological settings and drift domains

Lithological drift domain maps can be used to subdivide the area into various permeability zones based on lithology at surface. These maps also describe the drift geology at depth in terms of proportion of clay or sand and gravel and they are prepared using the existing geological map and borehole records. Some judgment /interpretation of borehole records is required where they do not bottom the drift sequence. These domain maps do not differentiate between sand and gravel associated with current fluvial deposits and those of older glacio-fluvial origin and peat has been included in with sand.

The Chalk-Crag and till system can be conveniently subdivided into four hydrogeological settings based on their geological and geomorphological characteristics as follows:

- Interfluves
- Tributary valley
- Valley sides (upper and lower)
- Main valley floor

These settings are shown in Figure 4.1 and are discussed below.

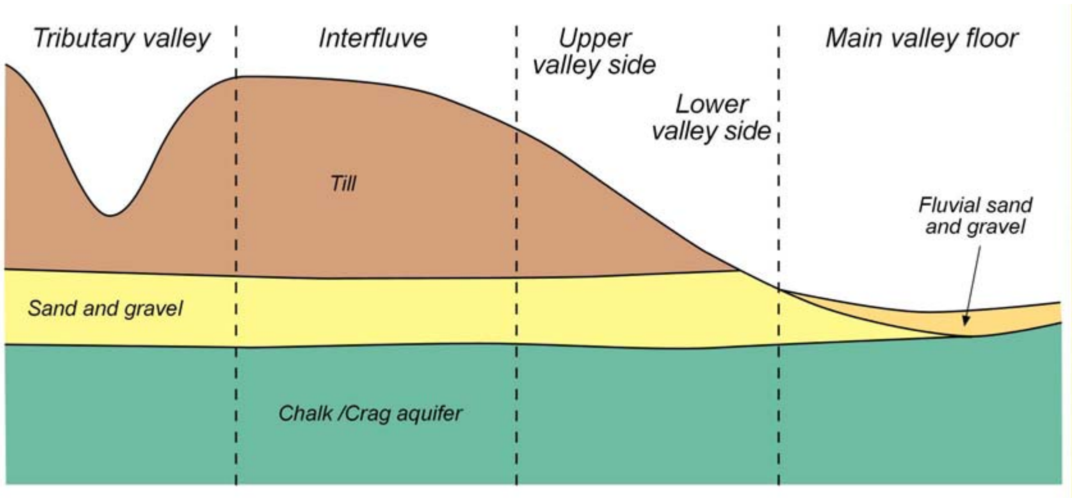

Figure 4.1 Hydrogeological settings.

4.1 INTERFLUVE SETTING

The interfluve is defined here as the undulating till-covered plateau. The till reaches more than 30 m in thickness and this setting can account for a large fraction (>50%) of the total catchment.

The principal drift lithological domains associated with this setting are those with clay forming more than 50% of the drift thickness. In some areas outliers of sand and gravel overlie the till (Figure 4.2) but these are generally not extensive and may not significantly influence the recharge to the underlying aquifer. Recharge rates are low, less than 20 mm/a and most of the effective rainfall runs off to adjacent areas.

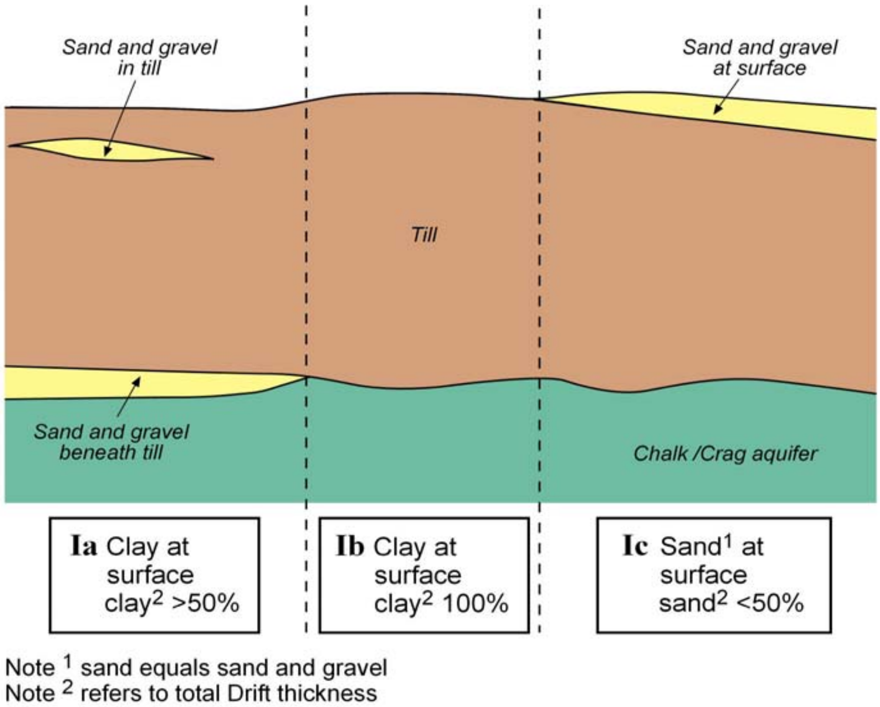

Figure 4.2 Principal lithological domains: Interfluve setting.

4.2 TRIBUTARY VALLEY

Tributary valleys are defined as those valleys where streams flow across the till sheet and where the till is less than 10 m thick beneath the streambed. Stream flow is maintained by (a) overland flow, (b) interflow within the weathered zone of the till and (c) ditches that connect to the land drain network. Tributary valleys make up about 10% of the total catchment. The principal lithological domains are presented in Figure 4.3. This area is likely to have higher rates of recharge than the interfluve due to the reduced till thickness, increased likelihood of more permeable deposits at surface and increased likelihood of a surface water source.

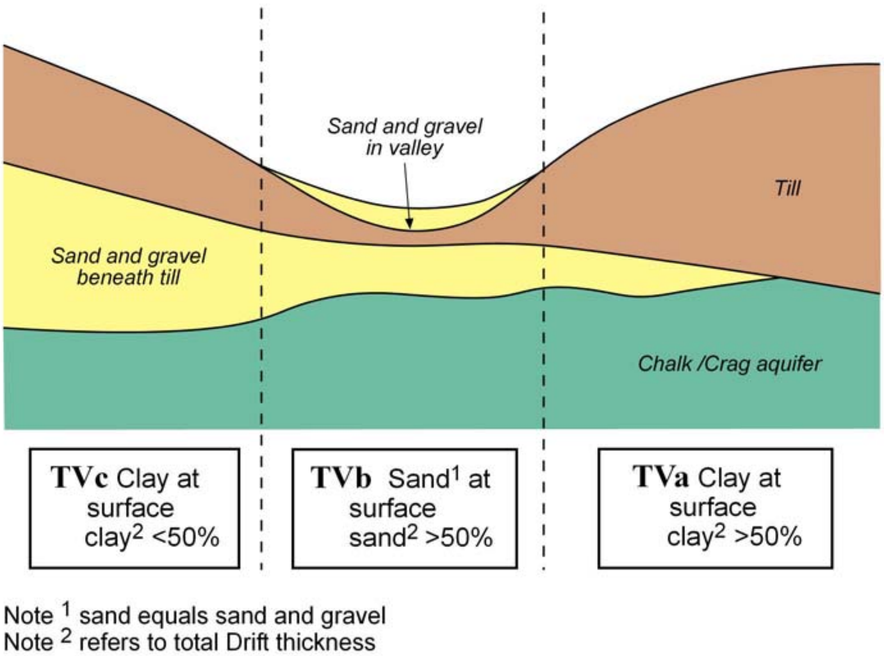

Figure 4.3 Principal lithological domains: tributary valley (TV) setting.

4.3 VALLEY SIDE SETTING

The valley sides are defined as the generally steeper slopes that form the boundary between the river valleys and the interfluves. The width of this setting is typically several hundred metres and this setting can account for about 30% of the total catchment area. The valley side setting can, in turn, be subdivided into (a) the upper slopes and (b) the lower slopes (Figure 4.4 and 4.5).

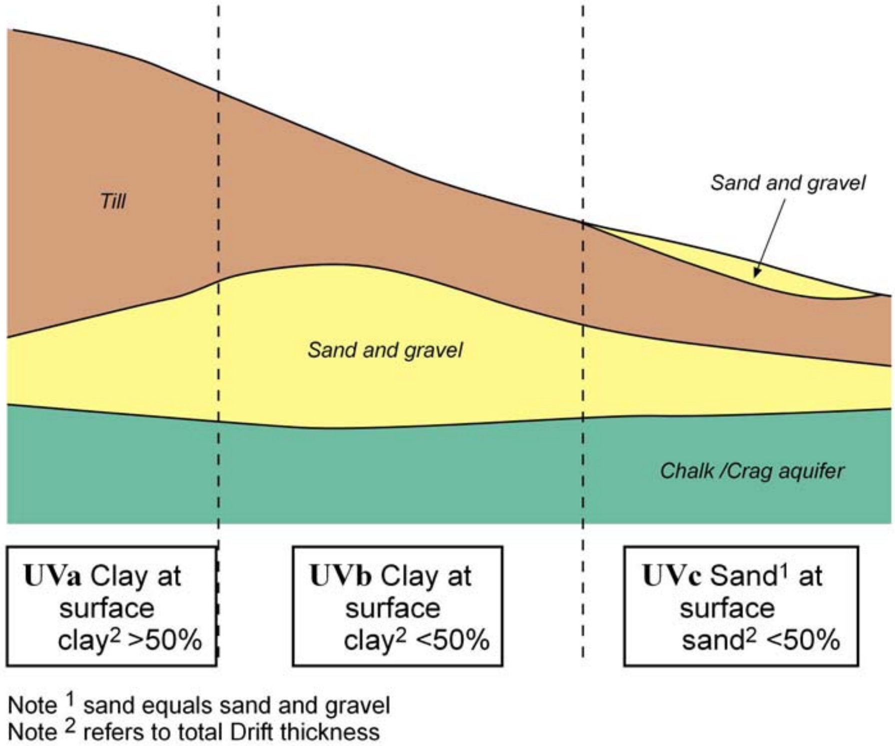

Figure 4.4 Principal lithological domains: upper valley (UV) side setting.

The lithological drift domains on the upper slopes are similar to those on the interfluve and usually are till at surface with clay making up more than 50% of the total drift thickness. On the lower slopes the domains are more varied and may include till (<50% clay), sand and gravel or even exposed bedrock. These lower slopes potentially represent a major recharge area for the underlying aquifer.

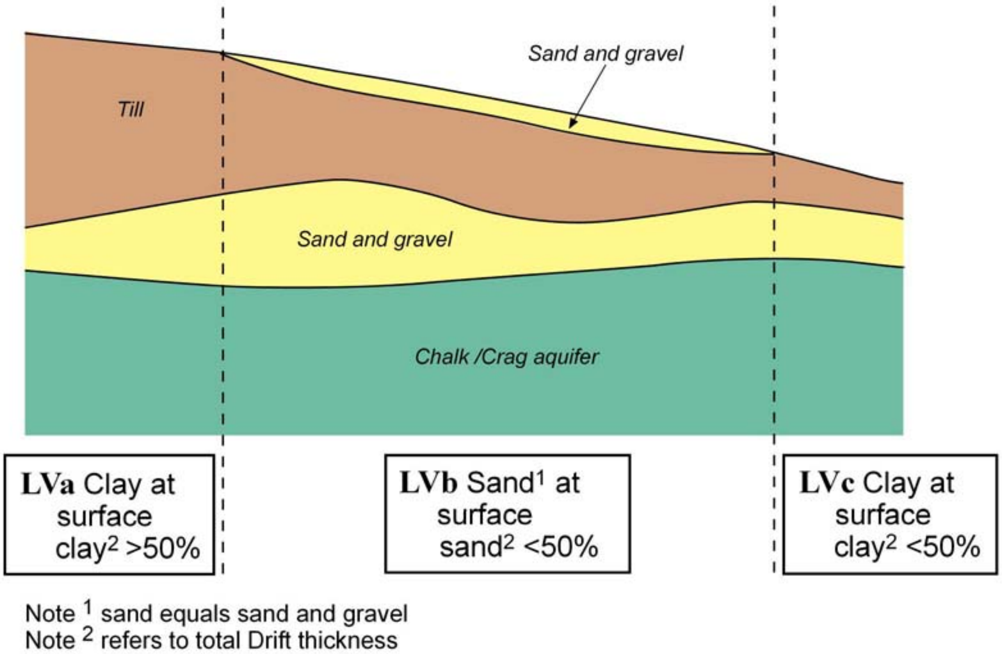

Figure 4.5 Principal lithological domains: lower valley (LV) side setting.

4.4 MAIN VALLEY FLOOR

The main valley is defined as an area of gentle slopes where (a) till is generally absent and (b) river-flow is maintained by groundwater baseflow. Various lithological domains occur within the valley (Figure 4.6) although the surface lithologies are often permeable permitting high infiltration rates.

This setting usually accounts for about 10% of the total catchment and represents the main groundwater recharge and discharge areas for the aquifer. Recharge occurs as both rainfall recharge and as runoff from the adjacent, less permeable till sheet. Discharge occurs as both baseflow to streams and as abstraction from boreholes. Abstraction boreholes are mostly located within the valley because this is where Chalk permeability is usually greatest. Groundwater abstraction is likely to reduce river flow by (a) lowering groundwater levels and increasing infiltration to the subsurface, at the expense of direct runoff from the till sheet into the main river, and (b) inducing leakage from the riverbed itself.

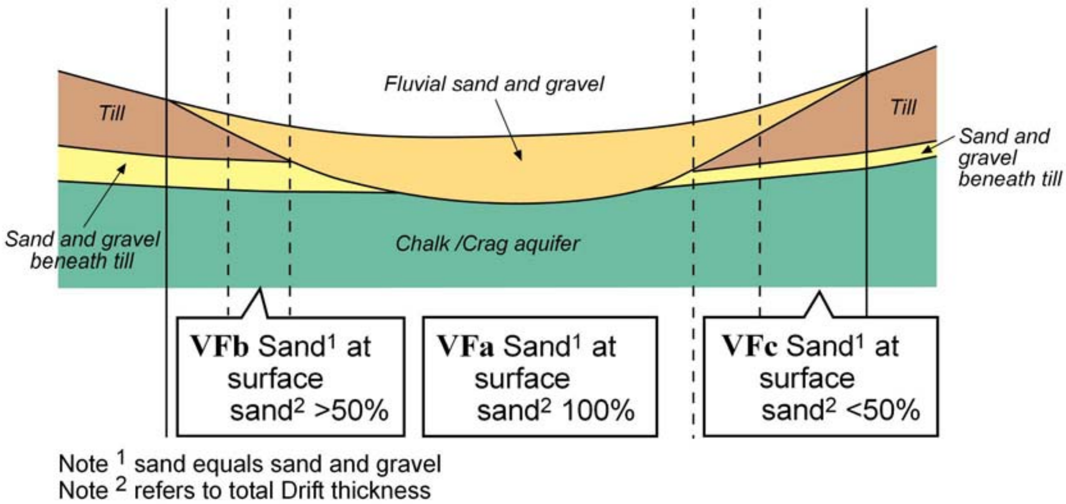

Figure 4.6 Principal lithological domains: main valley floor (VF) setting.

The characteristics of the different hydrogeological settings are summarized in Table 4.1.

Table 4.1 Characteristics of the hydrogeological settings

Hydrogeological setting	**Typical fraction of catchment area (%)**	**Average width (m)**	**Till thick-ness (m)**	**Principal lithological domains**	**Topo-graphy**	**Likely recharge rates (mm/a)**	**Comments**
Interfluve	>50	Several kilometres	Considerably in excess of 10 and often >20	Clay dominant	Undulating plateau	Low (<20)	Low recharge: most of the effective rainfall runs off to adjacent areas.
Tributary valley	10	About 200	0-10	Various (clay dominant)	Gentle valley slopes	Moderate, but may be high (20-40)	Moderate recharge; rate depends on till thickness and slope.
Valley sides (a) upper slopes	20	About 400[1]	5-10	Various (clay dominant)	Steeper valley slopes	Low - Moderate (<20-40)	Moderate recharge; rate depends on till thickness and slope.
Valley sides (b) lower slopes	10	About 200[1]	<5	Various (sand dominant)	Gentle valley slopes	Moderate to high, could be up to potential rate	Important recharge zone, especially where slopes are gentle. Some runoff to valley floor.
Valley floor	10	200-400	0	Sand dominant	Flattish fluvial plain	High, probably up to potential rate	Important recharge and discharge zone. Some runoff to surface water.

Note [1] includes both sides of valley

5 Methodology

This methodology is based on a desk study: field measurements are needed to validate the semi-quantitative recharge estimates presented here and to improve confidence in the conceptual models proposed.

The methodology we propose comprises three steps. The first is to use till thickness to identify (and delineate) the main recharge areas (that is where recharge rates are 'moderate-high' or 'high'). Recharge in these zones may include a significant component of runoff from adjacent areas with a thick till cover as well as direct rainfall.

Second, to estimate the volume of runoff potentially available as recharge to these zones. This estimate is the product of the catchment area covered by thick till and the assumed runoff rate of 140 mm/a (Runoff rate = effective rainfall (160 mm/a) – infiltration to groundwater (20 mm/a)).

Third, to make a qualitative assessment of how much of this runoff is likely to infiltrate to groundwater and how much will leave the catchment as surface flow. This assessment is based on land slope, lithology at surface, evidence for disappearing streams and depth to water table.

5.1 STEP 1: IDENTIFY MAIN RECHARGE AREAS FROM THE TILL THICKNESS MAPS

A till thickness map is produced based on the existing drift-geology map and borehole records.

The till thickness is subdivided into four zones:

- Till absent
- Till present < 5 m thick
- Till between 5 and 10 m thick
- Till present >10 m thick

Recharge rates assigned to these zones are based on Table 3.1. Zones where till is absent or less than 5 m thick (equivalent to recharge rates moderate-high and high) are considered as the main recharge areas. Runoff from adjacent areas, where the till is thicker, may contribute significantly to recharge in these zones.

5.2 STEP 2: IDENTIFY AND DELINEATE SURFACE CATCHMENTS DRAINING TO THE MAIN RECHARGE AREAS

In the main recharge areas the effective rainfall (160 mm/a) is assumed to be able to infiltrate; the maximum potential recharge is the effective rainfall plus any additional runoff from adjoining areas. Not all the maximum potential recharge will necessarily infiltrate.

Surface water divides around the main recharge areas are demarcated from the topographic map and the area draining to the main recharge areas is calculated. These areas fall into two types: areas that drain directly to the main recharge areas and areas that drain to streams which then flow across the main recharge areas.

The available runoff draining directly to the main recharge areas is calculated as:

Volume of available runoff = assumed runoff rate (140 mm/a) x area drained (area from which runoff is derived)

The available runoff can be expressed as a potential (additional) recharge rate (mm/a) within the main recharge area (this assumes that all the runoff has an equal chance of recharging groundwater within the main recharge area) by dividing the volume of available runoff, estimated above, by the area of the main recharge area.

The volume of stream runoff can be calculated in the same way, but here the recharge area is restricted to the streambed within the main recharge area.

5.3 STEP 3: QUALITATIVE ASSESSMENT

This step provides guidance as to whether all, most or only a small fraction of the potential recharge component is likely to infiltrate to groundwater within the main recharge areas. This assessment is based on three lines of evidence:

- Lithology of Quaternary deposits at surface
- Slope of land surface
- Drainage (evidence for disappearing streams, depth to water table)

5.3.1 Lithology of Quaternary deposits at surface

Rates of groundwater recharge will vary depending on the lithology of the surface deposits: permeable lithologies will permit higher infiltration rates and water may be stored in these permeable deposits at shallow depths and then released slowly over time to percolate to the underlying aquifer. Conversely, where less permeable deposits are present at the surface, then some potential recharge may be rejected (to runoff) because the quantity of water arriving at the surface exceeds the infiltration capacity of these deposits.

5.3.2 Slope of land surface

Runoff rates are in part dependent on land slope; the steeper the slope the greater the runoff rate. Conversely, infiltration rates increase as the slope of the land surface decreases. Gentler slopes also correspond with increased outcrop of the more permeable layers on the lower slopes of the valley side.

5.3.3 Drainage

Drainage characteristics within recharge areas can be assessed using topographic maps. The depth to groundwater may also influence recharge rates; where groundwater levels are shallow recharge may cause the water table to reach the ground surface preventing further infiltration. In some areas surface watercourses ‘disappear’ or become intermittent in their lower reaches as they flow over permeable ground; this suggests that infiltration rates are close to the maximum potential rate and that most of the available runoff component of potential recharge infiltrates to groundwater.

6 Case studies

Two case study areas have been assessed either side of the River Waveney (Figure 6.1). The Harleston area is to the south of the River Waveney and has a geology of drift resting on Crag with Chalk at depth. The Diss area is to the north of the River Waveney and has a geology of drift resting on Chalk.

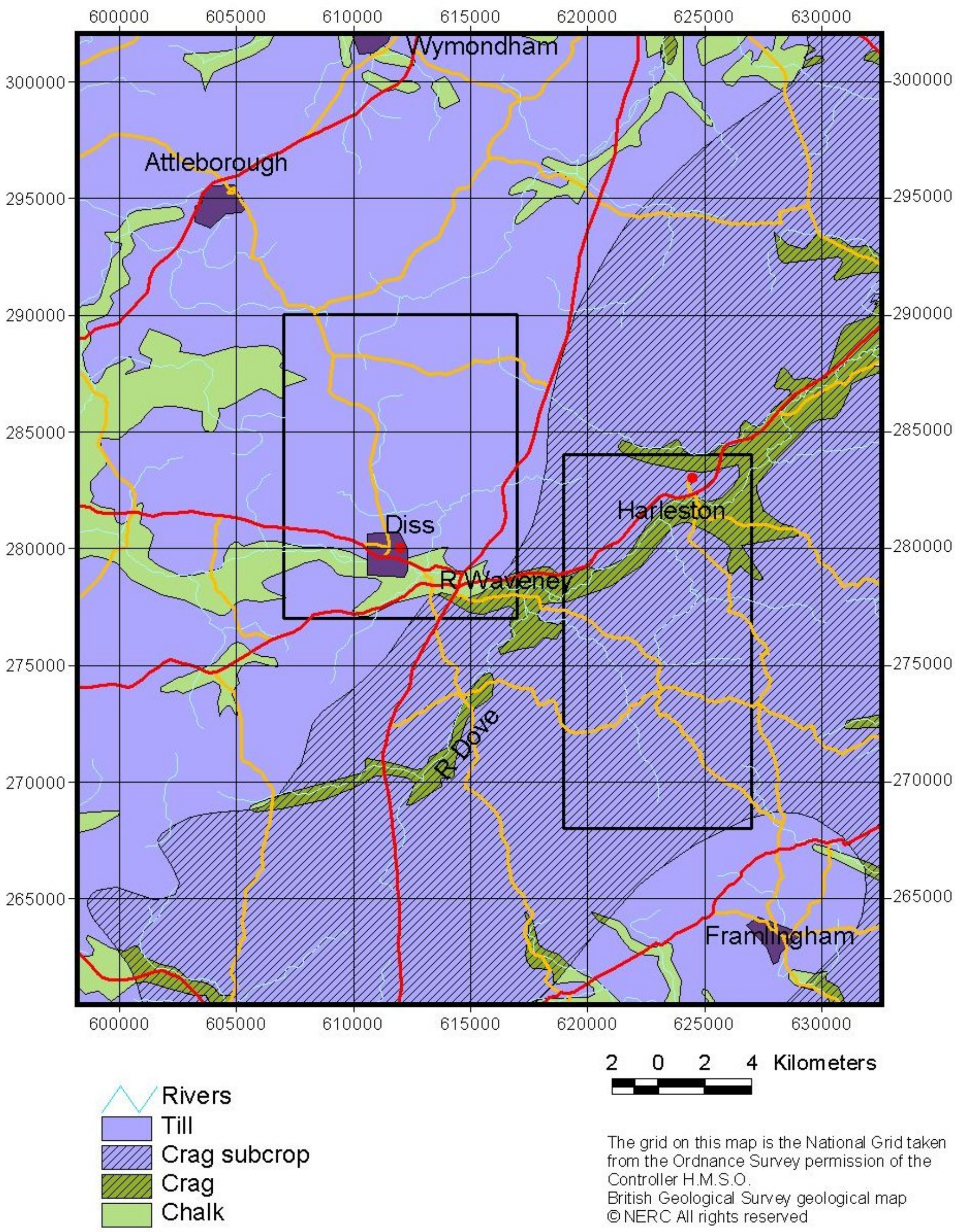

Figure 6.1 Location map for the case study areas

6.1 WAVENEY-HARLESTON

This case study area lies to the south of the River Waveney and is largely agricultural (cereal cultivation accounts for about 80% of the land use). The area is a till-covered plateau cut by two intermittent streams that flow through Fressingfield and Chickering and drain into the River Waveney (Figure 6.2).

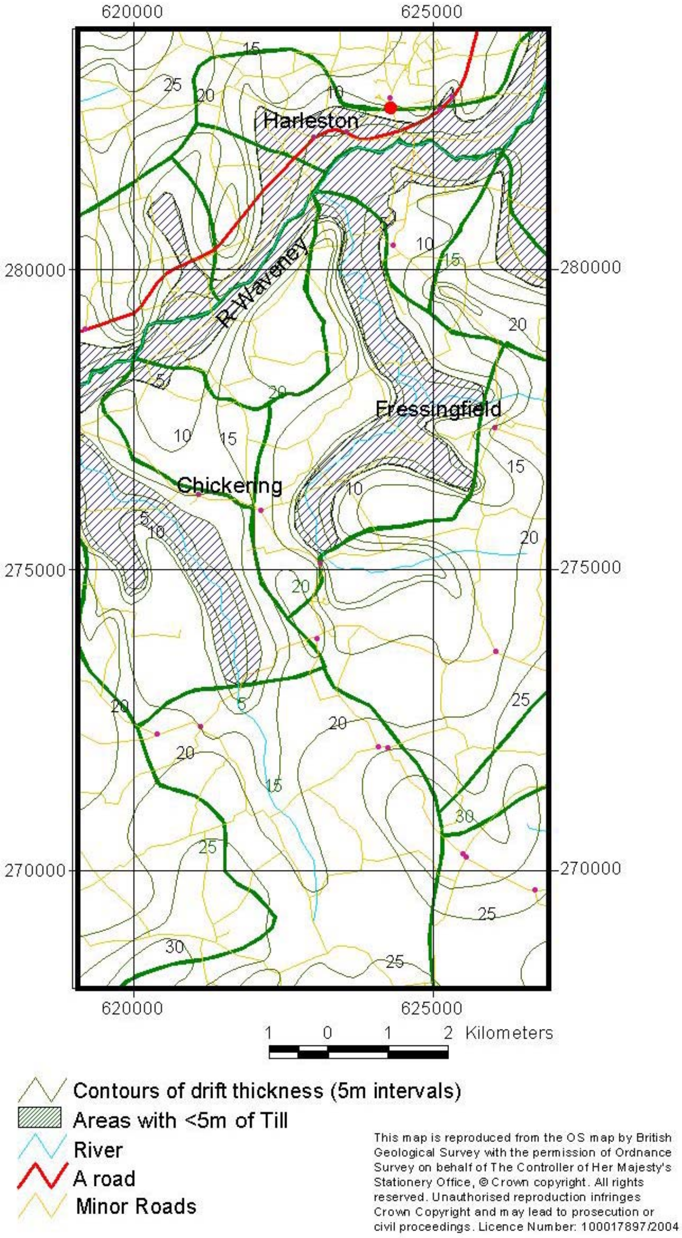

Figure 6.2 Harleston study area with till thickness

Over most of the area, thick till deposits overlie glacio-fluvial sand and gravel which in turn overlie the Crag (Figure 6.3). The Crag, which is an important aquifer in this area, is more than 30 m thick and rests unconformably upon the Chalk at depth. The Crag contributes baseflow to the River Waveney. The two intermittent streams that drain into the River Waveney have cut through the till in their lower reaches (Figure 6.2).

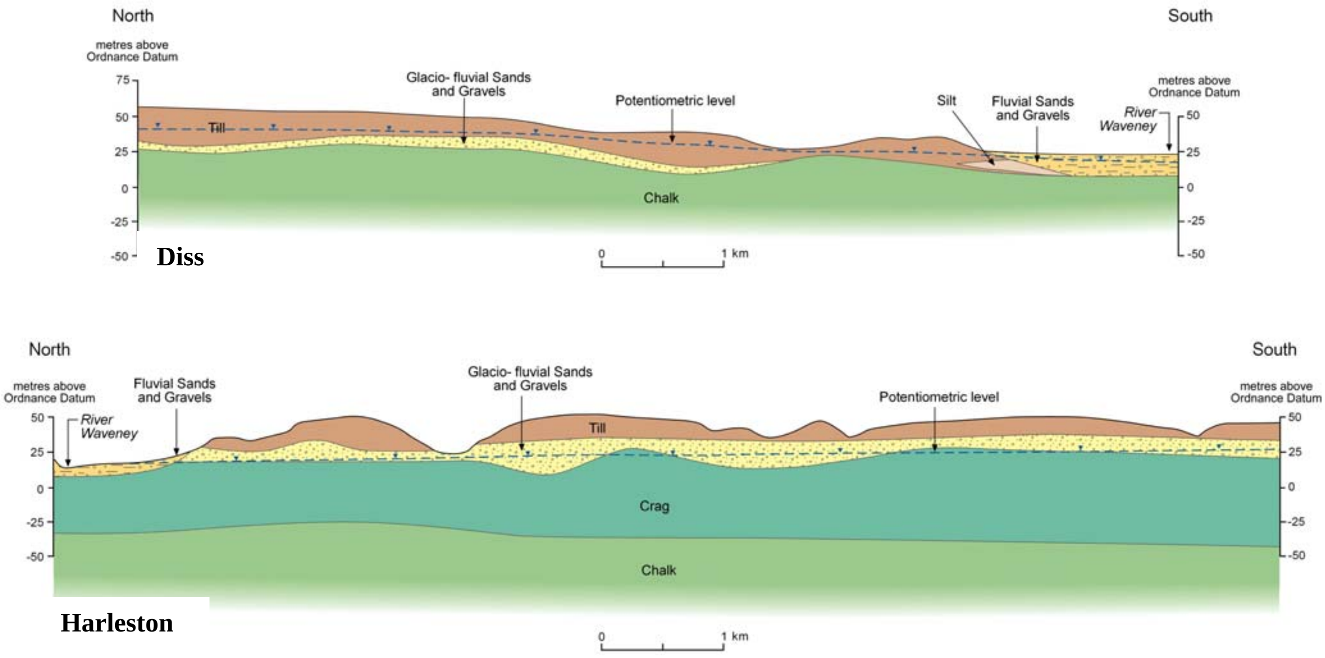

Figure 6.3 Geological sections of the Harleston and Diss study areas

6.1.1 Recharge assessment

STEP 1: DELINEATING THE MAIN RECHARGE AREAS

A till thickness map was prepared using borehole records (Figure 6.2); this showed that the major recharge zones (where till is either absent or less than 5 m thick) coincides with the valleys. These valley settings covered about 15% of the total catchment area.

STEP 2: ESTIMATE THE POTENTIAL RUNOFF RECHARGE COMPONENT

The surface water catchments, draining to the main recharge zones identified in Step 1, were delineated (Figure 6.4). Groundwater recharge to the main recharge areas comprises 2 or possibly 3 components:

1 Direct rainfall recharge

Within the main recharge area all the hydrogeologically effective rainfall (or residual rainfall) is assumed to infiltrate. The hydrologically effective rainfall for this part of East Anglia is 160 mm/a.

2 Runoff recharge from adjacent till-covered areas

Much of the rain falling on the till-covered areas, adjacent to the main recharge area, will runoff and enter the main recharge area:

- as overland flow
- via land drainage system
- via ditches/small streams (often receiving land drainage)

It is convenient to assume that the runoff component of recharge can potentially infiltrate over the whole of the main recharge area although in practice, recharge is likely to be concentrated along the course of the ditches and small streams and along the edge of the till cover. The amount of runoff available from adjacent till covered areas is equivalent to the difference between the hydrologically effective rainfall (160 mm/a) and the groundwater infiltration through thick till (20 mm/a). The volume of runoff can be considerable and depends on the area of the adjacent till cover that drains into the main recharge areas. The diffuse components of recharge over the main recharge area, therefore, are the direct rainfall recharge and the runoff component from adjacent till covered areas. An average rate can be estimated (Table 6.1).

3 Stream bed infiltration

A third component of recharge that may be available within the main recharge area is streambed infiltration. In those till-covered catchments not immediately adjacent to the main recharge area (and referred to in this report as upper catchments), runoff will flow, eventually, into the main stream draining these upper catchments. This stream will later flow into the main recharge area where infiltration through the streambed may occur. This component of recharge produces a linear zone of recharge.

The amount of streambed infiltration depends, amongst other factors, on:

- vertical hydraulic conductivity of the streambed
- the difference in head between the river stage and the aquifer
- stream dimensions

The volume of water draining these upper catchments is estimated as the product of the upper catchment area and the difference between the hydraulically effective rainfall (160 mm/a) and deep infiltration through the till (20 mm/a). The amount of infiltration can be estimated approximately (Rushton, 2003) and compared with the total stream flow.

In both the Fressingfield and Chickering catchments all available water is estimated to infiltrate through the streambed with an average distribution through the year (Table 6.2). However, it is likely that some high winter flows will exceed the daily maximum and runoff to the River Waveney will occur.

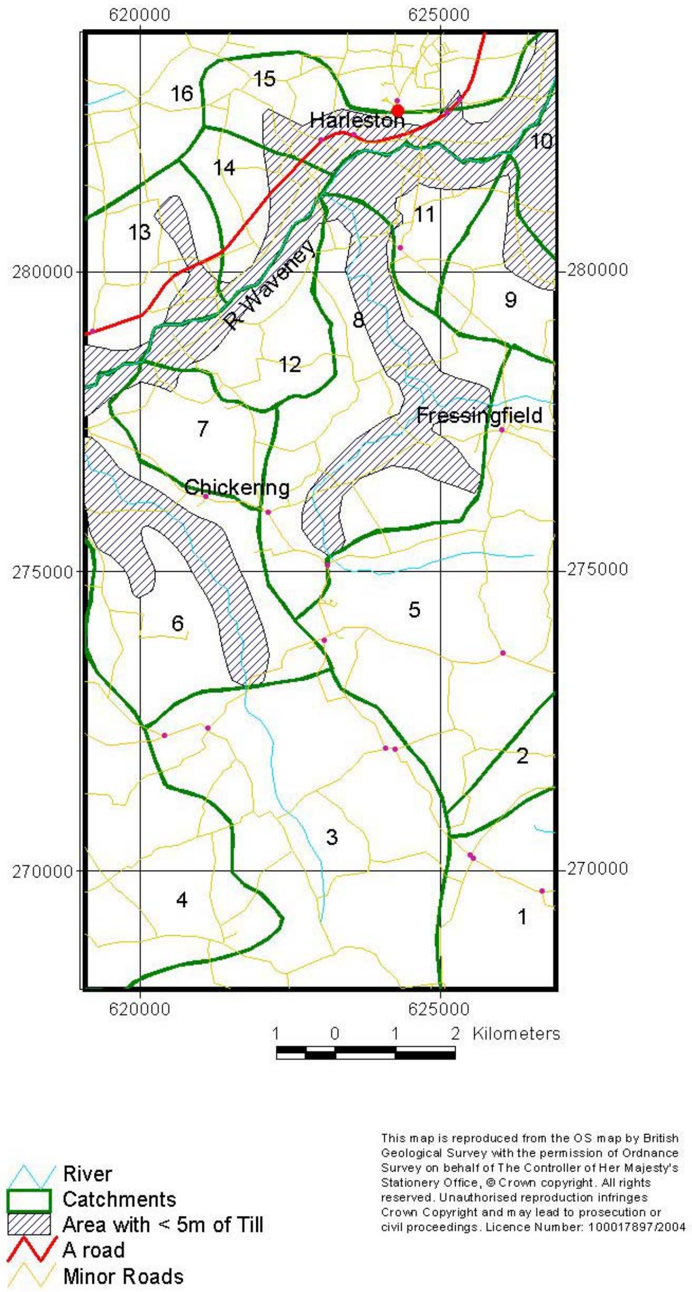

Figure 6.4 Surface water catchments with main recharge zones for the Harleston area

Table 6.1 Harleston: Potential resource available for recharge

	Sample sub-catchment	**Area (km^2)**	**Direct recharge (mm/a)**	**Runoff rate (mm/a)**	**Recharge and runoff volume (Mm^3/a)**	**Remarks**
1a	River Waveney (main recharge area)	9.8	160[1]	0	1.57	All hydrologically effect rainfall available for recharge
1b	River Waveney (adjacent till covered areas)	15.8	<20[2]	140[3]	2.21	This runoff is available for recharge within the main recharge area
2a	Fressingfield tributary (main recharge area)	5.7	160	0	0.92	All hydrologically effect rainfall available for recharge
2b	Fressingfield tributary (adjacent till covered areas)	9.6	<20	140	1.34	This runoff is available for recharge within the main recharge area
2c	Fressingfield tributary (upper catchment)	17.4	<20	140	2.44	Runoff flows to stream and is available for stream bed recharge in the main recharge area
1a	Chickering tributary(main recharge area)	4.7	160	0	0.75	All hydrologically effect rainfall available for recharge
1b	Chickering tributary(adjacent till covered areas)	8.1	20	140	1.13	This runoff is available for recharge within the main recharge area
1c	Chickering tributary(upper catchment)	18.8	20	140	2.63	Runoff flows to stream and is available for stream bed recharge in the main recharge area

Note 1 Recharge in main recharge area (equivalent to hydrologically effective rainfall (160 mm/a)).

Note 2 Infiltration through till is assumed to be 20 mm/a (but could be as low as 5 mm/a).

Note 3 Runoff assumed to be hydrologically effective rainfall – recharge through till (140 mm/a).

Table 6.2 Harleston: Potential recharge in the main recharge areas from the sub-catchments

Sample sub-catchment	Total area (km^2)	Main recharge area (km^2)	Direct recharge (Mm^3/a)	Runoff recharge (Mm^3/a)	Total diffuse potential recharge in main recharge area (Mm^3/a)	(mm/a)	Potential stream bed recharge (Mm^3/a)
River Waveney	25.6	9.8	1.57	2.21	3.78	386	NA
Fressingfield tributary	32.7	5.7	0.92	1.34	2.26	397	2.44
Chickering tributary	31.6	4.7	0.75	1.13	1.88	400	2.63

STEP 3: QUALITATIVE ASSESSMENT OF LIKELY RECHARGE (IN MAIN RECHARGE AREAS)

(i) Slope

The slopes on the valley sides and the valley floor margins to the south of the River Waveney are relatively gentle (Table 6.3) providing opportunity for most of the runoff component to infiltrate. Likewise, the intermittent streams, draining into the River Waveney, also have relatively flat valley floors and gently sloping sides in the lower part of the valleys.

Table 6.3 Recharge conditions in the main recharge areas within in the Harleston catchment

Main recharge areas	Slopes of land surface	Lithology at surface	Drainage	Depth to water table	Assessment
Valley of River Waveney	Gentle	Permeable alluvium (some peat)	Evidence of streams losing to groundwater	Shallow close to the River Waveney (recharge repelled during times of flood) but deeper at valley margins	Recharge rate may approach maximum potential
Fressingfield and Chickering tributaries	Gentle	Some thin clay till on valley slopes; sand and gravel on valley floor	Intermittent stream likely to dry during the summer. Evidence of streams losing to groundwater	Several metres below the river, which acts as a line source of recharge	Recharge rate may approach maximum potential

(ii) Lithology at surface

The valley floor of the River Waveney is underlain by generally permeable deposits (Table 6.3) and so recharge may be at the potential rate. However, the water table is shallow near to the centre of the valley (and this may limit infiltration rates) but deeper at the valley margins. The valley margins may represent the zone of most intensive recharge.

In the mid to lower valleys of the intermittent streams, the surface deposits are very permeable and the water table several metres below ground surface. Infiltration may be at the potential rate.

(iii) **Drainage**

The hydrogeological map (Moseley et al., 1981) shows the streams, draining to the River Waveney, to be intermittent (Table 6.3) over all but their lower reaches. Further, borehole records suggest that the water table is several metres below the floor of the valley and that the depth to the water table increases away from the river. The implication is that the river is a linear recharge source and that it is possible for some of the runoff flowing down the stream from the till sheet to infiltrate to groundwater in the valleys of the two intermittent streams.

The infiltration in the main recharge area of the River Waveney valley is probably close to 386 mm/a (Table 6.2) because most, possibly all, of the runoff component is able to infiltrate. Schematic hydrogeological sections showing recharge mechanisms in the zones of main recharge are presented in Figures 6.5 and 6.6

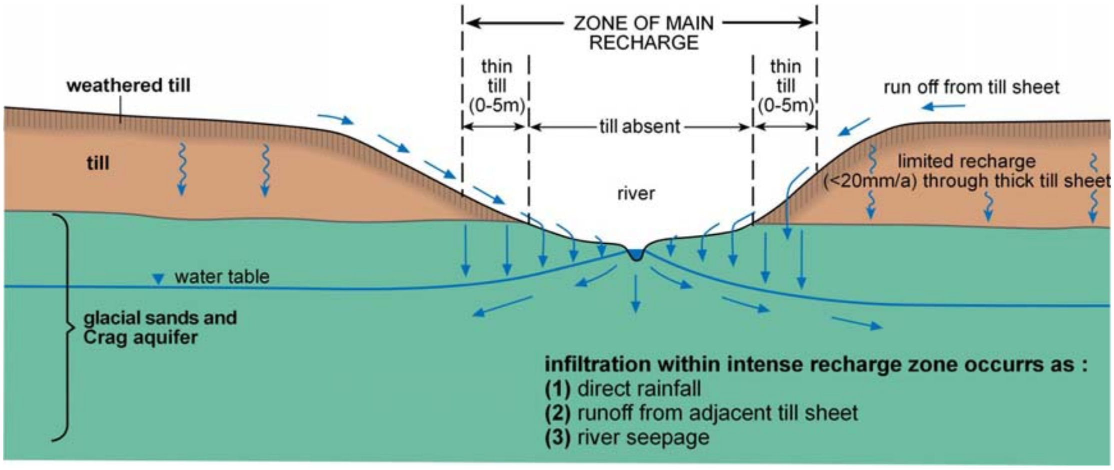

Figure 6.5 Schematic section showing recharge mechanisms within a tributary valley

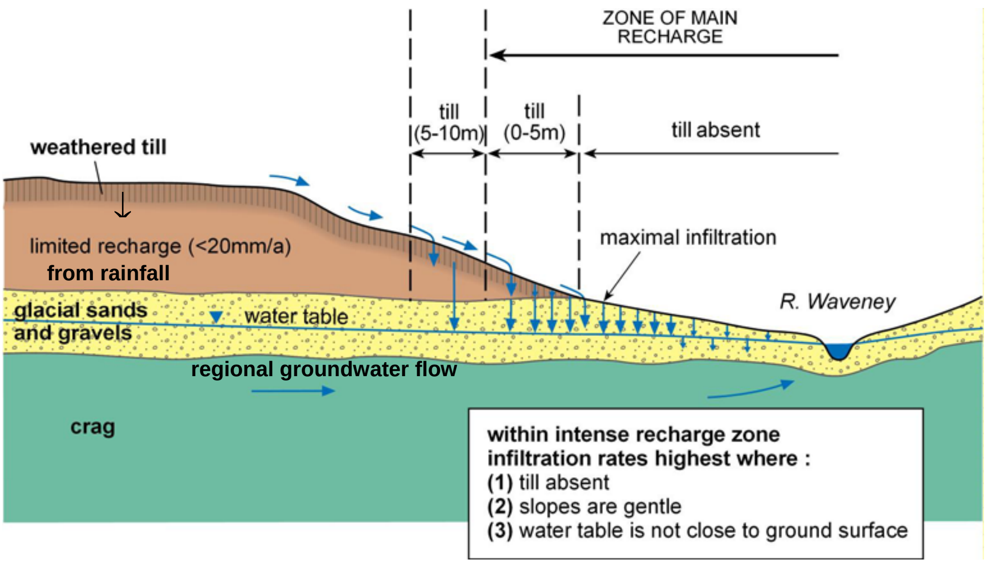

Figure 6.6 Schematic section showing recharge mechanisms within the main Waveney valley

Much of the recharge in this study area will occur within the Waveney and two tributary valleys, especially at the margins of the valleys where the water table is deeper.

6.2 WAVENEY-DISS

This case study area lies to the north of the River Waveney and includes the town of Diss. The area is mostly a till-covered plateau and is principally drained by the stream, which flows through Shelfanger into the River Waveney (Figure 6.7). Arable cultivation is the dominant land-use in the catchment.

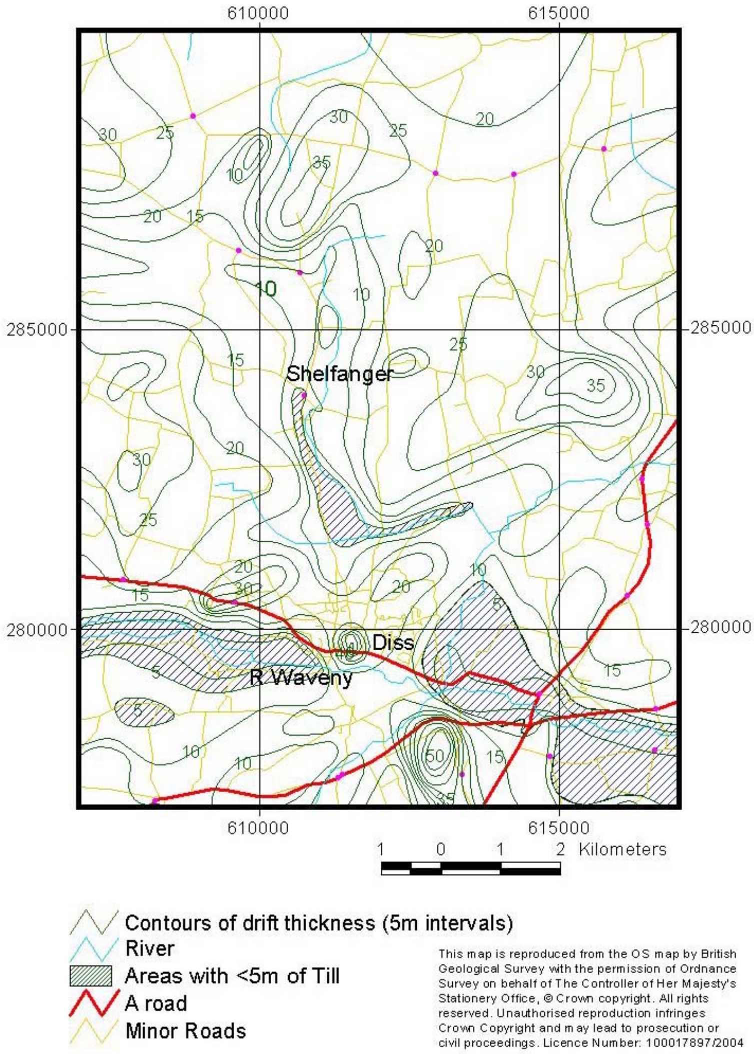

Figure 6.7 Diss study area with till thickness

A thick (up to 50 m) till sheet, which covers about 90 % of the catchment overlies the Chalk formation. Glacio-fluvial sand and gravel is usually present at the base of the till (Figure 6.3). In the Waveney valley, till is usually absent, apart from where a buried valley cuts across the present valley, and alluvium occupies most of the valley floor.

The Shelfanger stream flows over the till sheet, although in places the till thickness is less than 5 m. A thin ribbon of alluvium is present beneath most of the course of this stream.

6.2.1 Recharge assessment

STEP 1: DELINEATING THE MAIN RECHARGE AREAS

A till thickness map was prepared (Figure 6.7); this shows 3 major recharge zones where the till is either absent or less than 5 m thick. Two of these zones coincide with the Waveney valley (and are separated by the buried valley feature) and the third is within a reach of the

Shelfanger stream. In the first two areas till is absent and the area extends to where the till is 5 m thick and in the third area the till is present but less than 5 m thick. These main recharge areas make up about 10 % of the total catchment.

STEP 2: ESTIMATE THE POTENTIAL RUNOFF RECHARGE COMPONENT

The surface water catchments, draining to the main recharge areas identified in Step 1, were delineated (Figure 6.8). Potential groundwater recharge to the main recharge areas comprises 2 or possibly 3 components:

1. Direct rainfall recharge

All the hydrogeologically effective rainfall (or residual rainfall) is assumed to infiltrate within the main recharge area. The hydrologically effective rainfall for this part of East Anglia is 160 mm/a.

2. Runoff recharge from adjacent till-covered areas

Much of the rain falling on the till-covered areas, adjacent to the main recharge area, will runoff and enter the main recharge area:

(a) as overland flow

(b) via land drainage system

(c) via ditches/small streams (often receiving land drainage)

It is convenient to assume that the runoff component of recharge can potentially infiltrate over the whole of the main recharge area although in practice, recharge is likely to be concentrated along the course of the ditches and small streams and along the edge of the thick till cover. The amount of runoff available from adjacent till covered areas is equivalent to the difference between the hydrologically effective rainfall (160 mm/a) and the groundwater infiltration through thick till (20 mm/a). The volume of runoff can be considerable (Table 6.4) and depends on the area of the adjacent till cover that drains into the main recharge area. The diffuse components of recharge over the main recharge area are the direct rainfall recharge and the runoff component from adjacent till covered areas. An average rate can be estimated (Table 6.5).

3. Stream bed infiltration

A third component of recharge that may be available within the main recharge area is streambed infiltration. In those till-covered catchments not immediately adjacent to the main recharge area (and referred to in this report as upper catchments), runoff will flow, eventually, into the main stream draining these upper catchments. This stream will later flow into the main recharge area where infiltration through the streambed may occur. This component of recharge produces a linear zone of recharge.

The amount of streambed infiltration depends, amongst other factors, on:

- vertical hydraulic conductivity of the streambed
- the difference in head between the river stage and the aquifer
- stream dimensions

The volume of water draining these upper catchments is estimated as the product of the upper catchment area and the difference between the hydraulically effective rainfall (160 mm/a) and deep infiltration through the till (20 mm/a). The amount of infiltration can be estimated approximately (Rushton, 2003) and compared with the total stream flow.

In the Shelfanger sub-catchment the main recharge area is an area of thin till (<5 m) where recharge is limited by the low permeability of the till such that most of the available water resources is likely to flow out of the sub-catchment to the River Waveney (Table 6.5).

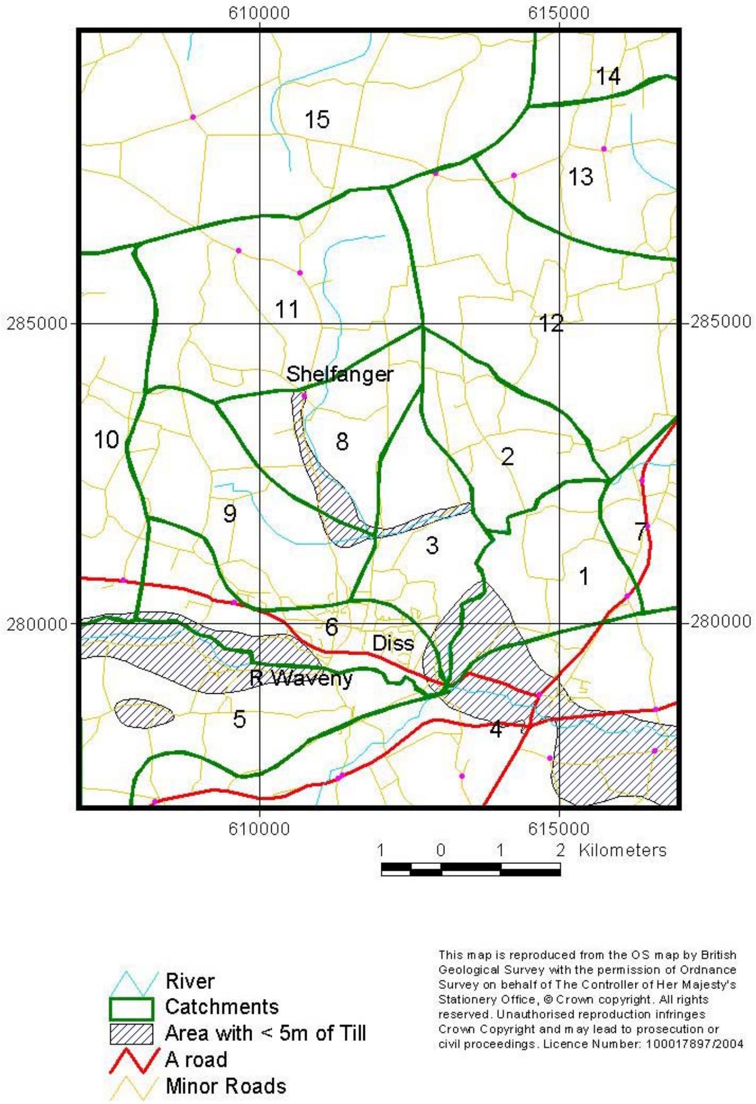

Figure 6.8 Surface water catchments with main recharge zones for the Diss area

Table 6.4 Diss: Potential resource available for recharge

	Sample sub-catchment	Area (km^2)	Direct recharge (mm/a)	Runoff rate (mm/a)	Recharge and runoff volume (Mm^3/a)	Remarks
1a	River Waveney (main recharge area)	8.8	160[1]	0	1.41	All hydrologically effect rainfall available for recharge
1b	River Waveney (adjacent till covered areas)	24.2	<20[2]	140[3]	3.39	This runoff is available for recharge within the main recharge area
2a	Shelfanger tributary (main recharge area)	0.7	160	0	0.11	All hydrologically effect rainfall available for recharge
2b	Shelfanger tributary (adjacent till covered areas)	5.1	<20	140	0.71	This runoff is available for recharge within the main recharge area
2c	Shelfanger tributary (upper catchment)	12.2	<20	140	1.71	Runoff flows to stream and is available for stream bed recharge in the main recharge area

Note 1 Recharge in main recharge area (equivalent to hydrologically effective rainfall (160 mm/a)).

Note 2 Infiltration through till is assumed to be 20 mm/a (but could be as low as 5 mm/a).

Note 3 Runoff assumed to be hydrologically effective rainfall – recharge through till (140 mm/a).

Table 6.5 Diss: Potential recharge in the main recharge areas from the sub-catchments

Sample sub-catchment	Total area (km^2)	Main recharge area (km^2)	Direct recharge (Mm^3/a)	Runoff recharge (Mm^3/a)	Total potential diffuse recharge in main recharge area (Mm^3/a)	(mm/a)	Potential stream bed recharge (Mm^3/a)
River Waveney	33.0	8.8	1.41	3.39	4.80	545	NA
Shelfanger tributary	18.0	0.7	0.11	0.71	0.82	1171	1.71

STEP 3: QUALITATIVE ASSESSMENT OF LIKELY RECHARGE (IN MAIN RECHARGE ZONES)

(i) **Slope**

The surface slopes in the valley floor and sides of the River Waveney are generally gentle (Table 6.6). The tributary valley of the Shelfanger stream also has mostly gentle slopes.

Table 6.6 Recharge conditions in the main recharge areas within the Diss catchment

Main recharge areas	Slopes of land surface	Lithology at surface	Drainage	Depth to water table	Assessment
Valley of River Waveney	Gentle	Permeable alluvium (some peat)	Evidence of streams losing to groundwater	Shallow close to the River Waveney (recharge repelled during times of flood) but deeper at valley margins	Recharge rate may approach maximum potential (140 mm/a)
Shelfanger tributary	Gentle	Some thin clay till in valley; sand and gravel on valley floor	Intermittent stream likely to dry during the summer	Several metres below the stream, which acts as a line source of recharge	Recharge rate may approach maximum potential (140 mm/a)

(ii) **Lithology of surface**

The valley floor of the River Waveney is underlain by permeable alluvium (Table 6.6) and so infiltration rates are potentially high. However, close to the River Waveney, the water table is shallow and so some potential recharge may be rejected during periods of high rainfall.

The Shelfanger stream has only a narrow ribbon of permeable alluvium and most of the main recharge zone is underlain by thin till. While the infiltration capacity of the weathered till is likely to be considerably greater than that on the adjoining interfluve it is unlikely to be sufficient to accept all the potential recharge available especially as the water level in the underlying Chalk aquifer is close to the ground surface (Figure 6.9).

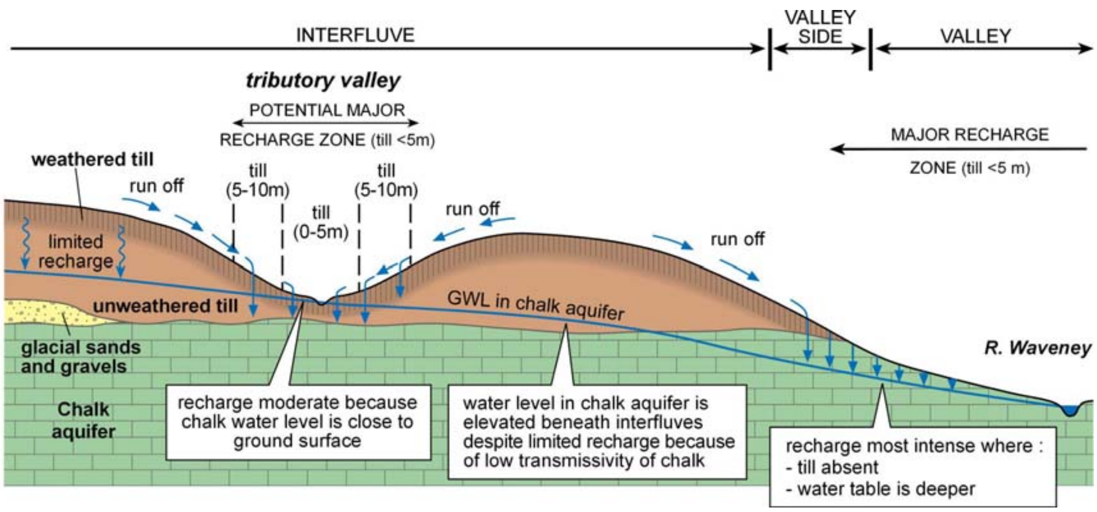

Figure 6.9 Schematic section showing recharge mechanisms in the Diss area.

(iii) **Drainage**

There is no evidence for the Shelfanger stream disappearing, although it is intermittent in the upper part (Table 6.6). As the water level of the underlying Chalk aquifer is shallow and fluctuates within the till, recharge to the Chalk aquifer is unlikely to be at the potential rate.

The River Waveney infiltration in the main recharge areas is probably close to 545 mm/a (Table 6.5) because most, possibly all, of the runoff component is able to infiltrate.

(iv) **Summary**

Much of the recharge to this catchment will occur within the Waveney valley, especially at the margins of the valley where the water table is deeper. Recharge rates within the main recharge area associated with the Shelfanger stream is certainly less than the potential rate and, given the limited area of thin till and the shallow depth to groundwater level, recharge quantities are likely to be moderate at best. Much of the potential diffuse recharge (0.82 Mm^3/a or 1171 mm/a) (Table 6.5) is, therefore, likely to runoff. Likewise much of the water potentially available as streambed infiltration will also runoff. Further investigations are required to provide any quantitative estimates.

7 Discussion

An assessment of the distribution of recharge in two catchments (with extensive till cover) has been made using the till thickness map. There are significant differences between these two catchments both in terms of overall catchment recharge (to groundwater) and, to a lesser extent, on the distribution of this recharge. Both areas largely drain to the River Waveney; one of these areas (Waveney-Harleston) is underlain by Crag whilst the other catchment (Waveney-Diss) is underlain by Chalk.

The main recharge zones for the Waveney-Harleston area are the valleys of the River Waveney and those of the two streams, which flow through Fressingfield and Chickering where till is absent and where alluvium, or fluvio-glacial sand and gravel, are exposed. The remaining areas in the catchment are largely covered by thick till (>10 m) and, therefore, will accept limited recharge (20 mm/a). Thus a considerable volume of runoff is available for groundwater recharge in the main recharge areas. Most of this runoff is likely to infiltrate because within the River Waveney and the Fressingfield and Chickering streams the slopes are relatively gentle and generally permeable sediments are present at the surface permitting high infiltration rates. In addition, the water table in the valleys of the Fressingfield and Chickering streams are several metres below ground level (and river base) and so the rivers act as a line source of recharge (Figure 6.5).

In the Waveney-Diss area, the recharge is largely restricted to the valley of the River Waveney. Recharge within the tributary valley of the Shelfanger stream is only moderate and much less than the infiltration rates estimated for the valleys draining to the River Waveney in the Harleston area; this is because:

1. The Shelfanger stream has not cut through the till sheet completely to expose the underlying aquifer, as did the Fressingfield and Chickering streams in the Harleston area.
2. The groundwater levels are deeper beneath the tributary valleys in the Harleston area compared with those beneath the Shelfanger stream.

The flatter (and lower) groundwater levels observed beneath the interfluves in the Crag aquifer when compared with those in the Chalk are due to the higher transmissivity of the Crag beneath the interfluves. The Crag has a relatively constant transmissivity based on intergranular flow while the Chalk transmissivity is very variable being high within the main valleys (>500m^2/d) but low beneath the interfluves (<50m^2/d). One consequence is that a greater proportion of the runoff from the till sheet will reach the River Waveney in the Diss area compared with that in the Harleston area.

The methodology presented here is based solely on a desk study and has not been verified by field-based measurements

There is a need for catchment scale water balance studies for various catchment types, which would include:

(i) measuring runoff and river flow

(ii) monitoring water quality in both groundwater and surface water

(iii) modelling of groundwater levels

Such research would help validate the conceptual models presented here and provide improved confidence in developing a methodology to estimate recharge primarily based on till thickness.

8 Conclusions

1. Till thickness appears to be the principal control on recharge and the till thickness map provides a useful first step to identifying the main recharge areas.
2. Infiltration through thick till (>10 m) is low and as a consequence, runoff from the till sheet is large and is potentially a significant component of recharge at the margins of the till sheet. Estimating the quantity of water that may runoff the till sheet is essential when attempting to assess the amount and distribution of groundwater recharge.
3. An important issue, when considering catchment water balances, is the relative proportion of runoff that infiltrates to groundwater at the margins of the till sheet, compared with that which flows directly into the river. A qualitative assessment based on lithology at surface, slope and depth to water table can be made. However, there remains considerable uncertainty as to how much infiltration may occur, especially where thin till is present. Catchment scale studies are required to evaluate how catchment characteristics influence the infiltration rates and the relative proportion of runoff from the till sheet that recharges groundwater compared with direct contribution to river flow.
4. It is important to recognize that groundwater is contained within a dynamic system and that abstraction, with a consequent lowering of the water table, may induce recharge down gradient of the till sheet at the expense of direct runoff into the main river.
5. The time-lag between rain falling at the soil surface and recharge arriving at the water table will be substantially shorter at the margins of the till sheet where the water table is generally less deep and recharge rates are higher (because of the additional recharge derived from runoff) when compared with areas of extensive Chalk outcrop where the depth to water table may exceed 20-30 m over large areas of the catchment. This has important implications for water quality, as widespread changes in land-use are likely to be observed more rapidly in groundwaters at the edge of the sheet than in areas of extensive Chalk outcrop.

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