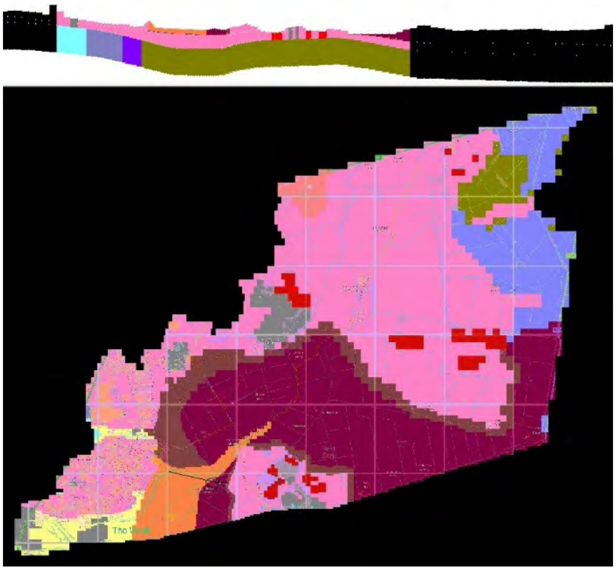
Hydrological Modelling of the Flag Fen Archaeological Site and Wider Landscape: Main Report

Final Report for Project 6187 MAIN

February 2015



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Contract

This report describes work commissioned by Zachary Osborne, on behalf of English Heritage, by an e-mail dated 18th June 2014. English Heritage's representative for the contract was Zoe Outram of English Heritage. Alice Davis, Sam Bishop and James Cheetham of JBA Consulting carried out this work. Dr Henry Chapman of the University of Birmingham provided archaeological assistance as a subcontractor to JBA.

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Purpose

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Acknowledgements

JBA would like to thank Sarah Wilson of Vivacity and Paul Sharman of North Level IDB for their help with this work.

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Executive Summary

Concern exists regarding the long-term viability of the archaeological remains of the Flag Fen basin near Peterborough, the principal archaeological site of which is the Bronze Age Scheduled Ancient Monument (SAM) timber platform and post alignment (causeway) of Flag Fen. The delicate organic archaeological remains associated with the site are thought to be degrading as a result of desiccation of the local soil and underlying deposits, resulting from a lowering of the water table. Indeed, the Bronze Age timber structure at Flag Fen was discovered during the deepening of a major drainage ditch (the Mustdyke) in 1982, and a year later the effects of drying out were clearly evident in the ditch banks (Pryor, 1992).

This project has developed a hydrogeological conceptual model of the Flag Fen site and surrounding area, and has used this as the basis for a numerical groundwater model. The numerical model has been used to better understand the current situation (especially the relationship between groundwater levels and preserved organic archaeology) and also to explore potential future scenarios. Future scenarios considered include both external threats (climate change and development) and potential water level management schemes.

Observed and modelled groundwater levels have been interpreted using the classification of Chapman and Cheetham (2002), which identifies three zones: the "dry" zone above the seasonal maximum water table (Zone 1), the zone of seasonal water table fluctuation which is intermittently wet and dry (Zone 2), and the deeper zone of permanent saturation (Zone 3). Archaeological wood is best preserved in Zone 3 and least well preserved in Zone 1. Much of the Bronze Age wooden structure at Flag Fen is located within Zone 2 (or even in Zone 1) of the Chapman and Cheetham (2002) scheme. The hydrological conditions are therefore not ideal for the long-term *in situ* preservation of the material.

The main factor controlling groundwater levels in the Flag Fen area is artificial drainage. Climate seems to be less of an influence. Drainage has lowered groundwater levels in what would naturally be a wet fenland area. The Mustdyke, a drainage ditch that crosses the eastern end of the Bronze Age platform/causeway, exerts a particularly strong influence.

In 1987 an artificial pond (the Large Mere) was constructed over the assumed location of the Bronze Age timber platform in order to raise groundwater levels by artificial recharge. Modelling undertaken for this study suggests that leakage from the pond may indeed be maintaining locally high groundwater levels. However, the extent to which artificial recharge is benefiting the wooden structure is unclear, partly because the location and extent of the platform are uncertain (recent exploration having cast doubt on the original assumptions), and partly because flushing by surface water may potentially affect the preservation of archaeological wood. Further work would be required to assess the benefits, or otherwise, of the artificial recharge.

One of the modelling scenarios investigated the potential impact of a nearby development (PREL Energypark) on groundwater levels in the area of the Bronze Age causeway and platform. This was to address the concerns of English Heritage that hardstanding associated with the development might reduce recharge to groundwater (through reduced infiltration) and thereby lower groundwater levels. The results of the modelling suggest that hardstanding associated with the development is unlikely to have a significant influence on groundwater levels at the Flag Fen archaeological site. By extension, wind farm developments (which involve only a small "footprint" of impermeable, or low permeability, structures) are unlikely to pose a significant threat to groundwater levels at Flag Fen.

If groundwater levels are to be raised at Flag Fen then it will be necessary to address the problem of artificial drainage. This study has used modelling to undertake a preliminary assessment of potential management options, including the creation of a wetland (through ditch blocking) to the south of Flag Fen and the diversion of drainage ditches away from the archaeological features. The ditch diversion scenarios gave the best results in terms of raising groundwater levels. Any ditch blocking or diversion scheme would require further studies to assess its feasibility and environmental (including flooding) impact, and English Heritage would need to liaise closely with the Environment Agency and Internal Drainage Board.

Contents

List of Figures

List of Tables

Abbreviations

DW .... Dipwell

IDB .... Internal Drainage Board

JBA .... Jeremy Benn Associates

mAOD .... metres Above Ordnance Datum

mbgl .... metres below ground level

MODFLOW .... MODular three-dimensional finite-difference groundwater FLOW Model

MORECS .... Meteorological Office Rainfall and Evaporation Calculation System

MoRPHE .... Management of Research Projects in the Historic Environment

SAM .... Scheduled Ancient Monument

SW .... Stilling Well

1 Introduction

1.1 Background

Concern exists regarding the long-term viability of the archaeological remains of the Flag Fen basin near Peterborough, the principal archaeological site of which is the Bronze Age Scheduled Ancient Monument (SAM) timber platform and post alignment of Flag Fen (Map 1 and Map 2). The delicate organic archaeological remains associated with the site are thought to be degrading as a result of desiccation of the local soil and underlying deposits, resulting from a lowering of the water table.

1.2 Aim and Scope of Study

English Heritage commissioned JBA to undertake a hydrogeological study to develop an understanding of how water management within the wider Flag Fen basin impacts upon the Flag Fen SAM. The project objectives included:

- Developing a conceptual model (understanding) of the hydrology and hydrogeology of the Flag Fen basin and wider fenland landscape.
- Developing a numerical groundwater flow model using existing data and using the model to (i) help understand the current situation and (ii) predict groundwater levels for future scenarios (e.g. land use change, drainage and drought).
- Understanding where data/knowledge gaps may exist that might limit the robustness of future decision-making in relation to the preservation of the Flag Fen SAM.
- Developing future water level management recommendations, the implementation of which will help secure the long-term preservation of the Flag Fen SAM and organic archaeological remains within the Flag Fen basin.

1.3 Data Sources

The data used in the desk study were obtained from the following sources:

- Previous reports and other relevant documentation relating to the site:
    - Peterborough Renewable Energy Limited (PREL), Peterborough Energy Park: A Hydrogeological Assessment of the impacts of construction and operation on the Flag Fen archaeological site (PREL, 2008).
    - CgMs Consulting report on behalf of Church Commissioners for England in respect of Red Brick Farm, Peterborough: Archaeological Desk Based Assessment (Dawson, 2011).
    - A number of relevant archaeological studies of Flag Fen and the surrounding area, including: Pryor (1991, 1992), French and Pryor (1993), Chapman and Cheetham (2002), Lillie and Cheetham (2002), Redding (2005), Bamforth (2007), Pryor and Bamforth (2010), Dawson (2011), DigVentures (2012) and Murrell (2013).
    - Information from Vivacity on the locations of archaeological excavations in the Flag Fen area. This took the form of maps and an accompanying spreadsheet.
- Topography and general mapping:
    - LIDAR Digital Terrain Model (DTM) (1 m and 2 m resolution)
    - Aerial photography (Google Earth and Bing Maps)
- Climate:
    - Flood Estimation Handbook (FEH) and CD-ROM (CEH, 2009)
    - Meteorological Office Rainfall and Evapotranspiration Calculation System (MORECS) data
- Geology and Soils:
    - BGS 1:50,000 Geology Map, Solid and Drift Edition, Sheet 158, Peterborough
    - BGS digital geology mapping
    - BGS Geological Memoir for the area covered by the above map. Geology of the Peterborough District (Horton, 1989)

- BGS online borehole database (BGS website)
    - BGS online Lexicon (BGS website)
    - 1:250,000 soils mapping (Soil Survey of England and Wales, 1983)
- Hydrogeology:
    - Aquifer classification (Environment Agency website)
    - Groundwater vulnerability (Environment Agency website)
    - Source Protection Zones (Environment Agency website)
    - Licensed abstractions and discharges (Environment Agency)
    - Groundwater quality (Environment Agency website; ESI, 2006)
    - Major (Principal) Aquifer properties manual (Allen et al., 1997)
    - Minor Aquifer properties manual (Jones et al., 2000)
    - General hydrogeological references (Freeze and Cherry, 1979; Brassington, 2007).
    - Water level monitoring data (2008-2011) for Flag Fen and a map showing the locations of monitoring points (supplied by English Heritage). The monitoring infrastructure had been installed by Atkins.
- Hydrology and drainage:
    - North Level Internal Drainage Board (IDB): catchments, rainfall, water level data, drainage network, flow directions and details of pumping (set levels and pump capacity).
    - Website of North Level IDB: http://www.northlevelidb.org/

Information on the elevation of archaeological wood within the ground profile at Flag Fen was obtained from Dr Henry Chapman (University of Birmingham) and from a review by JBA's Dr James Cheetham. Both Henry and James drew on the existing literature (see archaeological references listed above). Additional information was obtained during a visit to Vivacity.

A site visit was undertaken by a JBA Hydrogeologist on 15 to 18 September 2014. This included the following:

- Site walkover survey:
    - Examination of the ponds and visible features of the soils and drainage.
    - Estimation of ditch widths, water levels and bank heights.
    - Photography.
- Meeting with Paul Sharman (Engineer to the Board) of North Level IDB.
- Visit to Vivacity at Flag Fen to collect relevant information on the archaeology.

In addition, discussions were had with Bardon Aggregates (the operator of Pode Hole Quarry in the northern part of the study area), and also with the Environment Agency, in order to better understand the fate of water abstracted from the ground as part of the quarry working process at Pode Hole Quarry.

2 Hydrological Conceptual Model

2.1 Introduction

This chapter describes the hydrogeology of the Flag Fen Basin and surrounding Fenlands, and is based on a desk-based review of available information combined with observations made during a site walkover survey. The information contained in this chapter has been used to develop a hydrogeological conceptual model of the Flag Fen Basin.

A glossary of technical terms is provided in Appendix C.

2.2 A Brief History of the Fens

At the beginning of the Bronze Age, the River Nene flowed along the southern edge of what is now known as the Flag Fen Basin. During the Holocene era (10,000 BC to present) sea levels rose, with the North Sea encroaching further and further on to land. Over time, ground became saturated, peat began to form and the Fens were created.

People continued to live in this new area of marsh land. They retreated to higher ground situated at the edge of the Fens, built walkways to link together 'islands' of higher ground that emerged, and used boats for transportation. Deep layers of silt and peat built up forming a huge wet expanse of reed swamp and peat.

In the 17th Century, ditches were installed to drain the land for agriculture. Active drainage of the land continues to the present day, with open ditches maintained by Internal Drainage Boards. The Mustdyke, a major ditch passing through the eastern end of the Flag Fen archaeological site, was enlarged and deepened in 1972 in order to accommodate floodwater from eastern Peterborough (Pryor, 1992). It was further deepened in 1982, and it was this later deepening that led to the discovery of the Bronze Age wooden structures of Flag Fen (Pryor, 1992).

2.3 Topography, Climate and Land Use

2.3.1 Topography

The Flag Fen Basin is an area of low lying land (Map 3) which forms a part of the larger Fenland basin. The vast majority of the Fenland is fairly flat, with elevations generally between 0 and 3 mAOD (metres above ordnance datum). Higher land is present in the west and northwest of the study area. An increase in elevation to the west is concurrent with the area of outcrop of the older strata of the Ancholme Group, which comprise the bedrock in the area (see Section 2.4 on Geology).

2.3.2 Climate

The Flood Estimation Handbook (FEH) CD-ROM includes long-term average rainfall data for catchments in the UK. For the smallest FEH catchment covering much of the study area the Standard Annual Average Rainfall (SAAR) is 542 mm for the period 1961 - 1990 and 551 mm for the period 1941 - 1970 (CEH, 2009).

Monthly rainfall data was also provided by North Level IDB (Internal Drainage Board) taken from a rain gauge located at the Dog-in-a-Doublet Pumping Station in the south-eastern corner of the study area. This found the annual average rainfall for the period 2002 to 2013 to be approximately 505 mm/yr.

Figure 2-1 shows rainfall and evapotranspiration data derived from MORECS (Meteorological Office Rainfall and Evaporation Calculation System). The site lies within MORECS grid square 128 (40 km x 40 km). Figure 2-1 shows data for an average year from the period 1994 to 2013. The total average annual rainfall based on MORECS data is 615 mm; this is somewhat higher than the SAAR values from the FEH. As MORECS data are defined on a 40 km square grid, MORECS data values may not be representative of an individual small catchment, especially if the catchment is located at the edge of a square or if the terrain in the catchment is atypical. However, the site is not close to the edge of the relevant MORECS square, and most of the square consists of low-lying fenland with an altitude similar to that of Flag Fen. Nevertheless, the square does include some higher ground in the west, and this may be the cause of the higher average rainfall value for the square as a whole. During the winter, rainfall generally exceeds losses to evapotranspiration. During the late spring and summer, evapotranspiration generally exceeds rainfall and a Soil Moisture Deficit (SMD) develops.

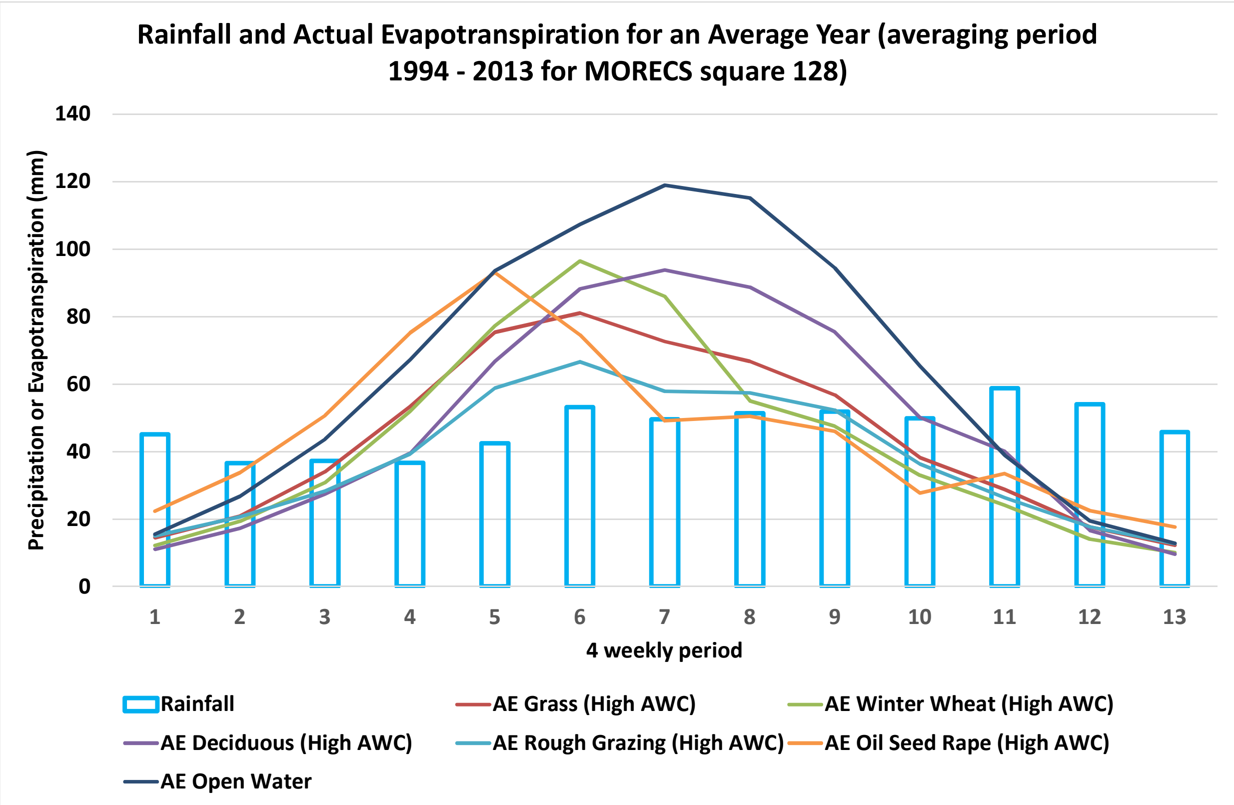
There is a degree of uncertainty as to the amount of rainfall received within the study area, with the obtained values for annual rainfall ranging from 505 mm/yr to 615 mm/yr. The highest value of 615 mm/yr was derived from MORECS for an area including higher ground to the west of the study area. It is possible that this higher rainfall may be a reflection of the inclusion of this higher ground within the MORECS square which is likely to receive more rainfall than the study area itself. The value of 542 mm/yr obtained from the FEH catchment containing much of the site is substantially lower than the MORECS value indicating that indeed the MORECS value may not be representative of the site. However, the FEH value is still significantly higher than that obtained from the local IDB rain gauge (505 mm/yr) and therefore some uncertainty as to the rainfall received on site remains. This study has used the MORECS rainfall data (so as to be consistent with the MORECS evapotranspiration datasets) but has also made reference to the FEH and local rainfall data.

2.3.3 Land Use

The vast majority of the study area comprises arable farm land. Arable farming has been made possible by the presence of extensive man-made drainage channels across the site. The city of Peterborough extends into the western part of the study area; with much of Fengate, a predominantly industrial area of the city, being located in the study area. Eye village is a predominantly residential area located in the north-west of the study area.

There are a number of lagoons associated with historical quarrying located within the study area. The Flag Fen basin has been exploited as a source of both sand and gravel for aggregate and Oxford Clay for use in brick-making. The area around Peterborough is peppered with these so-called ‘brick pits’.

Figure 2-1 Rainfall and Evapotranspiration for an Average Year



2.4 Geology and Soils

2.4.1 Bedrock Geology

The geology of the Flag Fen basin is summarised in Table 2-1. The vast majority of the study area is underlain by bedrock belonging to the Jurassic Oxford Clay Formation (Map 4). The bedrock dips approximately 1 - 2 degrees to the east with older, deeper formations cropping out in the west of the site around central Peterborough.

Table 2-1 Geology of the Flag Fen Basin

Age	Group	Formation	Member	Description	Thickness
Quaternary Flandrian			Alluvium	Normally soft to firm consolidated, compressible silty clay, but can contain layers of silt, sand, peat and basal gravel.	0 - 1.6***
	British Coastal Deposits Group	Fenland Formation	Terrington Beds	Interlaminated dull reddish brown clays and pale brown silts.	Up to ~3m *
	Organic Deposits	Floral Organic Deposits	Nordelph Peat	Peat	0 - 2.7***
	British Coastal Deposits Group	Fenland Formation	Barroway Drove Beds (Tidal Flat Deposits)	Soft grey clays and silty clays.	
			Lower Peat	Peat	0 - 1.5***
Quaternary Pleistocene			River Terrace Deposits	Sand and gravel, locally with lenses of silt, clay or peat.	0 - 6.2***
	Ouse-Nene Catchments Subgroup	Nene Valley Formation	Woodston Member	Silt and sand containing pollen, plant macrofossils, evidence of deposition under temperate conditions.	Up to 3 m *
	British Coastal Deposits Group	Fenland Formation	March Gravels Member	Sandy flint gravel to clayey, silty, pebbly sand.	0 - 6.8***
		Mass Movement Deposits	Head	Polymict deposit, comprises gravel, sand and clay, depending on upslope source and distance from source.	
			Glaciofluvial Deposits	Sand and gravel, locally with lenses of silt, clay or organic material.	
			Till	Boulder clay	
			Glacio-lacustrine Deposits	Silt and clay, laminated, commonly rich in organic matter, locally interbedded with peat.	
Jurassic	Ancholme Group	West Walton Formation		Calcareous mudstone, silty mudstone and siltstone with subordinate fine-grained sandstones and argillaceous limestone or siltstone nodules.	Up to 30 m **

Age	Group	Formation	Member	Description	Thickness
		Oxford Clay Formation		Silicate mudstone, grey, generally smooth to slightly silty, with sporadic beds of argillaceous limestone nodules.	63 - 65 m **
		Kellaways Formation	Kellaways Sand Member	Silicate sandstone and silicate siltstone, pale grey, calcareous cemented, with interbeds of sandy and silty mudstone. Sandstone/siltstone generally weakly cemented, but locally strongly cemented.	1.9 - 4.6 m **
			Kellaways Clay Member	Silicate mudstone, grey commonly smooth in basal part, but more generally silica-silty or silici-sandy, locally with thin beds of siltsone and sandstone, and nodule of argillaceous limestone.	1.4 - 5.8 m **
	Great Oolite Group	Cornbrash Formation		Limestone, medium to fine grained, predominantly bioclastic wackestone and packstone with sporadic peloids; generally and characteristically intensely bioturbated and consequently poorly bedded.	1.2 - 4.3 m **
		Blisworth Clay Formation		Silicate-mudstone, grey, commonly variegated purplish red, yellow and green, poorly bedded to blocky.	3 - 6 m**
		Blisworth Limestone Formation		Pale grey to off-white or yellowish limestones with thin marls and mudstones.	1.9 - 5.1 m**
		Rutland Formation		Interpreted as a succession of up to seven shallowing upward, essentially delta type rhythms, comprising ideally of a grey marine mudstone passing up into non-marine mudstone and siltstone, with a greenish grey rootlet bed at the top.	6 - 14 m**
	Inferior Oolite Group	Lincolnshire Limestone Formation		Limestone, typically calcilutites, and peloidal wackestones and packstones in the lower part sand; high energy ooidal and shell fragmental grainstones in the upper part.	0 - 25 m **

Age	Group	Formation	Member	Description	Thickness
Notes: * taken from BGS Lexicon of named Rock Units ** taken from Geological memoir: Geology of the Peterborough District (Horton, 1989) *** data obtained from local borehole records available on the BGS GeoIndex					

2.4.2 Superficial (Drift) Geology

The Quaternary succession in and surrounding the Flag Fen Basin is complex (Map 5), and comprises glacial and interglacial Pleistocene deposits which are overlain by Flandrian sediments. The Flandrian sediments include alluvium, peat and tidal flat deposits which cover most of the low-lying Fenlands. The Pleistocene deposits include glacial lake deposits, till, glacial sand and gravel, fluvial gravel terraces and marine gravels.

Flandrian Deposits

Alluvial flood plain deposits and tidal flat deposits are the uppermost deposits of the superficial succession and are both comprised broadly of clay and silt, with the alluvium containing some sand and gravel.

Nordelph Peat covers much of Flag Fen Basin and is of particular importance to this investigation as it is the peat in which the Bronze Age archaeology is preserved. During the last geological survey performed by the BGS areas with more than 0.3 m of peat or peaty soils were included within the mapped peat outcrop. Comparing the current outcrop, to that mapped in 1877, it is apparent that peat has been lost over an area extending 4 km to the west of the current outcrop, however a different peat criteria may have been used for this historical mapping. Nonetheless that amount of peat loss is great, and can be primarily attributed to the effects of drainage and arable farming. Drainage has lowered the water table and facilitated the oxidation of the peat. This has allowed for a change from pastoral to arable farming in the area. The nature of arable farming leads to bare soil being exposed at the surface. Bare soil is liable to drying and oxidation of peat material and therefore contributes to peat loss, wind erosion can also blow peat away.

The Fens are now significantly affected by dust storms caused by wind erosion of the ploughed soil (BGS, 1989).

The Nordelph peat is commonly underlain by the Barroway Drove Beds which consist mainly of dark grey, very soft, slightly humic and silty clays. The Barroway Drove Beds overlie the Lower Peat, though the Lower Peat sequence is absent over the vast majority of the study area. It is possible that the Lower Peat may have once extended westwards into the study area but was subjected to erosion prior to the deposition of the Barroway Drove Beds.

Pleistocene Deposits

The River Terrace Deposits are the only Pleistocene deposits which are present extensively across the study area, though the March Gravels are present on the higher ground near Eye and Whittlesey.

2.4.3 Soils

The area in the east and southeast of the study area is underlain by soils belonging to the Downholland 1 Soil Association. These soils typically develop over marine alluvium and fen peat and comprise deep stoneless, humose, clayey soils, calcareous in places. In this area they are coincident with the presence of mapped tidal flat deposits and peat. There are some peat soils and some deep humose calcareous silty soils: they are typical of flat land on which groundwater is commonly controlled by ditches and pumps.

The central northern area of the study area is underlain by soils belonging to the Shabbington Soil Association. These soils typically develop over river terrace drift, in this location the Shabbington soils are coincident with areas of river terrace drift, March Gravels, alluvium, and areas over which drift deposits are mapped as being absent. These soils are deep fine loamy and fine loamy over sandy soils variably affected by groundwater. There are some slowly permeable seasonally waterlogged fine loamy over clayey soils.

The west of the study area is mapped as being unsurveyed with respect to soils as it encompasses mainly urban and industrial areas.

The central southern area of the study area is underlain by the Waterstock Soil Association which develops over river terrace deposits comprising deep, permeable, mainly fine loamy soils variably affected by groundwater. Some soils can be deep well drained fine and coarse loamy soils.

The central and south-western area of the study area, including the Flag Fen site, is underlain by soils belonging to the Midelney Soil Association which typical develop on river alluvium over peat, the superficial geology present in this region. The Midelney Soil Association comprises soils which are stoneless and clayey, variably affected by groundwater, which is in places controlled by ditches and pumps.

The Ireton Soil Association overlies River Terrace Deposits in the east of the study area. These soils typically overlie glaciofluvial drift and are permeable, humose coarse and fine loamy soils, associated with humose calcareous coarse loamy over sandy soils.

In the very north-eastern corner of the study area there is a small area underlain by the Oxpasture Soil Association. These soils comprise fine loamy over clayey and clayey soils with slowly permeable subsoils and slight seasonal waterlogging, and some slowly permeable seasonally waterlogged clayey soils.

Many of the soil types present across the Fenland reflect the presence of near surface groundwater and the presence of drainage to lower water levels and have developed following drainage of the area and land management practices involving drainage.

2.5 Surface Water Hydrology

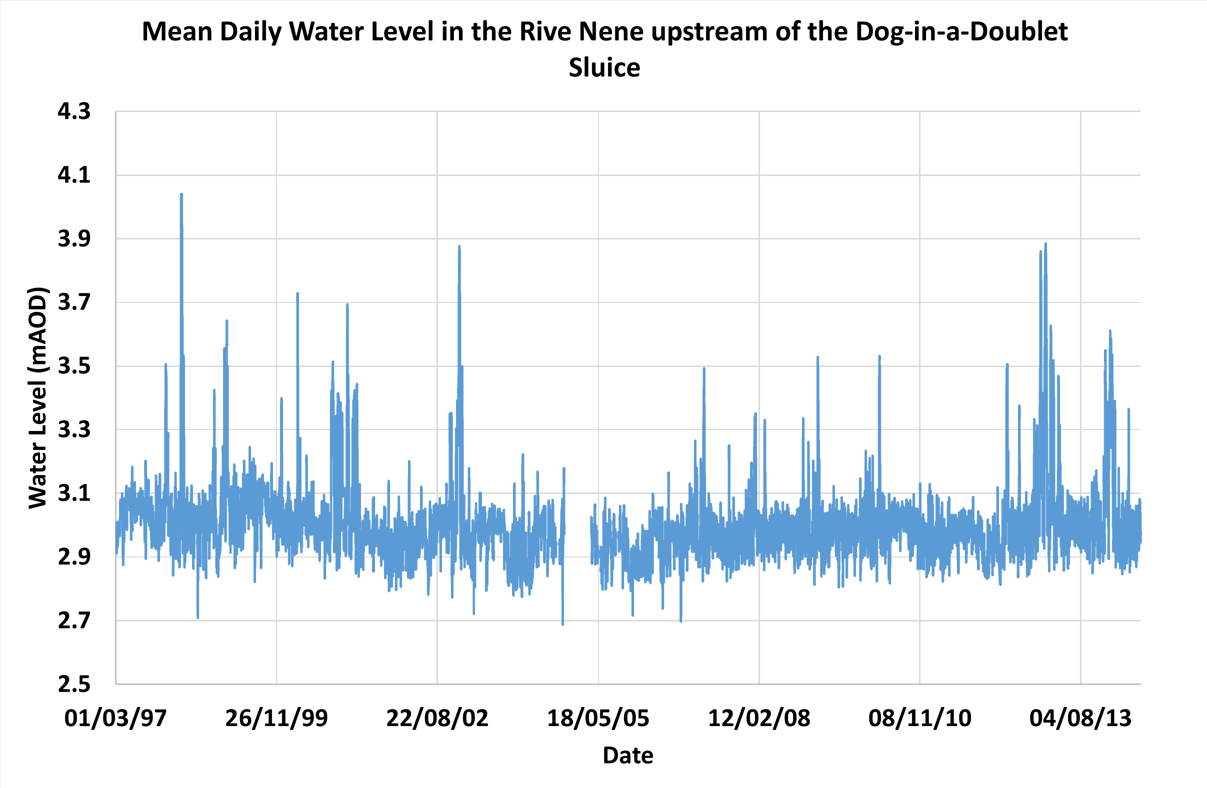
The Fenlands in the district are drained mainly by two rivers: the Welland in the north and the Nene in the south. The River Welland lies approximately 7 km to the north of the study area. The River Nene constitutes the southern boundary of the study area. It flows through the uplands to the west of the study area and is canalised downstream from its entry into the Fens at Peterborough. Both the Welland and the Nene ultimately discharge to The Wash.

2.5.1 The drainage network

The study area is dominated by manmade drainage ditches and dykes, created to drain the fenland and make it suitable for farming and development (Map 6). The vast majority of the drainage network across the fenland is managed by the North Level District IDB, with the greater part of the study area falling within the IDB's Dog-in-a-Doublet catchment. A smaller catchment named the Padholme catchment is managed by the EA and contains the Flag Fen site itself. The western extent of the study area falls within the Peterborough City District and is under the control of Anglian Water and is largely hydrologically separate from the rest of the study area. Anglian Water also operate to the east of Peterborough handling wastewater from Peterborough Sewage Works.

The Dog-in-a-Doublet area is situated in the south-eastern corner of the study area. Here is located the Dog-in-a-Doublet sluice on the River Nene. The sluice forms a boundary between the freshwater Nene to the west and the tidal Nene to the east. The sluice aims to maintain a water level of 3 mAOD in the freshwater Nene with 2.8 mAOD being regarded as the low level and 3.3 mAOD being regarded as the high level. The high high level is 3.6 mAOD and would indicate a major flood event. There is no fall in water level between Peterborough and the Dog-in-a-Doublet sluice. Figure 2-2 shows the mean daily stage of the Nene measured upstream of the Dog-in-a-Doublet sluice.

Figure 2-2 Mean daily water level in the River Nene upstream of the Dog-in-a-Doublet Sluice



Anglian Water

To the northeast of the sluice is located the Dog-in-a-Doublet pumping station managed by Anglian Water. This pumps water from Counter Drain to the tidal stretch of the Nene. Counter Drain simply contains wastewater from Peterborough Sewage Works. If the flows within Counter Drain become too large for the Anglian Water Dog-in-a-Doublet Pumping Station to deal with, there is capability for excess water to flow east from the Anglian water pumping station along the extension of Counter Drain entering the IDB managed catchment.

North Level IDB

There are two Dog-in-a-Doublet pumping stations managed by the IDB located to the northeast of the Anglian water pumping station. The 'Old' pumping station was built in 1938 and replaced by the 'New' pumping station in the 1970's. Since the installation of the new pumping station the old pumping station has been reinstated to increase pump capacity. These two pumping stations pump excess water from the Dog-in-a-Doublet catchment to the tidal section of the Nene. There is also an overspill function to allow excess water from the Dog-in-a-Doublet catchment to enter the adjacent Cross Gates IDB catchment which can be used in times of particularly high flow. The IDB also pump water from the River Nene Dog-in-a-Doublet pumping station north up the Thorney River to allow for the distribution of water for irrigation across the wider IDB network. The Thorney River, which is in fact a large drainage ditch, constitutes much of the eastern boundary of the study area.

Set levels for pumping from the Dog-in-a-Doublet Pumping Station are set at -1.2m AOD during the summer and -1.8 mAOD during the winter. The water level at of the Thorney River is constantly at around 0 mAOD significantly higher than the surrounding drainage ditches. Figure 2-3 and Figure 2-4 display water levels in Middle Drain, the intake to the IDBs Dog-in-a-Doublet pumping station for August 2013 and January 2014. The differences in pumping regime between the summer and winter months is apparent, with pumping in August less frequent and a lowering of water levels (the target as mentioned previously is approximately -1.2 mAOD). In winter, as shown in the January hydrograph pumping is much more frequent and aims to maintain a significantly lower water level of -1.8 mAOD.

Figure 2-3 Water level in Middle Drain at the Dog-in-a-Doublet pumping station, August 2013

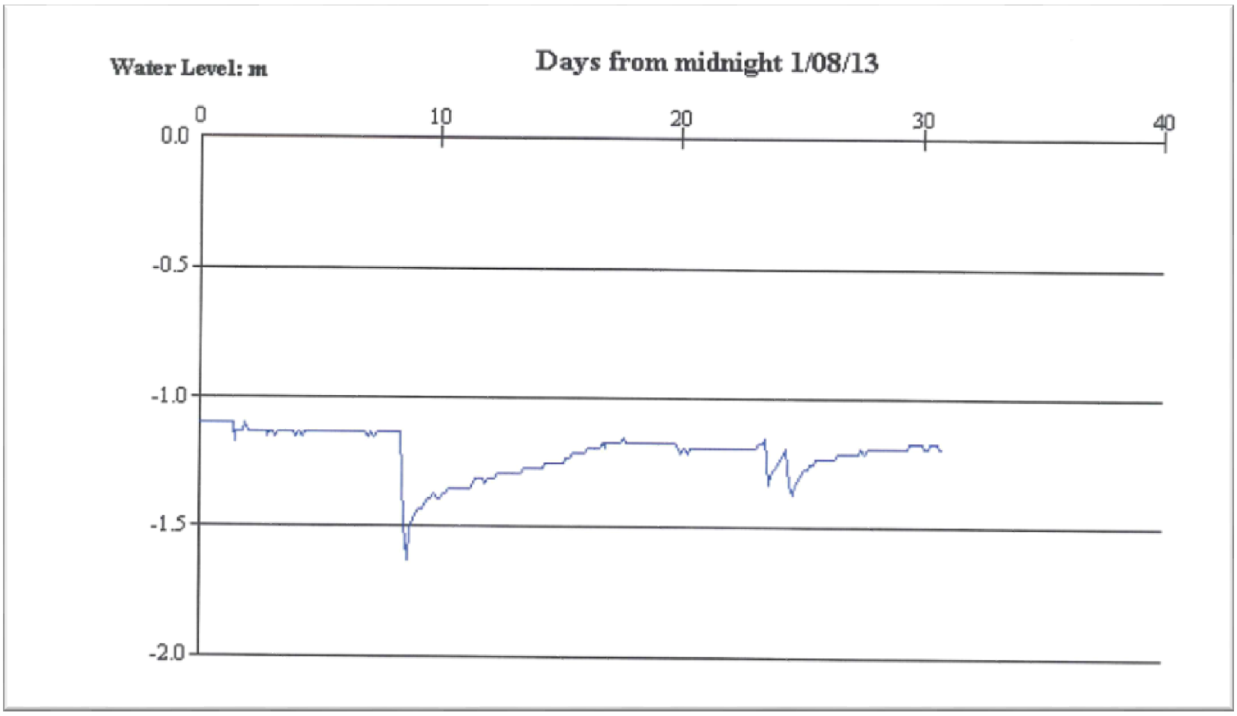
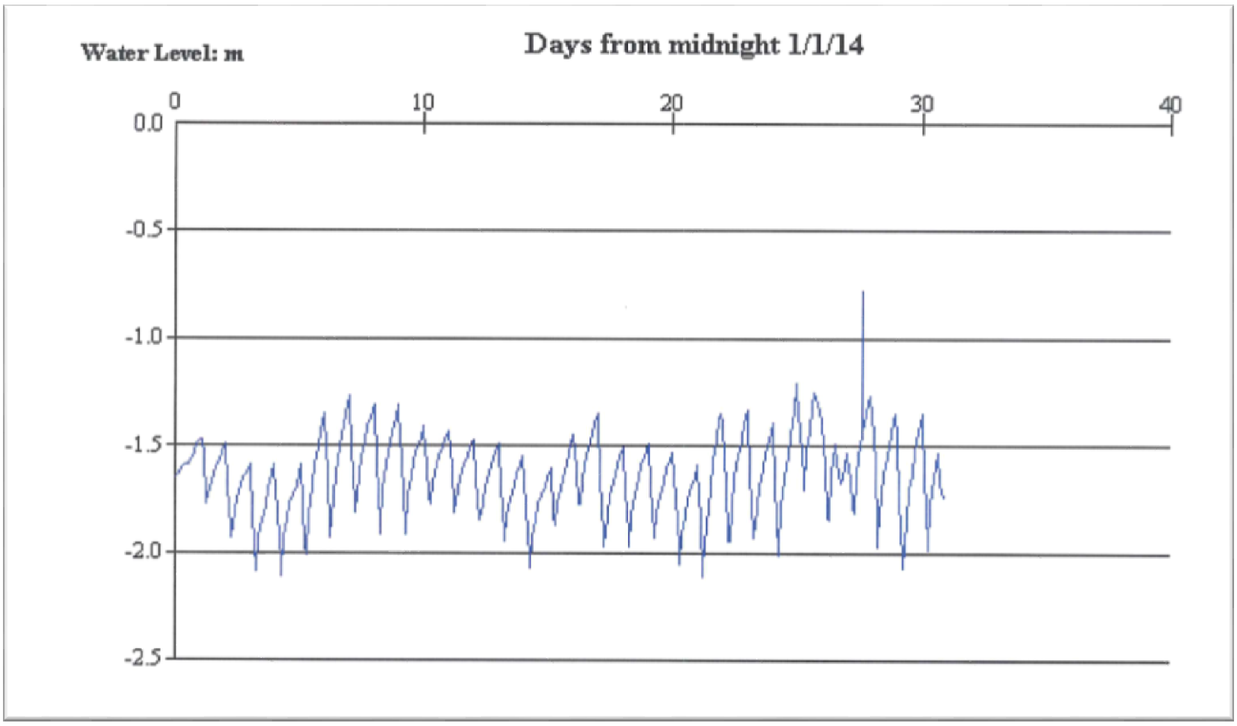
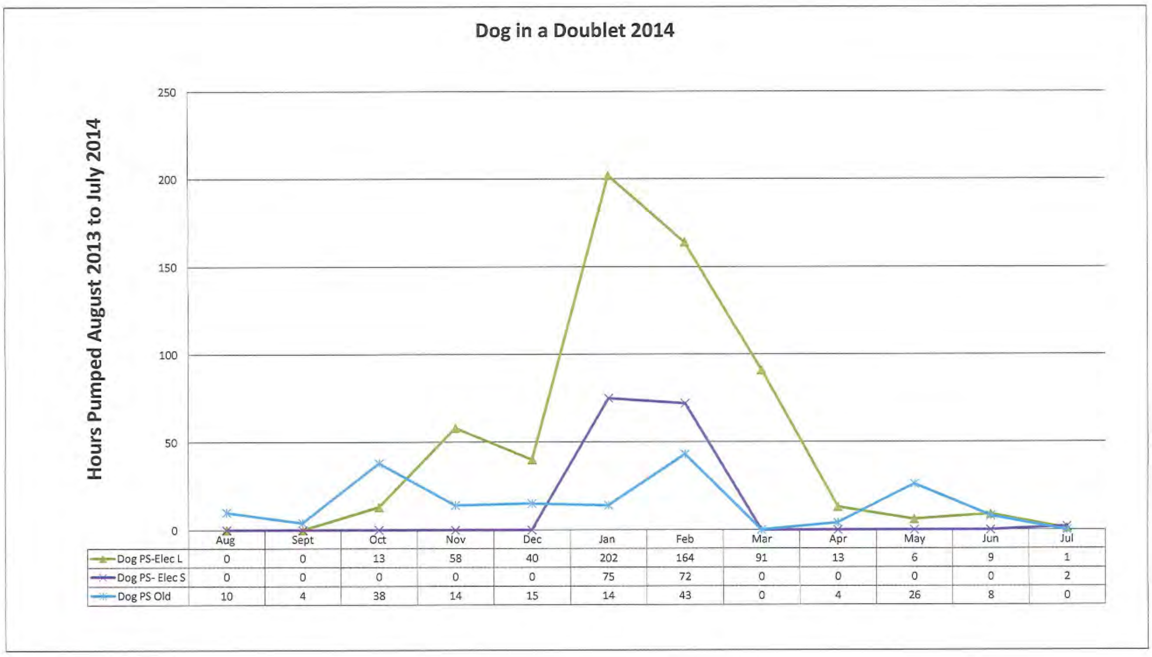


Figure 2-4 Water level in Middle Drain at the Dog-in-a-Doublet Pumping Station, January 2014



The maximum pump capacity at the Dog-in-a-Doublet pumping station is 5.8m^3/s using all six available pumps. This total capacity is only utilised for the extreme events, such as 1 in 100 year floods. Usual operation is for only one pump to run with an approximate capacity of 1.1m^3/s. Occasionally two pumps will run providing approximately 2.2m^3/s capacity. Figure 2-5 shows the hours pumped at the Dog-in-a-Doublet pumping station from August 2013 to July 2014. The pumps hours displayed are per pump and therefore represent approximately 1. 1m^3/s capacity pumps. Significantly more water is pumped from the catchment during the winter months.

Figure 2-5 Hours pumped at the Dog-in-a-Doublet Pumping station from August 2013 to July 2014



	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
Dog PS-Elec L	0	0	13	58	40	202	164	91	13	6	9	1
Dog PS- Elec S	0	0	0	0	0	75	72	0	0	0	0	2
Dog PS Old	10	4	38	14	15	14	43	0	4	26	8	0

Environment Agency

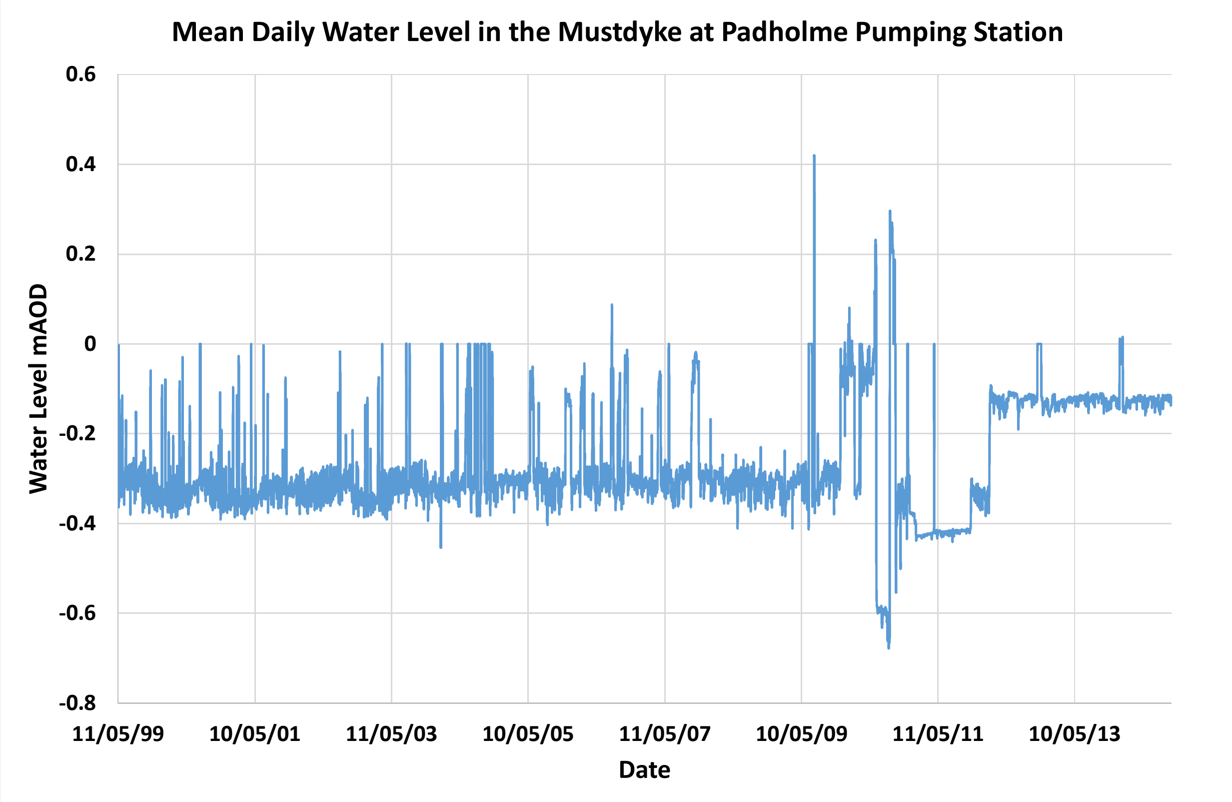
The area immediately surrounding the Flag Fen visitor centre does not actually fall within the IDB managed Dog-in-a-Doublet catchment, it falls within a smaller catchment managed by the Environment Agency via the Padholme pumping station which is located to the south of the visitor centre. The Padholme pumping station discharges water from this catchment to the River Nene (fresh water section). The Mustdyke is the water course which flows through the Flag Fen visitor centre to the Padholme pumping station. The Mustdyke comes into being at Flag Fen at the confluence of three other water courses: Cat's Water Drain to the west, an unnamed drain to the north (which does receive some water from Peterborough City), and Catswater Drain South to the northeast.

The Padholme Pumping Station does not appear to be as heavily managed as the IDB's Dog-in-a-Doublet. The Padholme catchment is significantly smaller than the Dog-in-a-Doublet and the drains within this catchment appear less intensively managed than those in the IDB catchment. There is no seasonal variation in the set levels of the Padholme Pumping Station. The Padholme Pumping Station contains three pumps which have the following set levels:

- The first duty pump starts at -0.1 mAOD and stops at -0.25 mAOD
- The second pump assists at 0.0 mAOD and stops at -0.15 mAOD
- The third pump assists at 0.1 mAOD and stops at -0.15 mAOD.

Figure 2-6 shows the mean daily water level in the Mustdyke at Padholme Pumping Station from May 1999 to May 2013. The step towards the end of the record may represent a rise in the pump set level.

Figure 2-6 Mean daily water level in the Mustdyke at Padholme Pumping Station



Catswater Drain passes through the study area broadly north-south though the direction of flow changes numerous times within the study area. North of Pearces Road Catswater Drain is controlled by the IDB, and to the south it falls within the Padholme catchment and is under the control of the EA. Catswater Drain South is separated from the IDB network by a structure located on the western side of the culvert under Pearces Road. On the day of the site visit there was some flow from the EA managed catchment into the IDB managed catchment over the structure located on Catswater Drain South.

Within the Padholme catchment Catswater Drain has two reaches whose confluence is at Flag Fen where they flow into the Mustdyke. The south eastern reach flows north to the Mustdyke and the northeastern reach flows south from Pearces Road to the Mustdyke. The unnamed drain which joins this confluence from the north conveys some water from Peterborough City.

Given its previous life as a branch of the Nene, Catswater Drain has a meandering channel unlike the vast majority of the rest of the ditches in the area which have straight channels as they were excavated by man.

2.5.2 Ponds and Lakes

There are numerous artificial ponds and lakes located across the study area which were created following the quarrying of sand and gravel. At least some of these quarries extracted the total thickness of the River Terrace Deposits to the top of the underlying Oxford Clay. Some of these disused quarries contain infilled ground, and some have been used for landfill; though many of these disused quarries remain as quarry lagoons of an unknown depth. It is likely that these quarries are in contact with the surrounding groundwater (unless filled with lined landfill).

At the Flag Fen visitor centre is a man-made pond named Large Mere. Located where the Bronze Age platform was believed to exist, it was designed to keep the underlying ground saturated in an attempt to preserve the archaeological wood (Pryor, 1991, 1992). It is understood that the mere contains a slowly permeable lining which holds water to a certain degree but also allows leakage into the underlying ground. Pryor (1991) describes how polythene film was built into the embankments around the Mere. The water is topped up via an abstraction from the nearby Mustdyke. Pryor (1992) stated that the Large Mere covered about two-thirds of the Bronze Age platform; however, more recent investigations suggest that the platform may not extend as far west as previously thought or that it may be discontinuous (DigVentures, 2012).

2.5.3 Surface Water Abstractions

The Environment Agency were contacted in April 2014 and provided details of all licensed abstractions within 1.5 km of the study area. There are 30 licensed surface water abstractions which fall within the study area (Map 7). All of these abstractions with the exception of the abstraction at Flag Fen which is used for the topping up of the Large Mere, are used for spray irrigation. These abstractions are likely to be used during dry periods (the summer), when there is limited rainfall.

Two abstraction returns (actual abstraction rates) were obtained for the Flag Fen abstraction: 16,180 m^3/yr (2008) and 6,248 m^3/yr (2009). These indicate how much water was used to top up the Large Mere against losses to ground (leakage) and to evaporation.

2.6 Catchment Descriptors

The FEH gives the Standard Percentage Runoff (SPR) for the site as 27.1%. The SPR is the percentage of rainfall responsible for the short term increase in river flow during and/or following a rainfall event (Boorman et al., 1995). This suggests that a fair amount of the rain falling on the catchment will pass rapidly into watercourses via overland flow or interflow (lateral flow through the soil). This moderate value reflects the presence of many drains within the catchment, designed to rapidly capture water entering the system. The queried catchment contains quite a large area of Peterborough, much of which will be covered by impermeable surfaces that will lead to much of the rainfall passing rapidly into watercourses in this area. Within the majority of the study area rainfall will permeate into permeable drift deposits or be transferred to the drainage system via interflow. Though interflow through the natural deposits may not be particularly high, it is believed that many of the agricultural fields (which cover the vast majority of the study area) are underlain by field drains which greatly increase the volumes of water transmitted via interflow.

The baseflow index (BFI) for the site is about 0.69 (CEH, 2009). This is the proportion of total stream flow made up of baseflow (mostly groundwater input). This value suggests that baseflow makes up a considerable amount of total streamflow. This is consistent with the presence of Secondary aquifers beneath the area, including alluvium (which includes permeable sand and gravel), river terrace deposits (sand and gravel), and peat deposits which can release water slowly. These aquifers will supply groundwater to rivers as baseflow.

2.7 Hydrogeology

2.7.1 Aquifers and Aquitards

An aquifer is a body of permeable sediment or rock that can store and transmit significant quantities of water under ordinary hydraulic gradients. In contrast, an aquitard is a low permeability sediment or rock that allows only slow groundwater seepage. A summary of the hydrogeological units is presented in Table 2-2.

In general the permeable parts of the Jurassic bedrock sequence are the limestones and subordinate sandstones, including ferruginous sandstones.

Table 2-2 Summary of local hydrogeology

Age	Stratigraphic Unit			Hydrogeological Role	Flow and Storage
Quaternary Flandrian			Alluvium	Secondary A Aquifer	Intergranular flow and storage
			Terrington Beds	Aquitard	
			Peat	Aquifer/Aquitard	Peat will store significant volumes of water
			Barroway Drove Beds	Aquitard	
Quaternary Pleistocene			River Terrace Deposits	Secondary A Aquifer	Intergranular flow and storage
			March Gravels Member	Secondary A Aquifer	Intergranular flow and storage
Jurassic	Ancholme Group	West Walton Formation		Aquitard	
		Oxford Clay Formation		Aquitard	
		Kellaways Formation	Kellaways Sand Member	Secondary A Aquifer	Intergranular flow and storage
			Kellaways Clay Member	Aquitard	
	Great Oolite Group	Cornbrash Formation		Secondary A aquifer	Flow and storage mainly within fractures
		Blisworth Clay Formation		Aquitard	
		Blisworth Limestone Formation		Principal Aquifer	Flow and storage mainly within fractures
		Rutland Formation		Secondary B Aquifer	
	Inferior Oolite Group	Lincolnshire Limestone Formation		Principal Aquifer	Flow and storage mainly within fractures. Aquifer of regional importance for water supply.

Sources:
BGS 1:50,000 mapping (BGS 1984, digital DiGmapGB-50)
Environment Agency website

Quaternary Deposits

In unconsolidated deposits comprising sands and gravels including the Alluvium, River Terrace deposits and March Gravels Member, groundwater will be present and transmitted via intergranular flow, particularly within the more permeable horizons. The Barroway Drove Beds are a clay deposit and will most likely behave as an aquitard.

The aquifer properties of peat are more difficult to predict. Peat can behave as both an aquifer and an aquitard. Peat deposits will almost certainly store significant volumes of water but their ability to transport water can vary greatly. Where peat is water logged and has not been subject to drainage and drying, permeabilities may be quite low. In contrast, in areas where there is drainage, lowering of groundwater levels and preferential flow towards drainage ditches the peat may have a higher permeability. In particular adjacent to drainage ditches lowering of groundwater levels in peat may result in cracking of the peat and development of preferential flow pathways along the cracks.

Shallow groundwater is likely to be in hydraulic continuity with local surface watercourses. Groundwater could be locally perched above the Barroway Drove Beds (BDB).

Jurassic Ancholme Group

The Jurassic Ancholme Group comprises mainly mudstones which behave as aquitards with the exception of the Kellaways Sand Member which comprises sandstone which will have intergranular flow and storage.

The West Walton Formation and Oxford Clay Formation display thick sequences of clays and shales and behave as aquitards. Broadly comprising mudstone, the Kellaways Clay Member also behaves as an aquitard. The Kellaways Sand Member comprises fine grained sands and fine grained sandy/silty mudstones. Hydraulic conductivity is low due to high fines content of the sands though it is capable of storing and transmitting groundwater, and as a result is regarded as a Secondary A aquifer by the Environment Agency.

Jurassic Great Oolite Group

The Great Oolite Group can be subdivided into the Rutland Formation at the base, overlain by the Blisworth Limestone, Blisworth Clay and Cornbrash Formations. The majority of the limestones are fractured and therefore behave as aquifers with fracture flow dominating, the stratum with clay and mudstone dominating behave as aquitards.

The Rutland Formation is generally regarded as a non-aquifer comprising silts, clays, and mudstones. However it does contain some sands and limestones and is regarded as a Secondary A aquifer by the EA in this region, meaning it will store and transmit limited volumes of groundwater.

The Blisworth Limestone is regarded as a Principal aquifer by the EA, with fracture flow dominating. It is overlain by the Blisworth Clay Formation which behaves as an aquitard.

The Cornbrash forms the uppermost unit of the Great Oolite Group and is separated from the main part of the Great Oolite Group by clays belonging to the Blisworth Clay Formation. It typically comprises fissured limestones and marls and is regarded as being a Secondary A aquifer by the EA. However the Cornbrash is not widely used for water supply in this area as it is relatively thin and separated from the underlying aquifers by the clays.

Jurassic Inferior Oolite Group

Groundwater movement within the Lincolnshire Limestone Formation is almost entirely by fracture flow along well developed bedding plane fractures and joints (Allen *et al.,* 1997). It is the most important aquifer in the region, outcropping immediately to the west of Peterborough.

2.7.2 Groundwater Abstractions

There are three licensed groundwater abstractions within the study area (Map 7), details of which are given in Table 2-3. Two of these abstraction are from the near surface River Terrace Deposits with the third being from the Northampton Sand Formation. The Northampton Sand Formation is part of the Jurassic Inferior Oolite Group and is located at a considerable depth beneath the surface. As a result this abstraction is unlikely to have any significant impact upon the shallow groundwater with which this study is primarily concerned.

Table 2-3 Licensed groundwater abstractions within the study area

Point Name	Source Unit	Use	Max Annual (m3)	Max daily (m3)	Easting	Northing	Distance from Flag Fen (m)
Two boreholes at Flag Fen Farm	Northampton Sand Formation	Direct spray irrigation	50000	650	522000	300400	1,600
Borehole at Willow Hall Farm	River Terrace Deposits	Direct spray irrigation	25000	818	524800	301900	3,600
Catchpit at Thorney	River Terrace Deposits	General washing and process washing	1322750	4858	526000	303400	5,500

2.7.3 Groundwater Source Protection Zones

There are no groundwater Source Protection Zones (SPZs) located within the study area. The nearest SPZs are located to the north-west of Peterborough with the closest being located over 5.5 km to the northwest of the site.

2.7.4 Aquifer Vulnerability and Water Quality

The vast majority of the study area is not monitored for groundwater quality, as the bedrock beneath the majority of the site is the Jurassic Oxford Clay Formation. This behaves as an aquitard and does not store or transmit significant volumes of groundwater.

Groundwater vulnerability mapping published by the Environment Agency indicates that the River Terrace Deposits constitute a minor aquifer of either intermediate or high vulnerability, the class of vulnerability will be largely governed by the leaching potential of the overlying soil which varies across the study area. The March Gravels and Alluvium are both also regarded as minor aquifers in the high vulnerability class. This vulnerability classification is consistent with the predominantly high permeability of these deposits (especially the river terrace sands and gravels) and also with the relatively shallow depth to groundwater. The peat is not classified as containing vulnerable groundwater. Deeper groundwater in the Jurassic aquifers has low groundwater vulnerability when overlain by low permeability Oxford Clay as the Oxford Clay will act as a barrier to the downward migration of contaminants. To the west of the study area where these aquifers outcrop around Peterborough they are regarded as being highly vulnerable to contamination originating at the ground surface.

2.8 Hydraulic Properties

The following hydraulic properties determine the extent to which the ground materials beneath the study area can store and transmit water:

- Properties related to the transmission of water:
  - Hydraulic conductivity (K) - this is a measure of the permeability of the material: the higher the value the more readily the material transmits water.
  - Transmissivity (T=Kb) - this is the product of hydraulic conductivity, K, and saturated thickness, b. The higher the transmissivity, the more readily the material transmits water.
- Properties related to the storage of water:
  - Porosity - this is the fraction of void space within the material and determines the volume of water that can be stored.

- Specific Yield, Sy - this is the volume of water that can be obtained by gravity drainage of a unit volume of saturated material. It is lower than the porosity because some water is held by capillary forces and cannot be drained under gravity alone (also, some pores may be isolated).
- Storage coefficient, S - this is the volume of water generated per unit surface area of aquifer per unit decline in hydraulic head. In confined aquifers (those fully-saturated aquifers in which the water is held "under pressure" by an overlying low permeability stratum) S represents water released by compaction of the aquifer and expansion of the water. In unconfined aquifers (with a water table) S is essentially equivalent to the specific yield, Sy, as almost all the water comes from gravity drainage of the pore network (compaction/expansion effects are negligible by comparison).

Table 2-4 Literature values for Hydraulic Conductivity (Unconsolidated Sediments)

Material	Hydraulic Conductivity, K (m/d) order of magnitude range
Gravel	10^3 - 10^4
Clean sand and sand/gravel	10 - 100
Silty sand	10^{-2} - 10
Silt	10^{-4} - 1
Silt, clay and mixtures of sand, silt and clay	10^{-4} - 10^{-2}
Glacial till	10^{-7} - 10^{-1}
Unweathered clay	10^{-7} - 10^{-4}
Sources: Freeze and Cherry (1979) and Brassington (2007)	

Table 2-5 Literature values for Storage Properties (Unconsolidated Sediments)

Material	Porosity (%)	Specific Yield* (%)
Coarse gravel	28	23
Medium gravel	32	24
Fine gravel	34	25
Coarse sand	39	27
Medium sand	39	28
Fine sand	43	23
Silt	46	8
Clay	42	3
Source: Brassington (2007) These are indicative values. Natural deposits have variable porosity and specific yield. * Drainable storage.		

2.9 Groundwater Levels

Shallow groundwater is present in the superficial deposits across the study area. Borehole records have been obtained across the study area. Some of these simply record the geology and any water strikes encountered, and some have been monitored for fluctuations in groundwater over time. Map 8 shows the locations of groundwater monitoring boreholes in the vicinity of Flag Fen.

2.9.1 Borehole records obtained from the BGS GeoIndex online

BGS borehole records indicate mainly water strikes, which show shallow groundwater to be present across the study area. Some rest water levels, obtained after some time (e.g. 20 mins+ to 24 hours) are also available.

2.9.2 Lillie and Cheetham (2002)

Lillie and Cheetham (2002) monitored the water table around Flag Fen between the 1st February 2002 and 8th April 2002 using fourteen piezometers contained within five boreholes. The locations of the boreholes are shown in (Map 8). Each of the boreholes contained a piezometer nest (multiple piezometers installed within a single borehole but at different depths) with the aim of monitoring water levels in different horizons within the ground. Unfortunately many of the results appear to show a fairly constant water level located at the base, or slightly above the base of the piezometer. It is possible that such data simply reflect the presence of wet mud in the base of the piezometer and do not represent true water level readings. It is suggested that these data should be regarded with caution, as the true water table may be lower. Some of the recorded water levels do however sit sufficiently high above the base of the piezometer for it to be a fair assumption that they do represent water sitting in the piezometer.

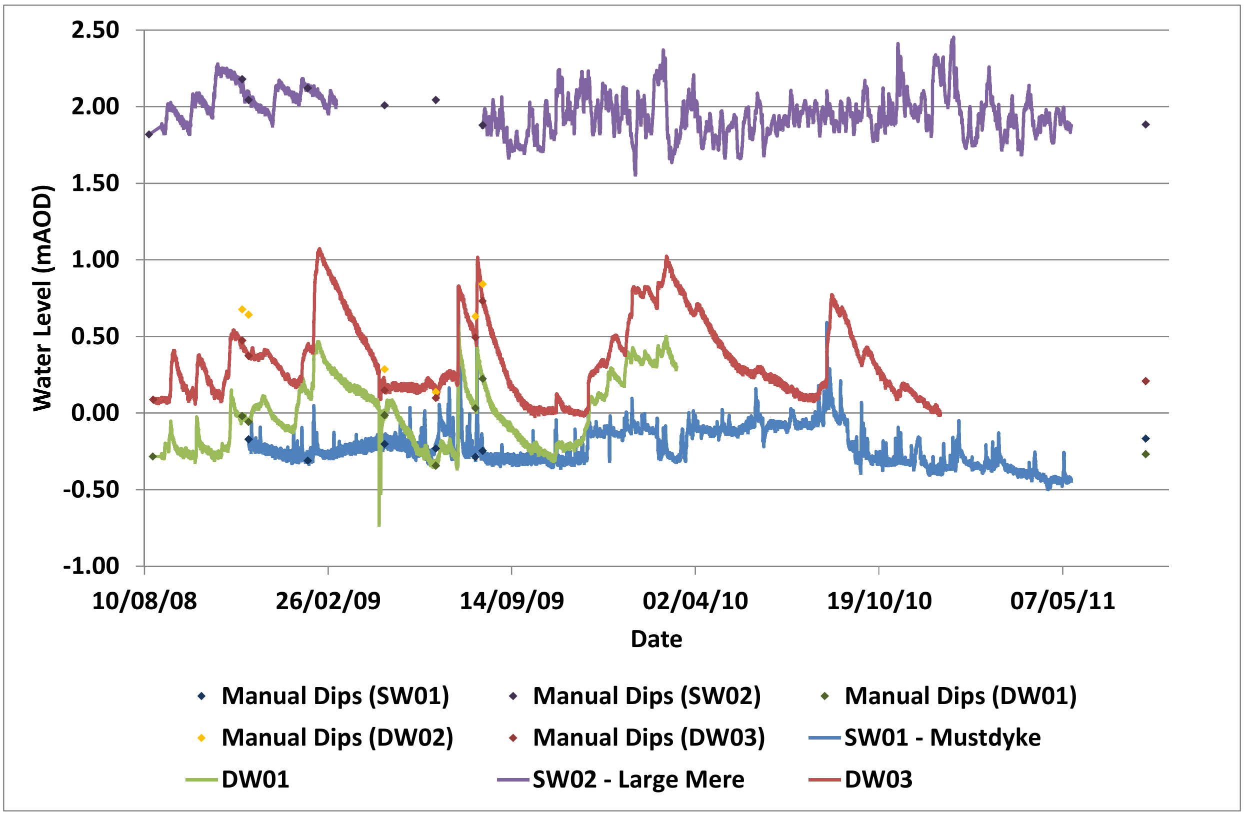
Piezometers 3 - 5 were located in a line running roughly west to east with piezometer 3 located farthest to the west the greatest distance from Large Mere and piezometer 5 farthest east, closest to Large Mere. Though these boreholes were monitored for a relatively short period of time they do show the pattern that fluctuation in groundwater level increases with distance from the Large Mere. This suggests that the presence of Large Mere does have the effect of keeping groundwater levels fairly constant in its proximity.

The water level results presented by Lillie and Cheetham (2002) are of limited use but do suggest that groundwater is present across the projected post alignment at a depth of between -0.2 and 0.34 mAOD.

2.9.3 Atkins

Atkins were commissioned by Peterborough City Council to install water level monitoring equipment and monitor water levels at five locations across the Flag Fen site (Map 8). The monitoring array consists of three shallow dipwells for monitoring groundwater and two stilling wells one of which is located within the Mustdyke (SW01) and one within the Large Mere (SW02). Monitoring data is available from this array for the period August 2008 to May 2011. Water levels are lowest in the Mustdyke with nearby groundwater levels in DW01 generally higher, though occasionally draining to the level in the Mustdyke. The trace from DW03 suggests that groundwater levels increase with distance from the Mustdyke though manual dips taken from DW03 which is located further from the Mustdyke do not always support this theory. Water levels are much higher in the Large Mere, though this is to be expected as its water level is artificially maintained via topping up from the Mustdyke.

Figure 2-7 Water levels from the Atkins water level monitoring array at Flag Fen (data provided by English Heritage)



2.9.4 Peterborough Renewable Energy Limited (PREL)

Peterborough Renewable Energy Limited (PREL) plan to build an Energypark located off Storeys Bar Road to the northwest of the Flag Fen visitor centre (PREL, 2008). Three groundwater monitoring boreholes have been installed on the proposed development site and the groundwater levels in each have been monitored on a weekly basis since July 2007. The distribution of the monitoring boreholes across the proposed Energypark development can be seen in Map 8. At the time of writing this report JBA Consulting managed to obtain the data presented in Figure 2-8 which covers the period from July 2007 to January 2008.

The data provided in Figure 2-8 are presented in metres below ground level (mbgl) though a map of likely groundwater contours is provided in the PREL report (2008), which is given as Figure 2-9. Figure 2-9 shows groundwater levels of between 0.71 and 0.13 mAOD on the PREL site which are in a similar range to those measured by Atkins on the Flag Fen site.

Figure 2-8 Groundwater levels from PREL (from PREL, 2008)

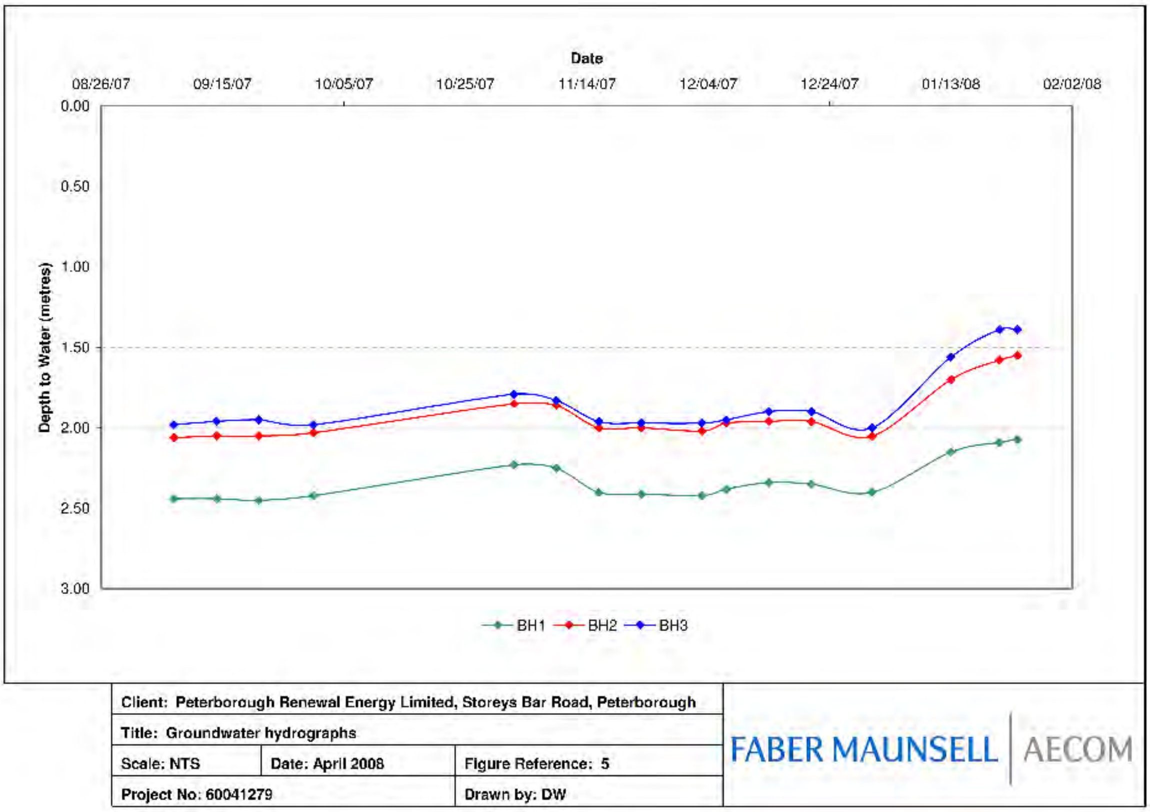
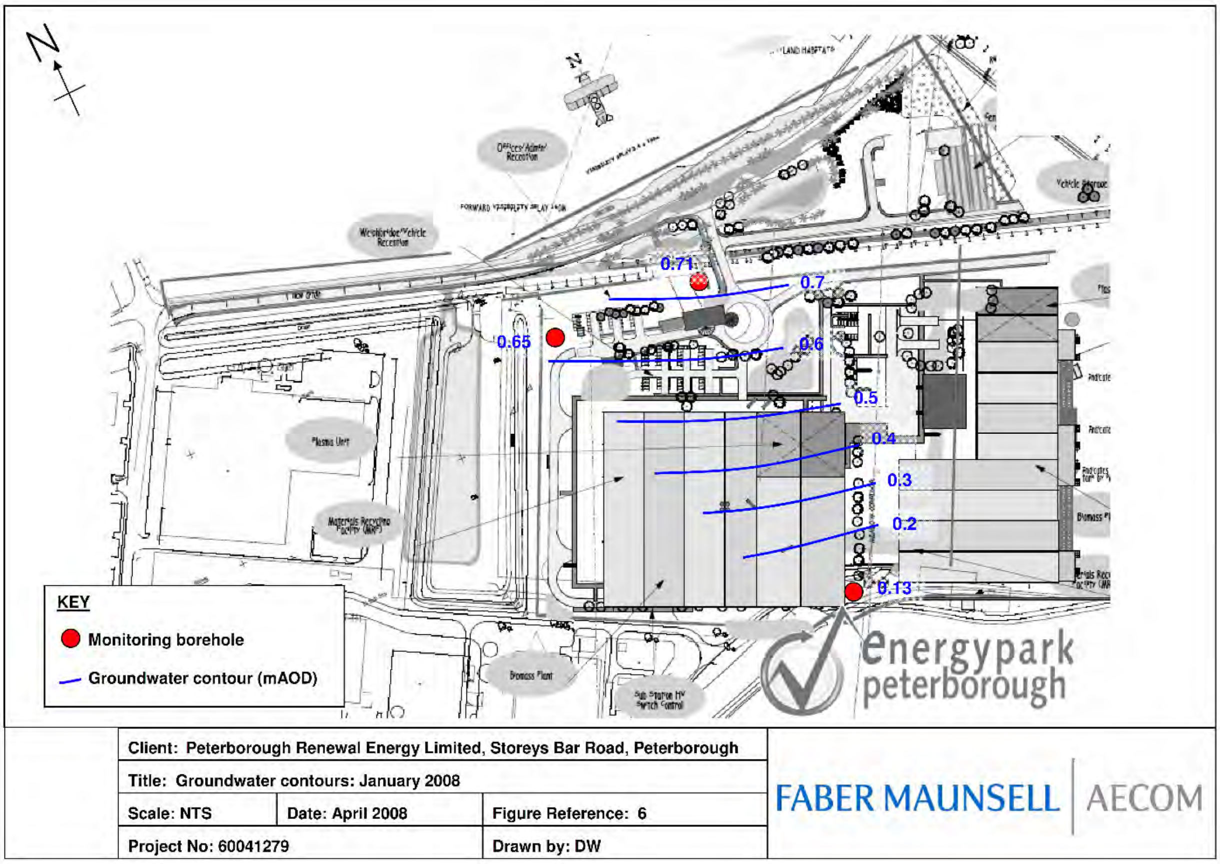


Figure 2-9 Groundwater contours across the proposed Energypark development (from PREL, 2008)



2.10 Depth of Archaeological Features of Interest

Map 9 shows the highest known elevation in mAOD of the archaeological wood at various locations along the Flag Fen timber causeway and platform. The data points along the causeway were provided by Dr Henry Chapman of Birmingham University and are based on investigation reports referenced in Pryor and Bamforth (2010) and DigVentures (2012). Additional points from the (assumed) platform area in the east were added by JBA based on French and Pryor (1993) and DigVentures (2012), and included minimum as well as maximum elevations. Table 2-6 summarises the data. Appendix D contains a complete listing of the archaeological elevation data used in this study.

Table 2-6 Elevations of Archaeological Wood within the Bronze Age Causeway and Platform at Flag Fen

Easting	Northing	Name	Maximum Elevation (mAOD)	Minimum Elevation (mAOD)
522868	298885	DV_T1_D0164	0.95	0.1
522747	298884	DV_TP2_D0148	0.92	-0.435
522686	298936	DV_TP3_D0159	0.43	0.21
522712	298907	EAA_DYKE10_Timber	0.8	-0.6
522823	298884		0.49	
522438	298956		1.1	
522342	298977		0.83	
522226	299010		0.94	
522135	299036		1.24	

DV = DigVentures; EAA = East Anglian Archaeology (French and Pryor, 1993).

Sources:
French and Pryor (1993)
Investigations referenced in Pryor and Bamforth (2010)
DigVentures (2012)

In general the vertical timbers tend to survive at higher elevations than the horizontal timbers as they are more resilient and better suited for surviving in the less consistently wet conditions.

Lillie and Cheetham (2002) noted that the archaeological timbers in proximity to the platform were believed to exist at a depth of between 0.7 and -0.13 mAOD and at an elevation of 1.6 mAOD at the western end of the post alignment near Peterborough Power Station. Exact locations for the recorded elevations are not given in the paper, so they are not plotted on Map 9. However, the values lie within the range given in Table 2-6. In DigVentures' Test Pit 3, the boundary between waterlogged peat (with preserved wood) and overlying desiccated peat was located at 0.49 mAOD; below about 0.35 mAOD the preservation of the wood was sufficient to allow the identification of woodworking methods (DigVentures, 2012).

2.11 Relationship between Archaeology and Groundwater Levels

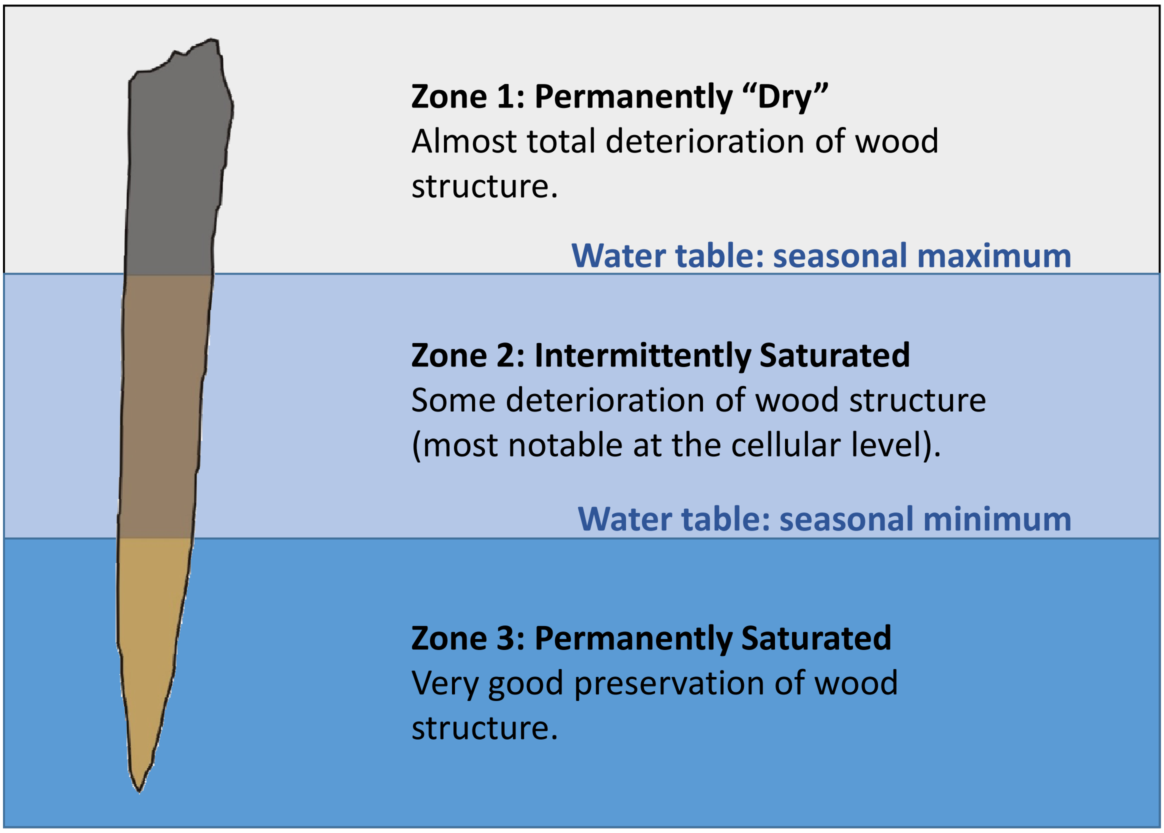
2.11.1 The Three Zone Model

Chapman and Cheetham (2002) developed a three-zone model to aid understanding of the influence of groundwater levels, and their seasonal variation, on the degree of preservation of archaeological wood. Their three zones are (Figure 2-10):

1. Permanently "dry" (strictly, permanently unsaturated)
2. Intermittently saturated (within the zone of seasonal water table fluctuation)
3. Permanently saturated (below the zone of seasonal water table fluctuation).

Zone 1 is the shallowest zone in the ground profile, and Zone 3 the deepest. The degree of preservation of wood increases with increasing zone number (Figure 2-10).

Figure 2-10 The Three Zone Model (after Chapman and Cheetham, 2002)



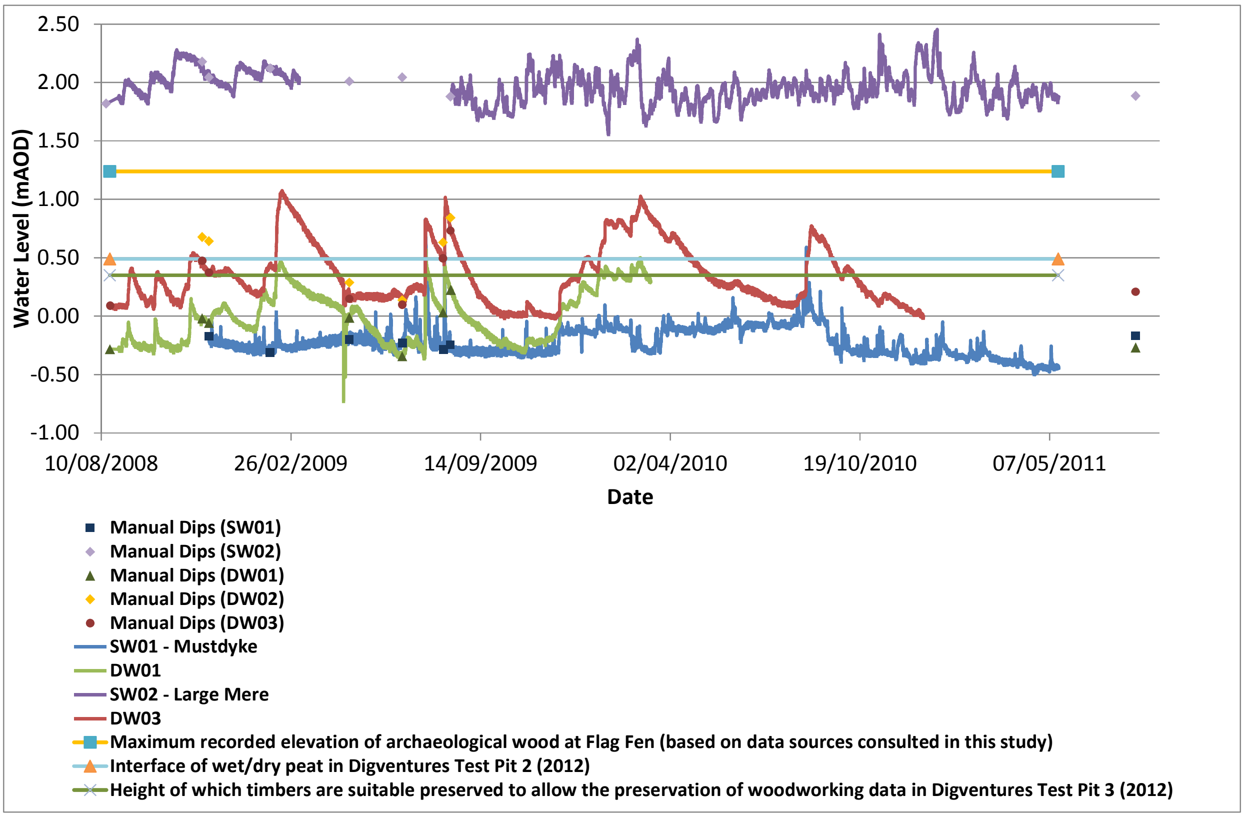
2.11.2 Archaeology and Groundwater Levels at Flag Fen

All the evidence suggests that the Bronze Age timbers beneath Flag Fen are best preserved when waterlogged conditions persist around them. Reductions in the water levels of the peat deposits may reduce the saturation of the deposits allowing oxidation to occur within the peat which results in degradation of any wooden archaeological remains they may contain.

The water level monitoring data collected by Atkins appear to be the most reliable data obtained during this investigation, as they were gathered by automatic water level monitoring devices on a frequent time step and over a significant time period.

Figure 2-11 shows the water level data gathered by Atkins alongside known elevations of Bronze Age timbers. It is immediately apparent that the Bronze Age timbers are commonly sitting higher than minimum groundwater levels. Groundwater levels monitored at DW03 towards the western end of the platform are the highest recorded on site and only occasionally reach the highest survival height of the timbers, and then for very short periods. However, groundwater levels here exceed the wet/dry peat interface given by Digventures (2012) for longer periods of time and the height of sufficiently preserved wood more frequently and for longer periods of time. Groundwater levels monitored at DW01 (near to the Mustdyke) are significantly lower and only ever manage to exceed the height at which timbers are suitably preserved very occasionally and for short periods of time. When groundwater levels here are highest they just reach the wet/dry peat interface given by Digventures of 0.49 mAOD, but never come near to the highest survival height of the timbers. It is apparent that the groundwater levels monitored by Atkins at Flag Fen (Figure 2-11) never reach the maximum "timber top" level of 1.24 mAOD listed in Table 2-6.

Figure 2-11 Water Levels and the depth of Bronze Age timbers at Flag Fen

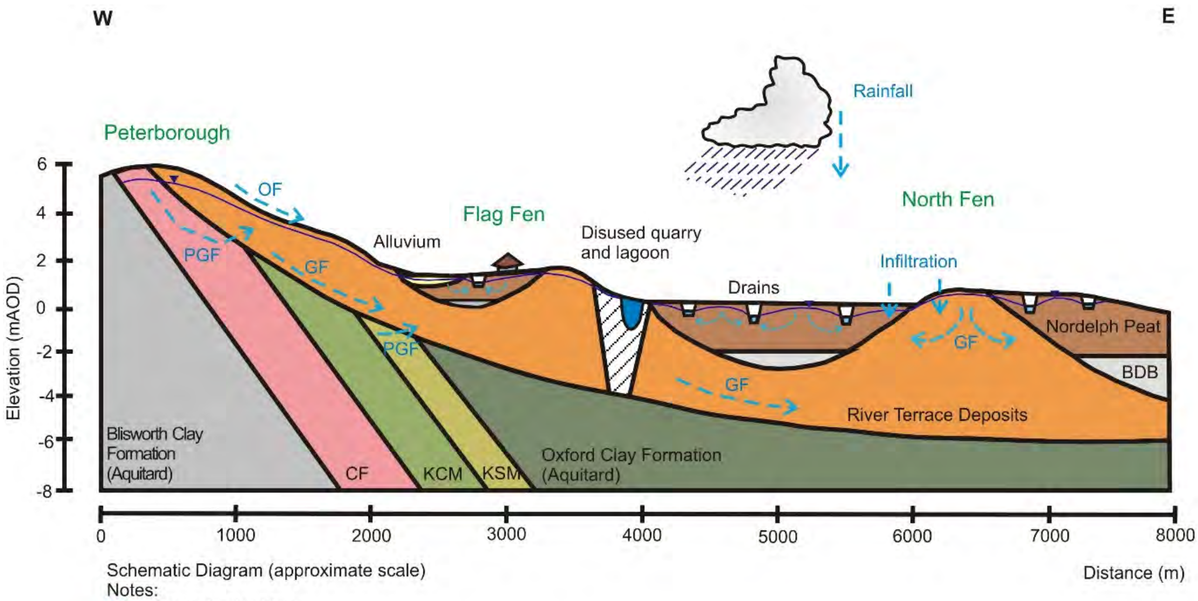


2.12 Hydrological Conceptual Model

The Environment Agency defines a conceptual hydrogeological model as "a description of how a hydrogeological system is believed to behave" and its development as "an iterative or cyclical process of development and testing in which new observations are used to evaluate and improve the model." (Environment Agency, 2002, p.4.1-2). A conceptual model summarises our understanding of the functioning of a groundwater system and is typically presented as a schematic summary diagram with accompanying maps and explanatory text as required.

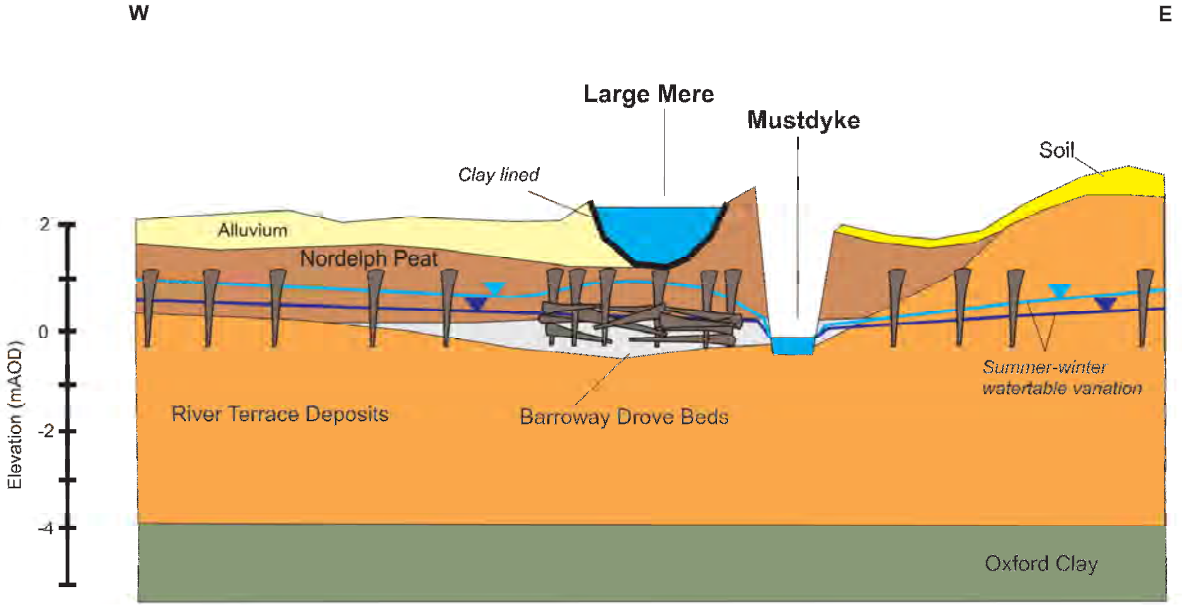
Figure 2-12 and Figure 2-13 summarise the hydrogeological conceptual model proposed for the wider Fenland area and the local area surrounding Flag Fen itself. It concentrates on the shallow hydrogeology and does not represent the Jurassic aquifers at depth.

Figure 2-12 Hydrogeological Conceptual Model for the wider Fen system



Schematic Diagram (approximate scale)
Notes:
GF = Groundwater Flow
PGF = Potential Groundwater Flow (contribution from bedrock)
OF = Overland Flow
BDB = Barroway Drove Beds (Aquitard)
KSM = Kellaways Sand Member (Aquifer)
KCM = Kellaways Clay Member (Aquitard)
CF = Cornbrash Formation (Aquifer)

Figure 2-13 Hydrogeological Conceptual Model for Flag Fen



Note: timbers associated with the Flag Fen Platform/Causeway are represented schematically.

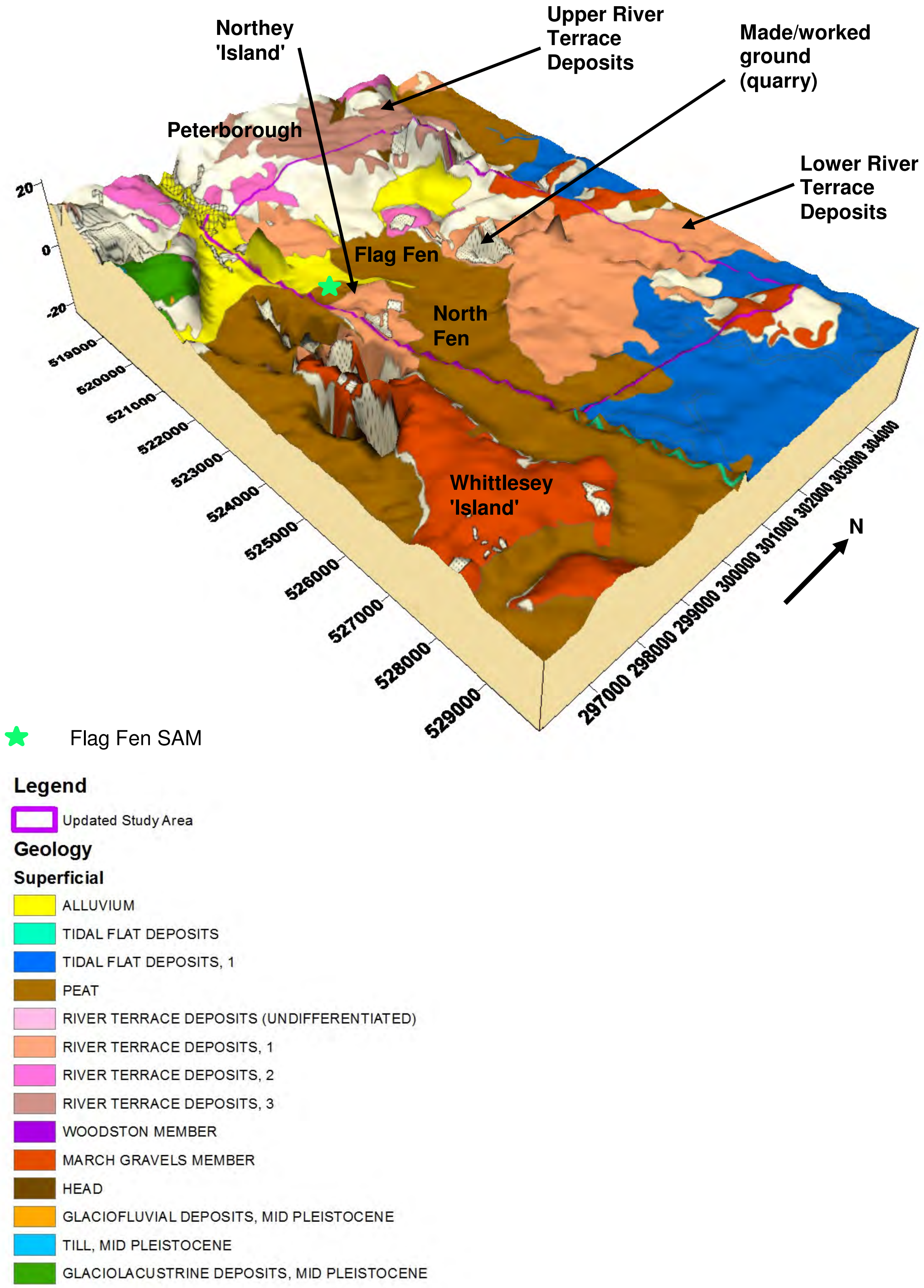
The main features of the conceptual model are as follows:

- Beneath Flag Fen, the top of the Oxford Clay aquitard forms an effective base to the shallow groundwater flow system within the superficial deposits. To the west of Flag Fen various other Jurassic strata crop out, some of which behave as aquifers and as a result may interact with shallow groundwater in the superficial deposits (Maps 3 and 4).
- Across the study area the thickness of the superficial aquifer varies from 0 to approximately 6 m (Map 4).
- The main superficial aquifer unit is the River Terrace Deposits composed of sand and gravel. Overlying alluvial deposits and peat deposits are likely to act as aquifers and/or aquitards.
- The superficial deposits are drained by an extensive network of artificial drainage ditches. There is a large drain named Mustdyke which passes through Flag Fen and is believed to penetrate the River Terrace Deposits (Map 5).
- The drainage network across the Flag Fen basin is controlled by two pumping stations, the larger of which is the Dog-in-a-Doublet pumping station managed by North Level IDB. This pumps water from the Dog-in-a-Doublet catchment to the tidal River Nene. The smaller pumping station is Padholme Pumping Station, which is managed by the Environment Agency. This smaller station pumps from the Padholme catchment (containing Flag Fen) to the freshwater River Nene (Map 5).
- There is a manmade, clay-lined pond at Flag Fen named Large Mere. The water level in Large Mere is maintained significantly above local groundwater levels and also above the water level in the Mustdyke. The Large Mere is designed to slowly lose water to the ground, helping maintain saturation of the underlying archaeological remains. Figure 2-13 shows a higher water table beneath the Large Mere, representing the impact of this artificial recharge. However, it is not known whether the ground profile beneath the Large Mere is fully saturated, or whether (as shown) there is an unsaturated zone above a groundwater mound.
- There are numerous sand/gravel quarries located within the study area. In many of these the sand and gravel deposits have been excavated to the bedrock. The disused quarries have been used for waste disposal (landfill), been infilled with material of an unknown nature, or left as open lagoons.

- Shallow groundwater is present in the superficial deposits across the study area. There are two licensed groundwater abstractions abstracting shallow groundwater from the River Terrace Deposits (Map 6).
- Groundwater levels in the vicinity of Flag Fen are believed to fluctuate mainly between 1 and -0.5 mAOD (Figure 2-11).
- Bronze Age timber posts preserved at Flag Fen are believed to have a maximum survival height of approximately 1.1 mAOD. Posts that survive in suitable condition to allow the preservation of woodworking data are believed to exist at a height of between 0.47 and 0.35 mAOD (Map 7).

Groundwater levels at Flag Fen rarely (if ever) exceed the highest elevation at which timbers are known to survive. Groundwater levels occasionally exceed the elevations at which the best preserved wood exists (Figure 2-11).

Figure 2-14 3-D Visualisation showing the Superficial Geology Draped over the Topography (OS grid references indicated along horizontal axes; elevation mAOD on vertical axis). Contains Ordnance Survey data © Crown copyright and database right 2015.



3 Numerical Groundwater Model

3.1 Introduction

"A model is a tool designed to represent a simplified version of reality" (Wang and Anderson, 1982, p.1). Models are very useful in everyday life, as well as in science and engineering. For example, the London Underground map is a model: a simplified representation of what in reality is a very complex system. However, the map captures everything that a traveller on the underground needs to know to plan a route from A to B.

A groundwater model represents the flow of water through the ground. Groundwater models help scientists and engineers to understand how groundwater systems work and to predict their behaviour. It is impossible, and unnecessary, to know every fine detail of an aquifer. Useful results can be obtained from a carefully constructed model that adequately captures all of the important features of the natural system.

Please note that this chapter omits some of the more technical details of the groundwater modelling undertaken for this project. These details are provided in Appendix B. A glossary of technical terms is provided in Appendix C.

3.2 Modelling Approach

The groundwater model constructed for this project is a mathematical model that runs on a computer. It has been produced using the Windows-based software Groundwater Vistas (ESI, 2011), which is a Graphical User Interface (GUI) for the United States Geological Survey's MODFLOW code (McDonald and Harbaugh, 1984; McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996a and 1996b; Harbaugh *et al.*, 2000; Harbaugh, 2005). It is called a numerical model because of the way it represents the equations that describe the physical process of groundwater flow.

The numerical model represents the ground as a three-dimensional grid of cells. Each cell is assigned particular properties (such as recharge, hydraulic conductivity and storage properties) and certain cells are also set to represent hydrological features such as rivers and drains. The model is necessarily a simplified version of the real system. Its spatial resolution depends on the spacing of the grid and its accuracy depends on the amount and quality of data available to inform model construction and calibration. Model calibration involves adjusting the parameters of the model until it reproduces observed groundwater levels and/or flow rates to an acceptable degree of accuracy. Once the model can reproduce observed behaviour of the system, it can be used to make predictions about future behaviour.

Often some parts of a model area are of greater interest than others. In the case of the Flag Fen Basin and surrounding area, English Heritage is particularly interested in groundwater levels in the vicinity of the SAM, and also in fields to the south of the Flag Fen Visitor Centre (these fields may be subject to drainage modification). JBA has reduced the grid spacing in these areas (this is called refining the grid) so that the hydrogeological processes can be represented in greater detail. Grid refinement is useful because it allows representation of significant local detail without having a fine grid everywhere. A uniform fine grid would increase computation time unnecessarily.

3.3 Model Extent, Grid and Layering

3.3.1 Model Extent

The area of the numerical model (Figure 3-1) corresponds approximately with the original study area defined in JBA's quotation (JBA Flag Fen Proposal Q14-1293_Revision 060614_Issued.pdf), although the northern, north-eastern and western boundaries have been modified to reflect the following:

- The shape of the surface water catchment of the Dog-in-a-Doublet Pumping Station run by North Level District IDB.
- Areas of low permeability geology along the western and north-eastern parts of the area (these have been excluded as they do not form a significant part of the groundwater flow system, instead forming barriers to flow).

The exclusion of areas of low permeability geology around the edge of the model represents a change from the initial approach outlined in JBA (2014).

3.3.2 Active Flow Area

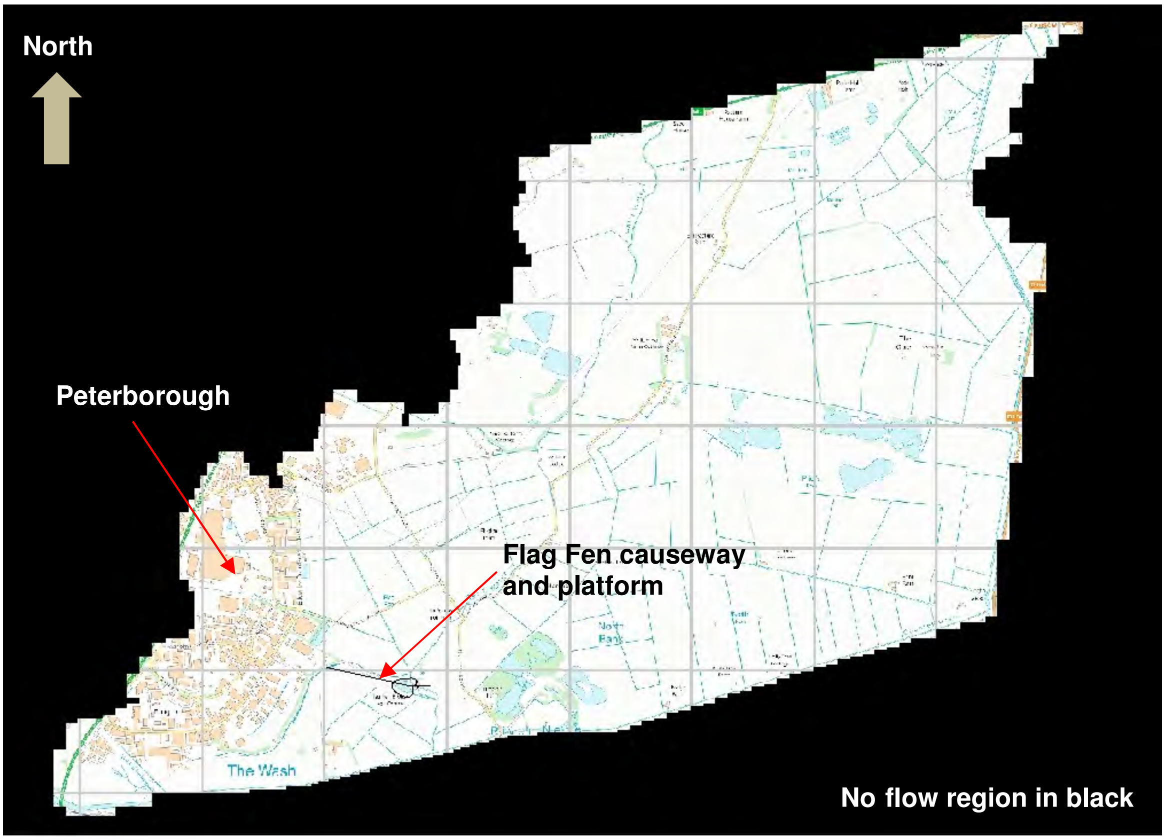
The MODFLOW grid is rectangular. Within this rectangular region, the irregular shape of the model area has been defined by specifying some cells as no-flow, i.e. inactive. These cells are black in Figure 3-1, Figure 3-2, Figure 3-3 and Figure 3-4. The model has 113,296 cells, of which 44,495 are active.

3.3.3 Model Grid and Layering

Initially the model grid was defined with a uniform spacing of 100 m, giving square cells measuring 100 m by 100 m in plan view. The grid was then refined in the vicinity of Flag Fen, first to 50 m spacing and then, in the area of greatest interest, to 20 m. Grid refinement generated cells that were rectangular in plan view. Figure 3-2 and Figure 3-3 show the refined grid.

Across most of the area the superficial deposits are underlain by low permeability Oxford Clay, the upper surface of which could form an effective "no-flow" base to the groundwater model. However, in the western part of the area there are permeable bedrock units that may interact hydraulically with the superficial deposits. For this reason the model represents the bedrock.

Figure 3-1 Numerical Model Extent in Plan View (each grid square on the OS base map measures 1 km by 1 km)



The model contains four layers for which the default identities are:

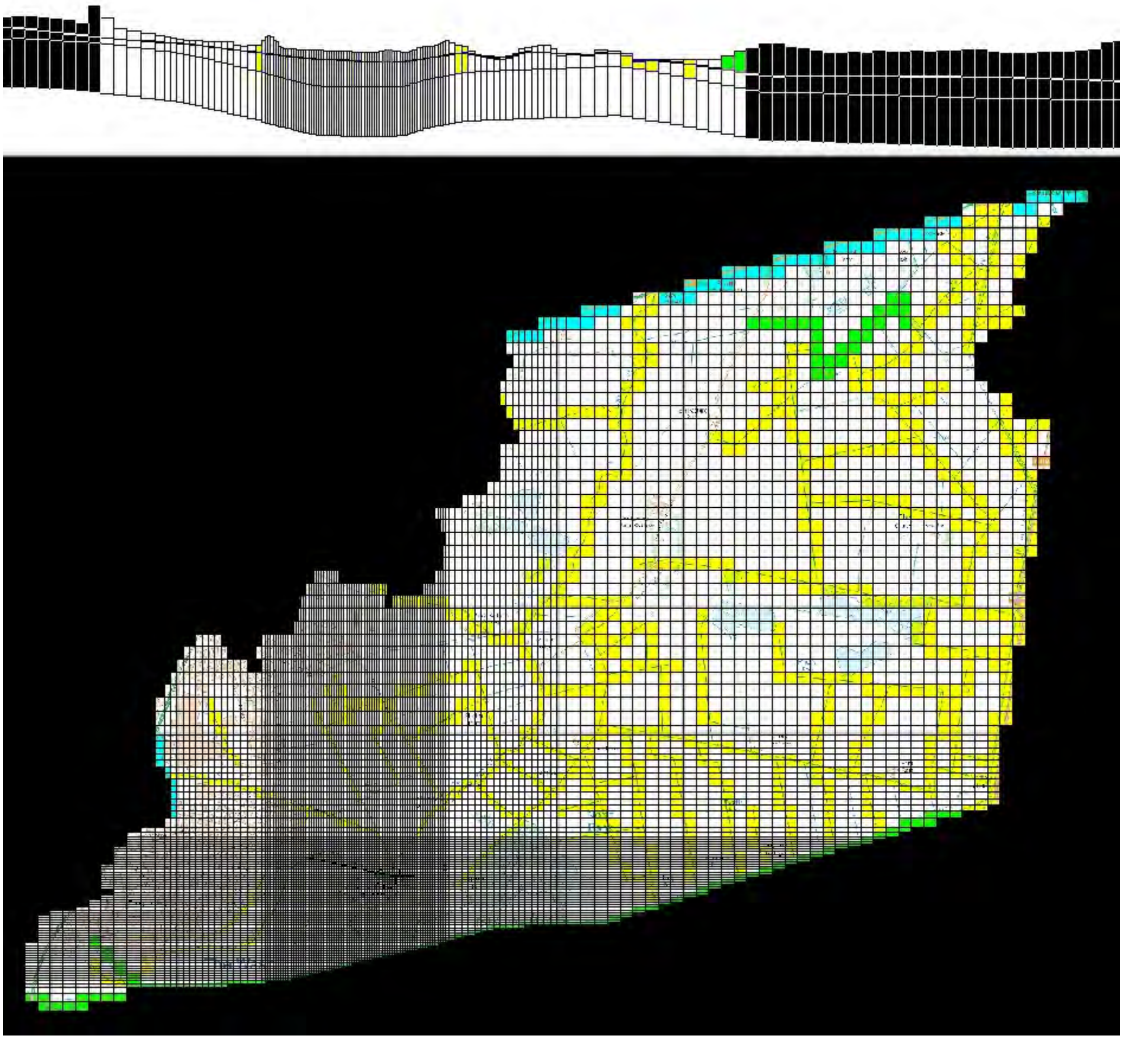
1. Peat, alluvium and made ground
2. Barroway Drove Beds (or clay/silt-rich layer at base of peat or top of river terrace deposits)
3. River terrace deposits and March Gravels
4. Layer to represent bedrock (allowing for influence of permeable bedrock in the west).

Layer 1 is the uppermost layer and Layer 4 is the lowermost layer. It is a feature of MODFLOW that all layers are defined across the whole model area. Where a particular geological unit is absent the model layer is made thin and given the properties of the underlying unit.

The elevation of the top of Layer 1 is based on LIDAR and OS Terrain 50 digital topographic data. Layer bases have been defined using borehole records, geological mapping and topographic data (Figure 3-2 and Figure 3-3).

Note that the number of layers has been reduced from five (JBA, 2014) to four. This change was made to address model stability issues caused by the repeated wetting and drying of very thin surface layers. Four layers are sufficient to represent the hydrogeology. In particular, the uppermost layer in the original 5 layer model was in some areas completely dry - hence not taking part in groundwater flow and so not usefully part of the model.

Figure 3-2 Model Grid, Layering and Boundary Conditions – Layer 1 (vertical cross-section above; plan view below)



Yellow = drain cells, green = river cells, blue = general head cells.
Contains Ordnance Survey data. © Crown copyright and database right 2015.

3.4 Boundary Conditions

In order to solve the equations describing groundwater flow it is necessary to define the model area and specify "boundary conditions". The boundary conditions are defined at the edges of the model and may be specified water levels (heads) and/or flows. The external boundaries of the model are as follows:

Northern boundary: approximate drainage divide = "general head" boundary that may allow some flow into, or out of, the model. This allows a large groundwater abstraction close to the northern edge of the model area to draw water from beyond the surface water catchment boundary.

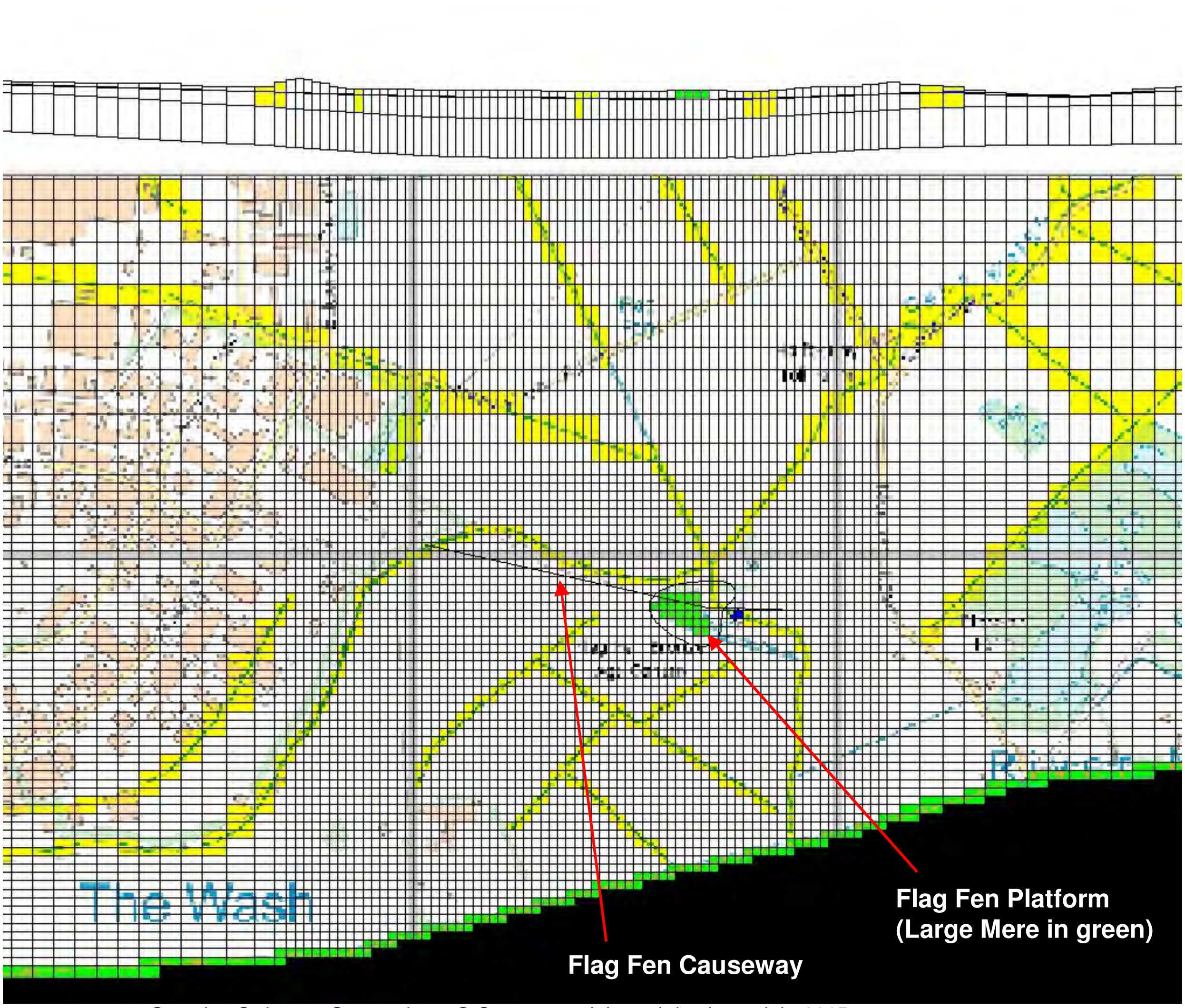
Eastern boundary: River Thorney or drain immediately to the west = specified head boundary.

Southern boundary: River Nene or drain immediately to the north = specified head boundary.

Western boundary: up-gradient edge of permeable superficial deposits = no-flow boundary ("general head" boundary defined locally to represent a drainage ditch immediately west of the model area).

Within the model area, MODFLOW drain and river cells are used to represent watercourses. Drain cells can only take water from the model, whereas river cells can give, as well as receive, water. River cells are used to represent watercourses that may lose water to the ground. They are also used to represent the Large Mere at Flag Fen, which is designed to leak water.

Figure 3-3 Close-up of Previous Figure showing Refined Grid around Flag Fen



The low resolution base map is used for reference in the model.

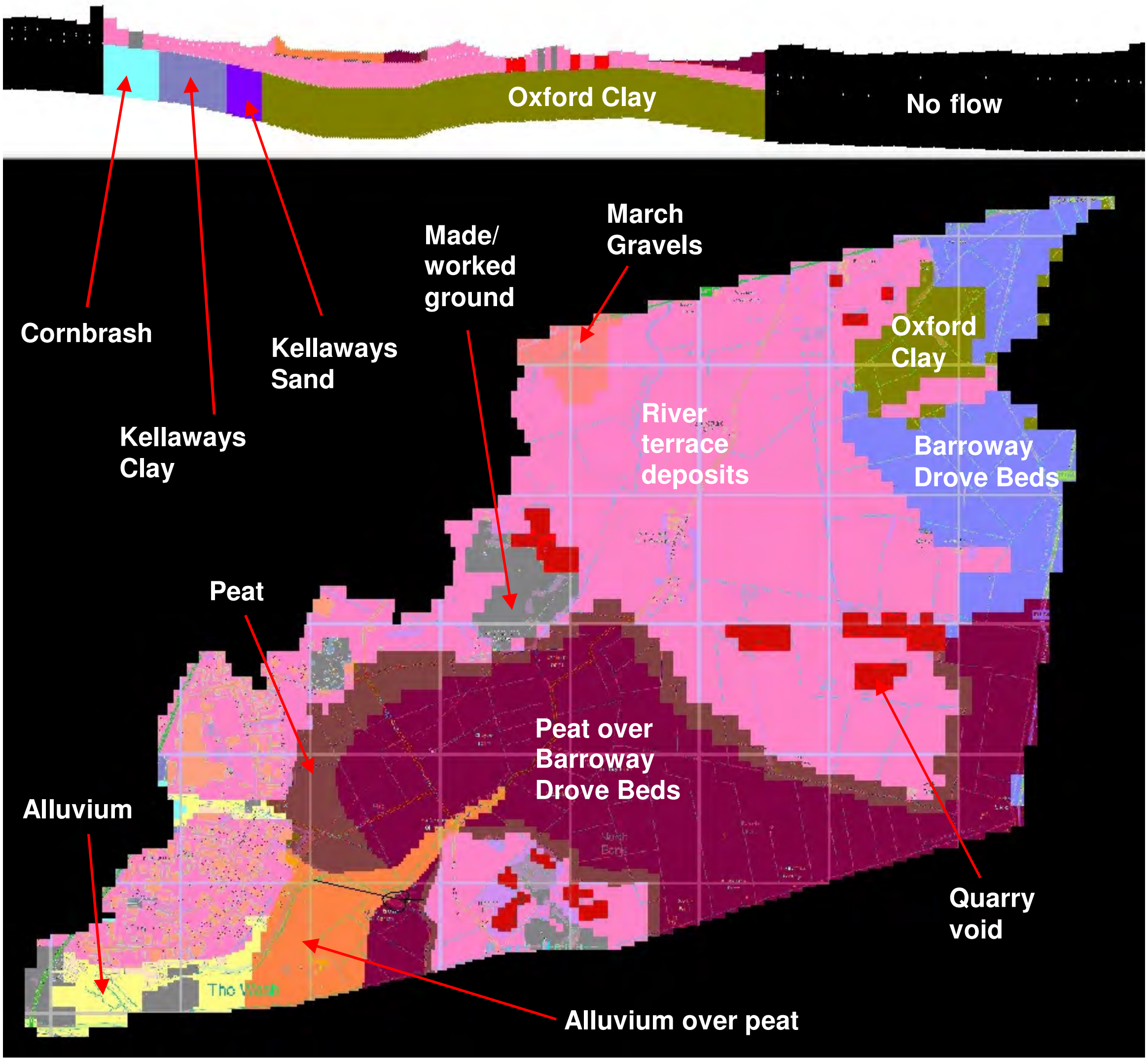
3.5 Hydraulic Property Zones

Hydraulic property zones have been defined to represent the geology (Figure 3-4). Each zone has associated with it the following hydraulic properties:

- Hydraulic conductivity (permeability to water):
    - Horizontal hydraulic conductivity (K_{xy})

- Vertical hydraulic conductivity (K_z)
- Storage parameters:
  - Porosity - the volumetric fraction of void space within the material.
  - Specific storage (S_s) - the volume of water generated per unit volume of saturated material per unit decline in hydraulic head. The water is generated by compaction of the solid matrix and expansion of the water, not by drainage of the pore spaces.
  - Storage coefficient (S) - the volume of water generated per unit surface area of saturated aquifer per unit decline in hydraulic head. $S = S_s \times b$, where b is the thickness of the aquifer layer.
  - Specific yield (S_y) - the volume of water that can be obtained by gravity drainage of a unit volume of saturated material.

Figure 3-4 Hydraulic Property Zones Defined to Represent Geology (vertical cross-section above; plan view below)



 Note that the plan view is shown for Layer 1 (the top layer) only.

Initially, hydraulic property values were estimated based on the following sources:

- Typical values from the geological literature for the types of materials known to be present in the Flag Fen area.

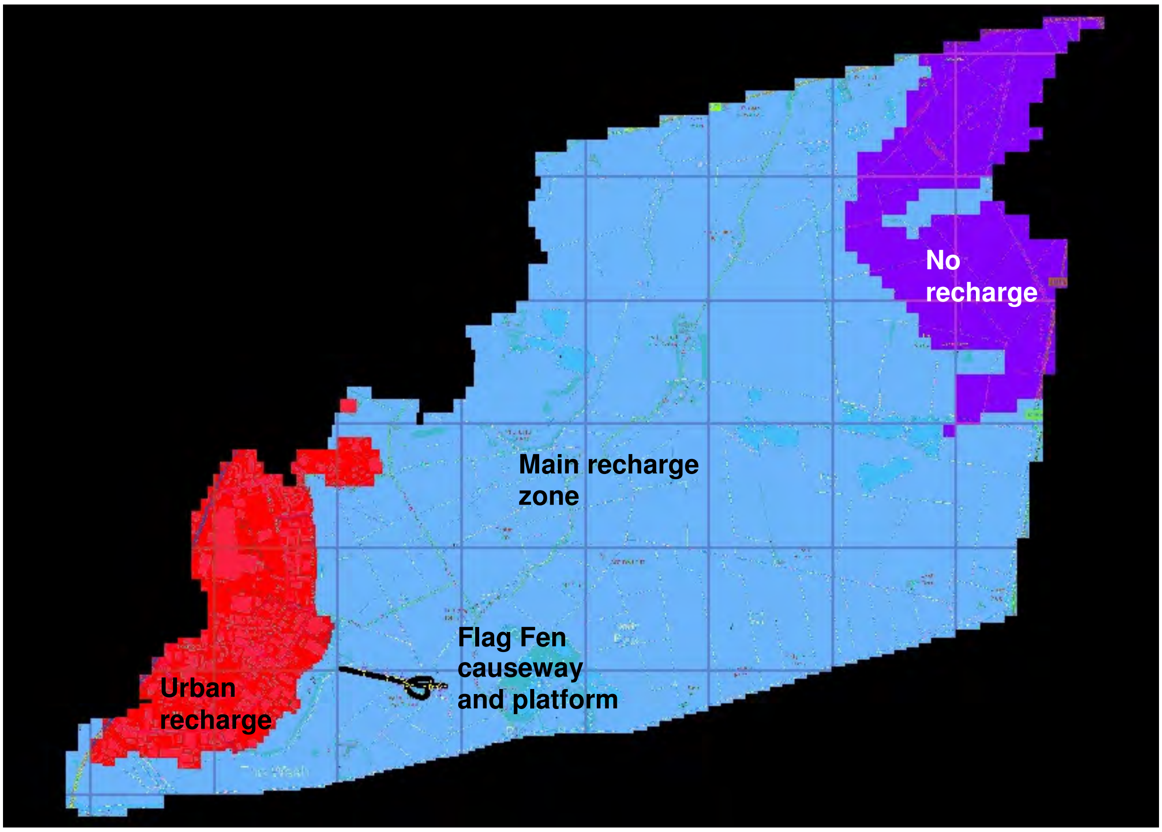
- Values estimated from grain size data for the river terrace deposits beneath the Flag Fen Heritage Centre (data in Ground Engineering, 2012). The values obtained were very high and unlikely to be representative of the river terrace deposits as a whole.

Hydraulic properties were refined during calibration of the model, with care taken to ensure that the values remained realistic for the geological materials concerned. The final values of hydraulic properties used in the modelling are provided in Appendix B.

3.6 Recharge

Some of the water that falls as rainfall is lost to evapotranspiration and some to surface runoff or (lateral) interflow through the soils; the remainder is available to recharge groundwater. MORECS rainfall and evapotranspiration data were used to estimate the effective rainfall: rainfall minus evapotranspiration. Effective rainfall may become runoff or recharge, so it provides an upper limit for recharge.

Figure 3-5 Recharge Zones



Three recharge zones were defined in the model:

- A main recharge zone covering most of the model area. Recharge was initially estimated at about 12 or 13% of long-term average rainfall.
- An area of reduced recharge covering Peterborough, reflecting the presence of impermeable surfaces and artificial drainage systems. Recharge in this area was initially estimated at 50% of the "main" value.
- An area of no recharge covering the outcrop of low permeability deposits in the north-eastern part of the model area. Recharge will be very low in this area. For the purposes of the modelling it was approximated as zero. This area is not close to the Flag Fen area of interest.

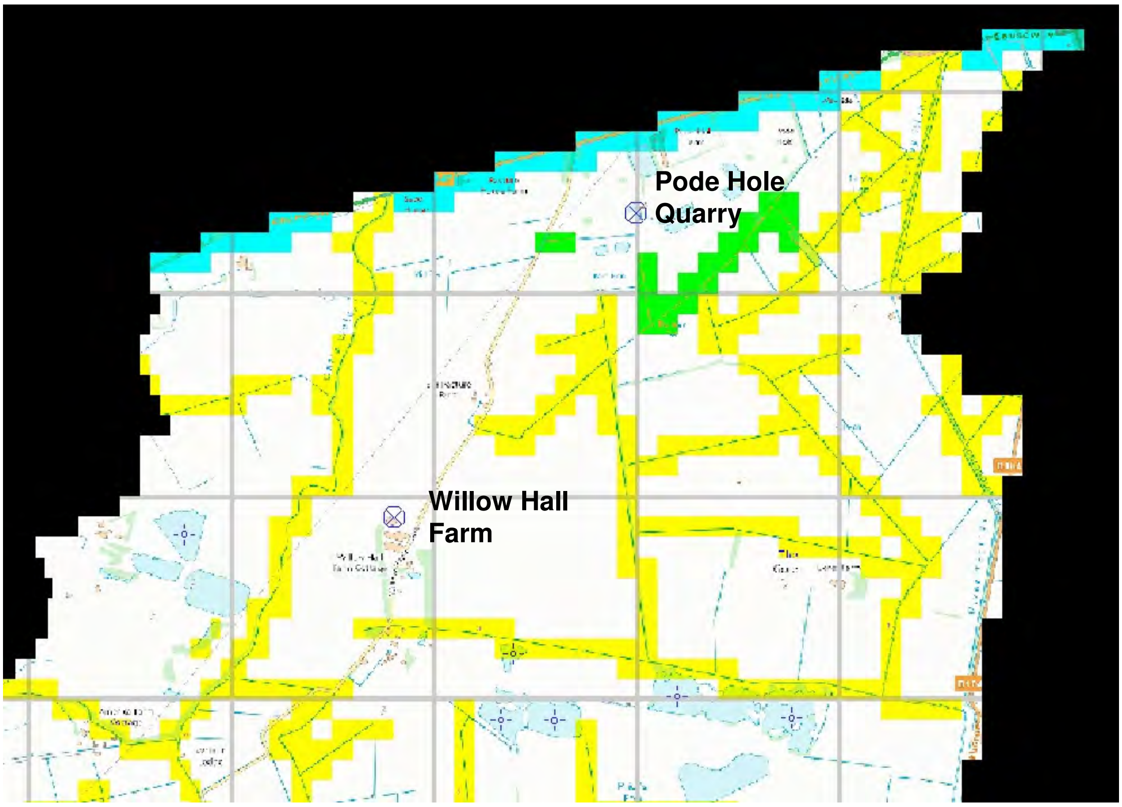
Recharge rates were refined during model calibration, with care taken to ensure that the values were realistic, given the effective rainfall and soil types in the area. Final recharge rates used in the modelling are provided in Appendix B.

3.7 Abstractions

Two licensed groundwater abstractions from the river terrace deposits are represented in the model as wells with defined abstraction rates (Figure 3-6). One abstraction (Willow Hall Farm) is represented at its full licensed rate. The other (Pode Hole Quarry, Thorney) is represented at 50% of its average returned (actual) abstraction rate, reflecting the fact that some of the abstracted water is recirculated into the ground as part of quarry operations. The 50% recirculation rate is estimated, but the abstraction is distant from Flag Fen and exerts little influence on groundwater levels and flows in the area of interest. Abstraction rates represented in the model are provided in Appendix B.

Abstractions from the bedrock (from deeper geological layers below the modelled low permeability bedrock strata) are not represented. These include two abstraction boreholes at Flag Fen Farm.

Figure 3-6 Groundwater Abstractions



3.8 Steady-state and Transient Simulations

The model runs in two modes:

- Steady-state:
  - Groundwater levels and flows are constant, i.e. they do not change with time. This mode is suitable for modelling "average" conditions, such as an average year.
- Transient:
  - Groundwater levels and flows are allowed to vary in time. This mode is suitable for modelling seasonal variations in groundwater level and flow.

For a transient numerical model it is necessary to define stress periods and time steps. A stress period is a block of time during which "stresses" on the system (such as recharge and abstraction rates) are constant. Each stress period is composed of time steps. The computer solves the groundwater flow equations for each time step. It is also necessary to define the "initial conditions": the groundwater levels from which the transient simulation is to start.

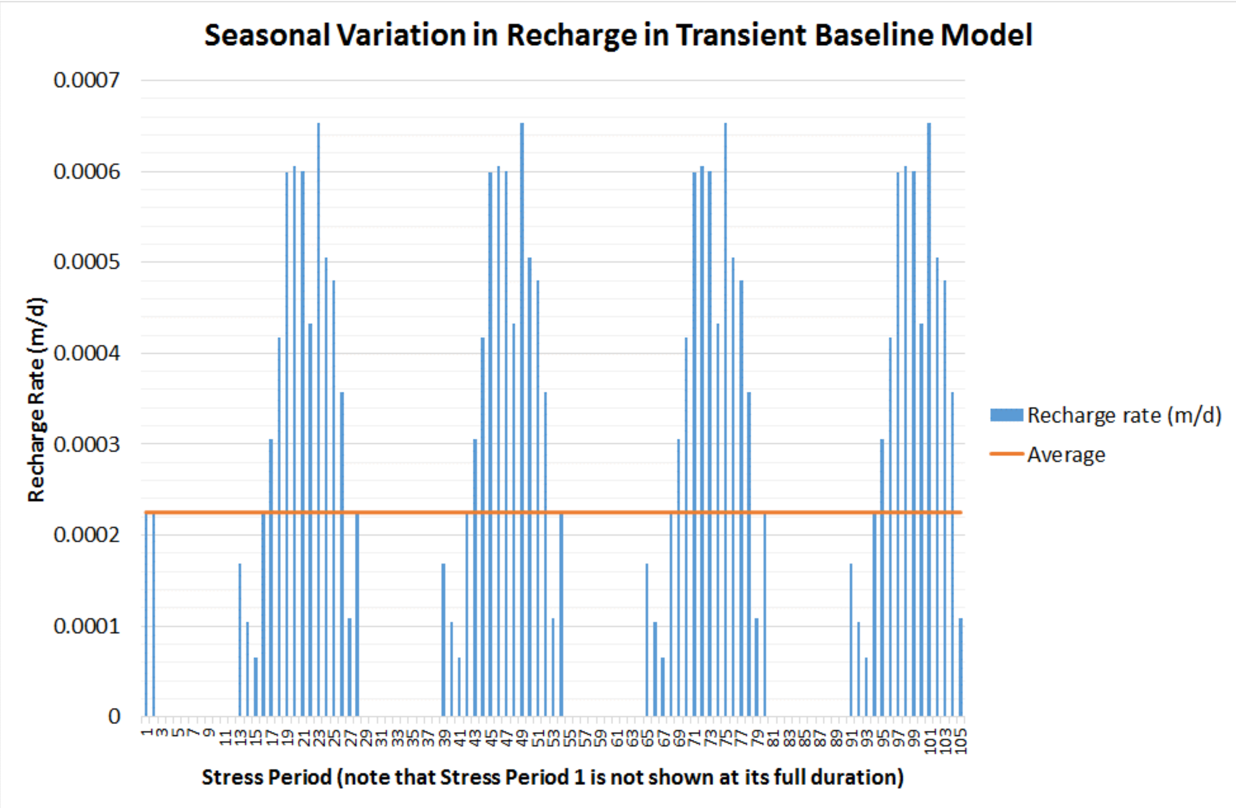
For the Flag Fen model, the following stress periods and time steps are defined:

- An initial steady-state stress period to obtain initial groundwater levels.
- 104 fortnightly stress periods, each composed of 14 time steps. The model simulates four identical annual cycles; this is to allow the model to "settle" and ensure that there is no progressive change in groundwater level from year to year.

The initial groundwater levels are defined as the output of a steady-state model run. The only stress varied during the transient simulations is the recharge, which is assumed to follow the same seasonal distribution as the MORECS effective rainfall (Figure 3-7). This allows representation of seasonal fluctuations in groundwater level. Transient recharge rates used in the modelling are tabulated in Appendix B. Note the presence of a double peak in annual recharge (Figure 2-7); this reflects a double peak in the average rainfall data used to derive the recharge.

Note that rates of groundwater abstraction were not varied transiently because (i) the abstractions are located far from the area of interest and (ii) quarry dewatering is likely to be undertaken throughout the year (unlike spray irrigation, for example).

Figure 3-7 Seasonal Variation in Recharge in Transient Baseline Model ("main" recharge zone)



3.9 Calibration of Steady-state Baseline Model

The steady-state model was calibrated using 29 observed groundwater levels, including:

- Average groundwater levels from monitoring boreholes

- One-off (spot) groundwater level measurements from boreholes
- Water levels for flooded sand/gravel quarries estimated from Ordnance Survey mapping and a Digital Elevation Model (DEM). These quarry pond levels are assumed to reflect local groundwater levels.

Model parameters were varied manually until a good match was obtained between observed and modelled groundwater levels. Automated sensitivity analysis (involving systematic variation of parameter values) was used to help identify which parameters were most important in the calibration process. Recharge, hydraulic conductivity and drain conductance (the degree of hydraulic connectivity between drains and the ground) were the main parameters varied during calibration. Care was taken to ensure that parameter values remained realistic. The groundwater level targets were matched to within 0.5 m, and commonly to within 0.3 m. The difference between a modelled level and the corresponding observed level is called a "residual".

Figure 3-8 presents a plot of observed versus modelled levels. Figure 3-9, Figure 3-10 and Figure 3-11 show the individual residuals, in metres, for Layer 1 (peat) and Layer 2 (river terrace deposits). Around the Flag Fen platform and causeway, most of the targets have been matched to within 0.2 m in Layer 1 and 0.1 m in Layer 2. This is a good calibration. A perfect match is unrealistic because (i) the targets are not all from the same instant, or period, of time, and (ii) the model is a simplified representation of a complex natural system. Note that the model captures the vertical hydraulic gradient between the peat and underlying river terrace deposits (groundwater levels/heads being higher in the peat). This has been achieved through suitable adjustment of layer vertical hydraulic conductivity, and also the hydraulic conductivity of Layer 2 where it represents a low permeability base to the peat (or top of the river terrace deposits).

Figure 3-8 Steady-state Calibration: Plot of Observed Groundwater Levels against Modelled Groundwater Levels

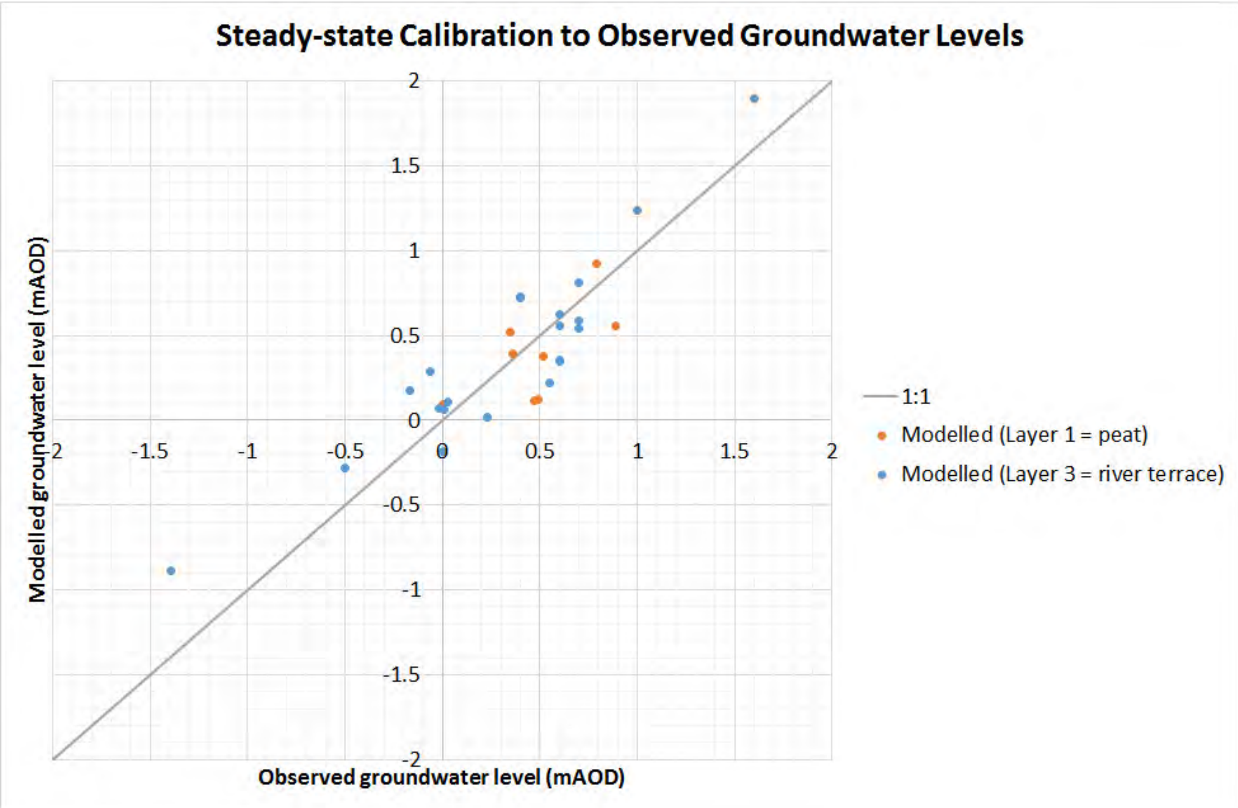
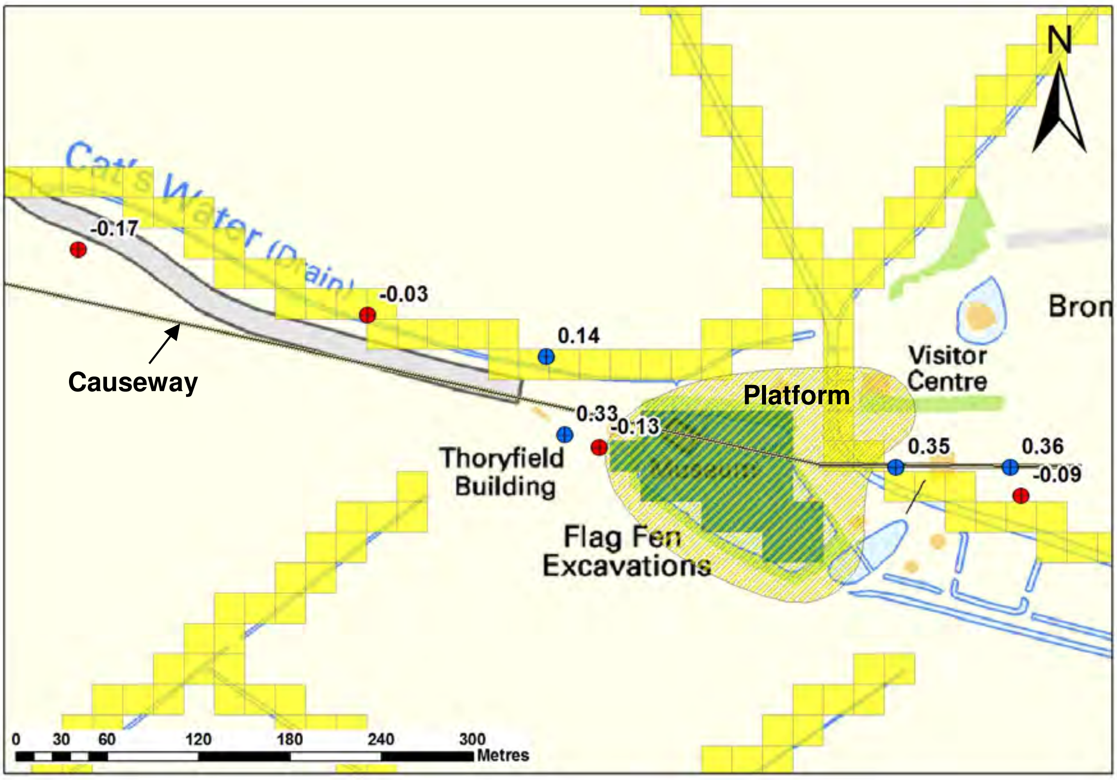


Figure 3-9 Target Residuals in Layer 1 (residuals in metres; red = model > observed; blue = model < observed)



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Yellow = drain cells; dark green = river cells.

Figure 3-12 shows the water balance for the calibrated model, i.e. the balance between inflows and outflows. It is apparent that rainfall recharge is the main input and flow to drains the main output.

Model flow rates have been compared with known flows to ensure that the model was providing a realistic representation of flows as well as levels. In a steady-state model, different sets of parameters can give the same groundwater levels but with different flow rates (i.e. a calibration to groundwater levels is non-unique). It is therefore advisable to calibrate to both heads and flows.

The "main" recharge rate is about 15% of the long-term average rainfall, which is reasonable (10 to 20% would be expected). The total flow of groundwater to drainage ditches in the model is 4,890 m^3 per day. For comparison, an upper estimate of the IDB pumping rate for Dog-in-a-Doublet is an average of 8,896 m^3 per day based on pumping hours and pump capacity. The IDB catchment is not identical to the model area, but is similar. The modelled flow of groundwater to drains is 55% of the IDB pumping volume, which is reasonable, given that some of the pumped water will have come from runoff rather than groundwater input. The modelled leakage rate from the Large Mere to ground is 26 m^3 per day, which is within the likely range of 10 to 40 m^3 per day (based on reports, for two years, on how much water was used to replenish the Mere - see Appendix B.7).

Figure 3-10 Target Residuals in Layer 3 (residuals in metres; red = model > observed; blue = model < observed)

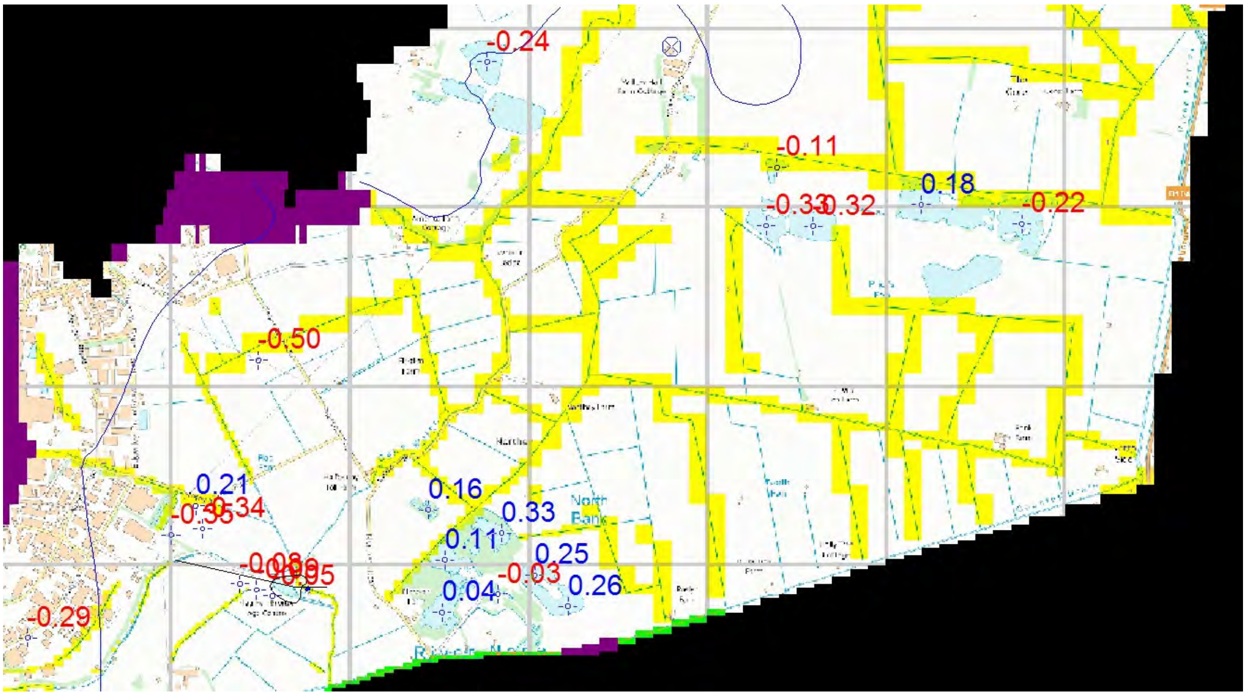

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Figure 3-11 Close-up of Target Residuals in Layer 3 around Flag Fen (residuals in metres; red = model > observed; blue = model < observed)

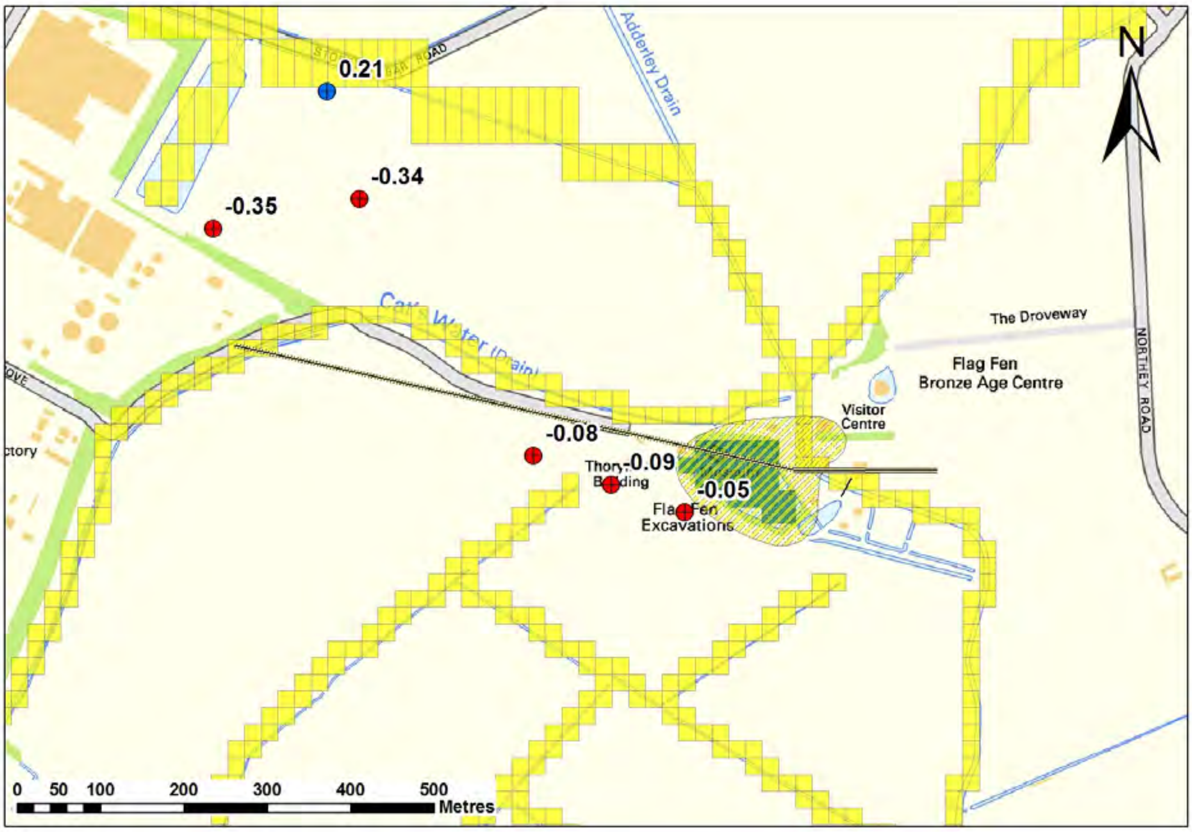

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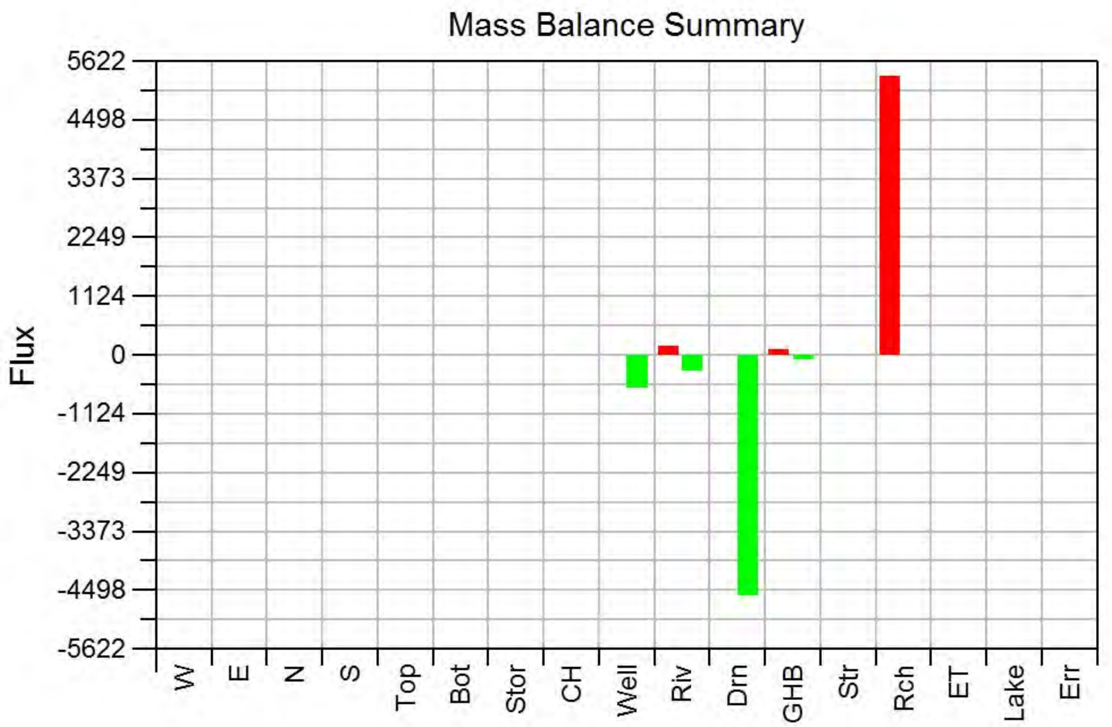
Figure 3-12 Water Balance for the Calibrated Steady-state Model (inflows in red; outflows in green)

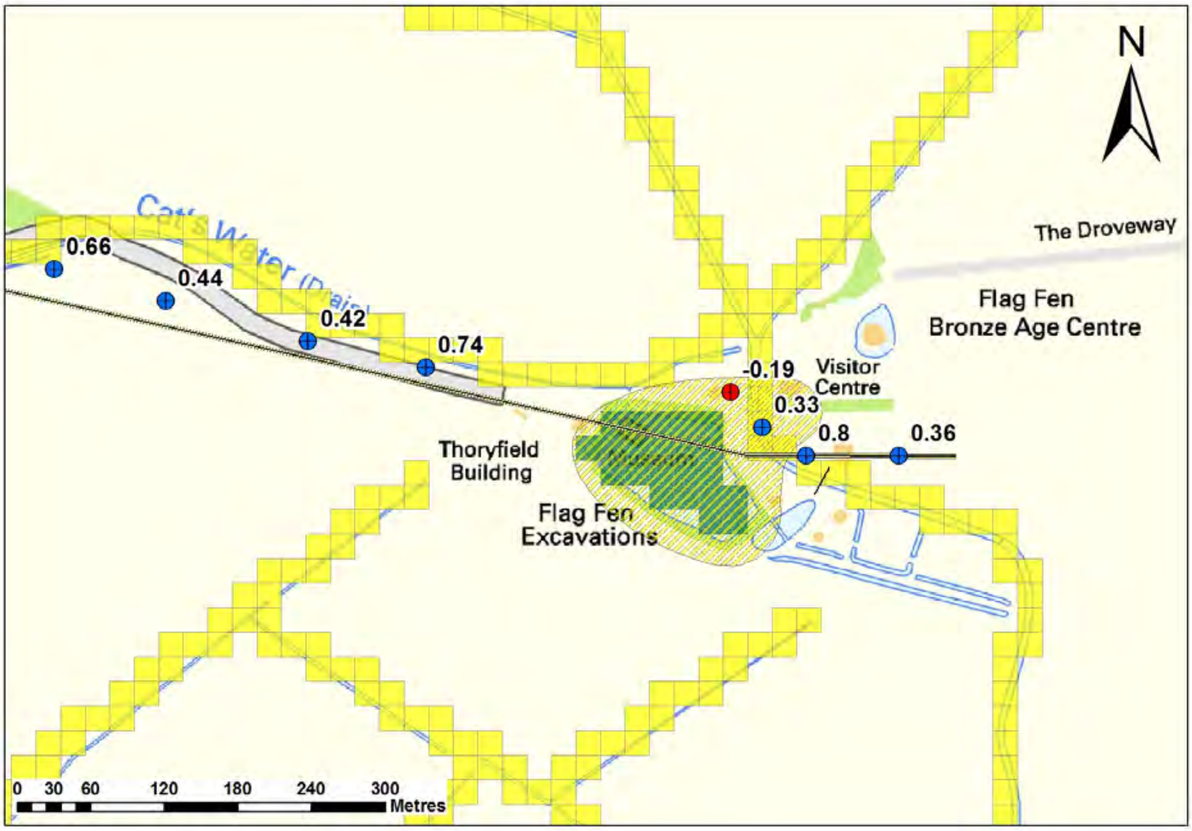


W = west, E = east, N = north, S = south, Top = top, Bot = bottom, Stor = storage, CH = constant head, Well = well, Riv = river, Drn = drain, GHB = general head boundary, Str = stream, Rch = recharge, ET = evapotranspiration, Lake = lake, Err = error in mass balance

3.9.1 Comparison of Steady-state Water Table with Depth of Archaeology

Elevation data for the top of the archaeological features of interest were added to the calibrated steady-state model as pseudo-targets. The residuals (Figure 3-13) show how far the calculated "average" water table surface is below the top of the archaeological features of interest. Locally the calculated water table elevation is up to 0.8 m below the top of the archaeology. It should be noted that groundwater levels will vary seasonally about the average.

Figure 3-13 Residuals for Pseudo-targets (Layer 1) showing how Far the Baseline Water Table is Below the Top of the Archaeology (in metres)



Residuals in metres. Blue residuals (positive) indicate groundwater level below top of archaeology; red residuals (negative) indicate groundwater level above top of archaeology.

3.10 Calibration of Transient Baseline Model

There are two types of transient calibration: (i) detailed calibration to a particular time series of observed groundwater levels and/or flows (requiring a reliable rainfall record covering the period of interest), and (ii) calibration of storage properties using the observed average magnitude of seasonal fluctuation in groundwater level. For this project the second approach has been adopted.

The higher the storage capacity of an aquifer layer, the lower the seasonal fluctuation, and vice versa. The following observed seasonal fluctuations have been used to calibrate the model:

- Borehole DW03 (peat): fluctuation of approximately 1 m.
- Borehole BH3 (river terrace sand/gravel): fluctuation of approximately 0.25 m.

The locations of the boreholes are shown in Figure 3-14. These boreholes were added to the model as observation wells, along with three other monitoring points labelled as FF_causeway, FF_platform and FF_platformE (Figure 3-14). These observation wells allowed monitoring of groundwater levels within the transient model. The results are shown in Figure 3-15.

The target seasonal fluctuations are matched fairly well by the model, the modelled fluctuations being 0.92 m for DW03 and 0.37 m for BH3. FF_platform displays a fairly constant high groundwater level; this is due to leakage of water from the Large Mere. The model suggests that the Mere is performing its function of keeping the underlying archaeology saturated with water.

However, this has not been confirmed by direct observation in the field. Groundwater level monitoring (in the form of a dipwell next to the Mere) could be installed to check this.

The pattern of seasonal variation in groundwater levels reflects the pattern of recharge applied to the model, and is similar to the observed groundwater level variation, with steep rises and more gradual falls (see Figure 2-3 in JBA, 2014). The model also captures the observed vertical hydraulic gradient between the peat and underlying river terrace deposits.

Figure 3-14 Location Map for Monitoring Wells used in the Transient Model

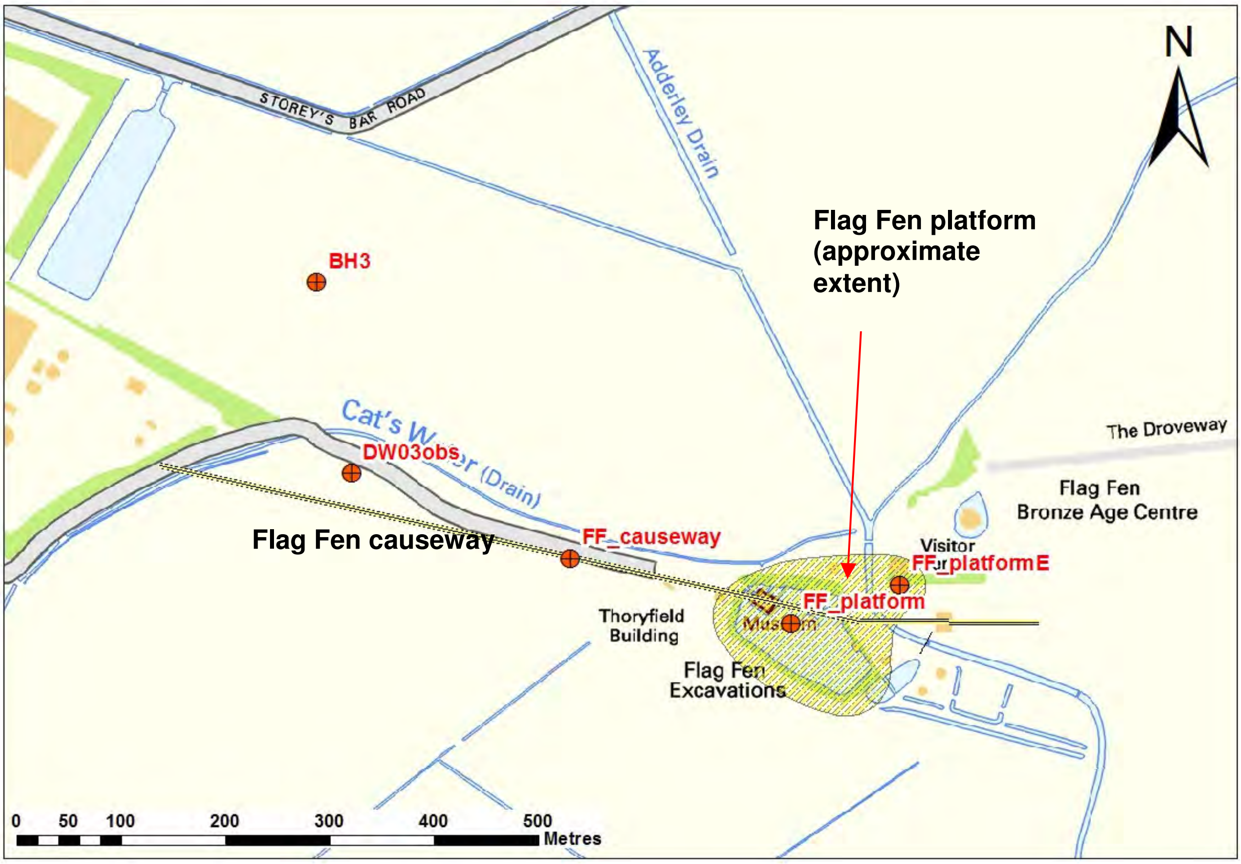
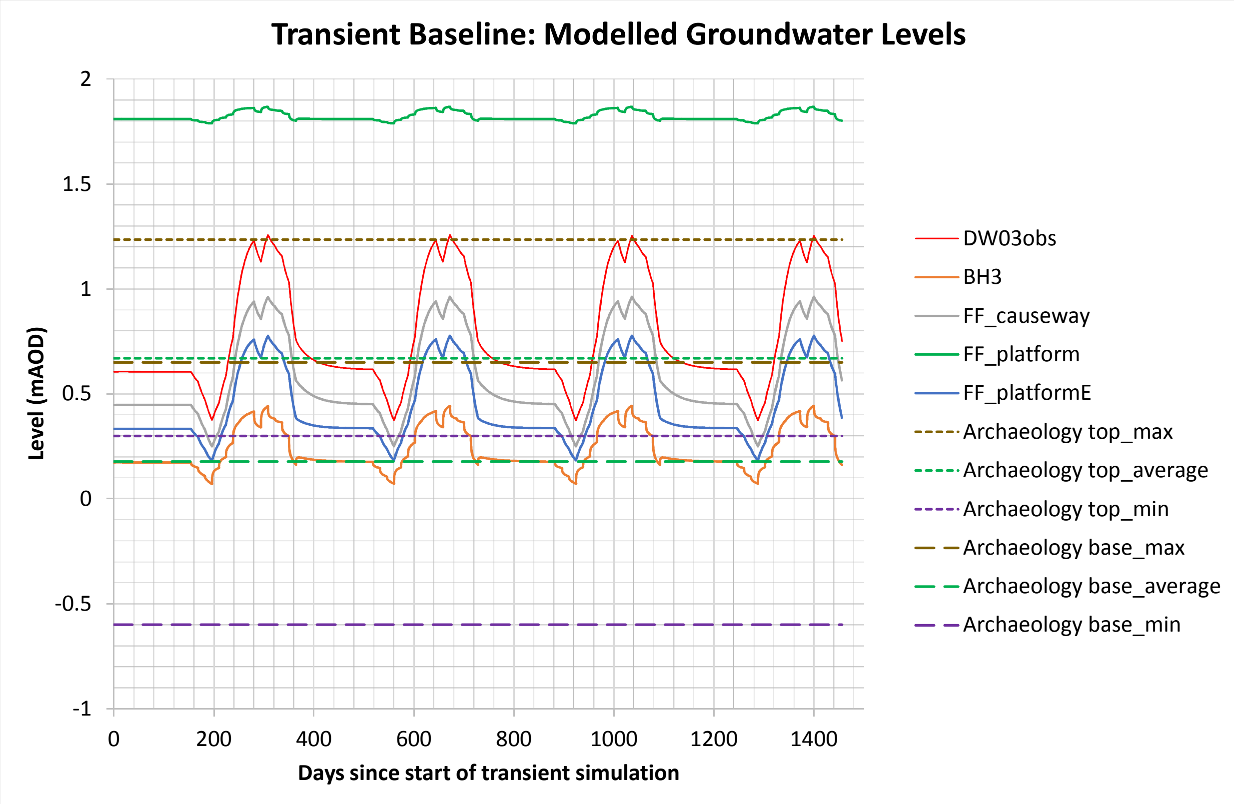


Figure 3-15 Output from Transient Baseline Model



3.10.1 Comparison of Transient Baseline Water Table with Depth of Archaeology

Figure 3-15 shows minimum, maximum and mean values for the uppermost elevation of the archaeology (40 observations) and the lowermost elevation (34 observations) (see Appendix D for the elevation data). Most of the data points relate to the eastern part of the structure (including the platform area), although there are a number of points spread out along the length of the causeway.

The following conclusions can be drawn from the figure:

- The data analysed suggest that the main archaeological interest at Flag Fen is concentrated within a fairly narrow elevation range: between about 1.2 mAOD and -0.6 mAOD, a height interval of less than two metres.
- Seasonal fluctuations in groundwater level mean that the upper parts of the archaeological structure at Flag Fen are typically located within (or even above) the zone of water table fluctuation. On average, the base of the archaeology is close to the base of the zone of fluctuation.
- The exception to the above observations about seasonal fluctuation is the area beneath the Large Mere, where the model suggests that leakage from the pond is maintaining groundwater levels above the highest elevation of the nearby archaeology (no data are available on the elevation of any archaeological wood present directly beneath the pond).

The extent to which artificial recharge from the Large Mere is benefiting the wooden platform structure is unclear, partly because the location and extent of the platform are uncertain (see Section 2.5.2), and partly because enhanced recharge and flushing by fresh surface water may potentially increase the rate of degradation. However, the role of any bed sediments at the base of the Mere in altering the chemistry of the water leaking from the pond (including oxygen levels) is not known. This could be further investigated. Certainly the eastern part of the structure has been adversely affected by drainage as it is cut by the Mustdyke. It was during deepening of the

Mustdyke in 1982 that the Bronze Age timbers of Flag Fen were discovered, and a year later the effects of drying out were clearly evident in the ditch banks (Pryor, 1992).

4 Numerical Modelling Scenarios

4.1 Modelled Scenarios

The calibrated transient model has been used to run the following six scenarios:

- DRYYR (climate change sensitivity):
    - Recharge profile adjusted to that of a dry year (2011: 64% of average rainfall).
- DRYYR50 (climate change sensitivity):
    - Recharge profile of average year applied, but with recharge values at 50% of baseline.
- PREL (Figure 4-1):
    - PREL Energypark development area represented as a new recharge area with an average recharge equal to 0.25 of the baseline value (assuming 75% hardstanding and all runoff from hardstanding areas routed directly to the surface water drainage system).
- WET (Figure 4-2):
    - Wetland created to the southwest of Flag Fen by removing/blocking the drains in this area (deleting them from the model).
- DIVERSION 1 (Figure 4-3):
    - Diverting Cat's Water and part of the Mustdyke within the Padholme catchment and blocking drains to the southwest of Flag Fen.
- DIVERSION 2 (Figure 4-4):
    - Diverting water from Padholme (Environment Agency pumping) catchment into the IDB catchment and blocking drains to the southwest of Flag Fen, as well as the Mustdyke and part of Cat's Water.

Note that both of the diversion scenarios involve adding new drainage to serve the sewage works.

For each scenario the transient model was set to simulate a four-year period (following an initial "run-in" period to establish the starting groundwater levels) (Section 3.8). The four years had identical recharge patterns. Four years were specified in order to check that the groundwater levels were returning to the same point after each year, i.e. that the model was not becoming progressively wetter or drier. The intention was that there should be no net change in groundwater storage between years. This is appropriate for the simulation of a generic year under given (scenario) conditions. Had the model been calibrated to a particular historical time period then it may well have been appropriate to allow changes in storage between years.

Figure 4-1 Recharge Zones for PREL Development Scenario

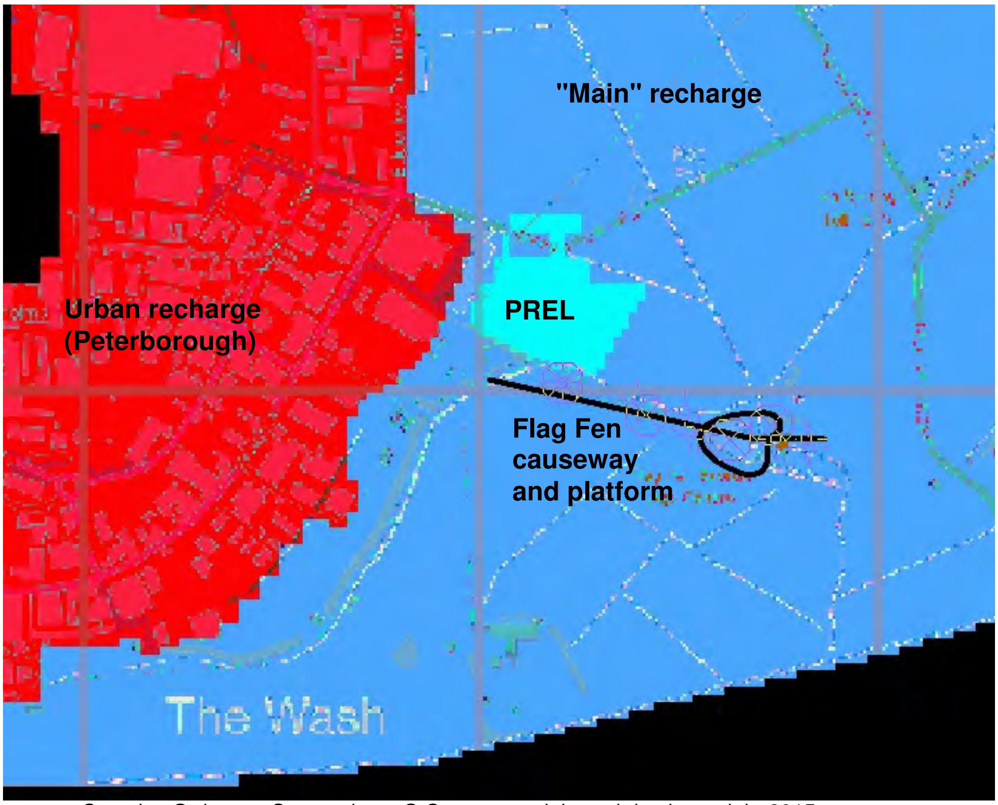


Figure 4-2 Wetland Scheme involving Drain Blocking/Removal

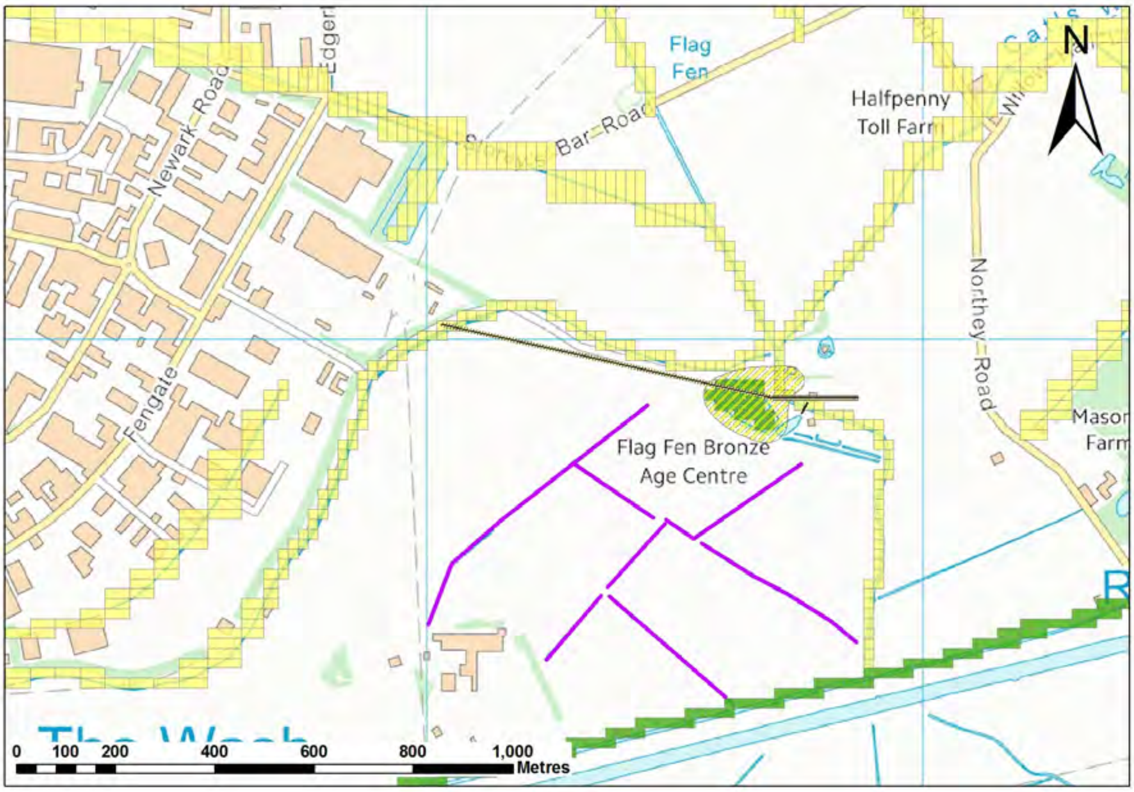


Figure 4-3 Drain Diversion Scheme: DIVERSION 1 (new drains in orange)

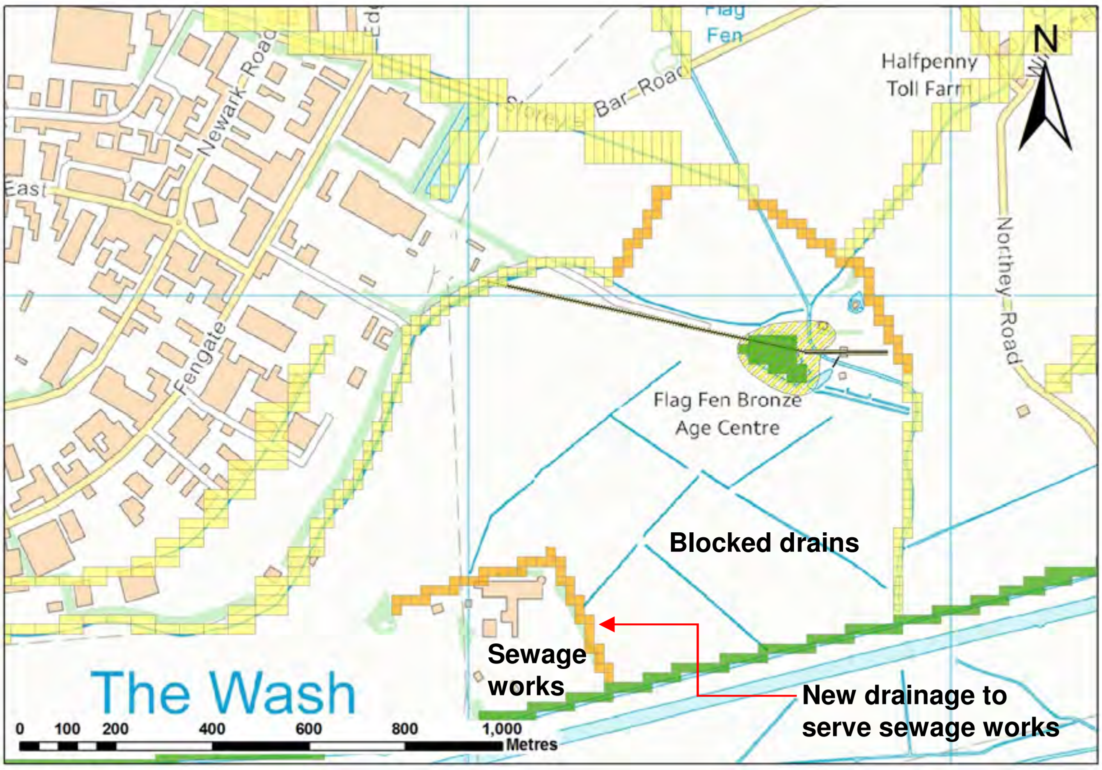


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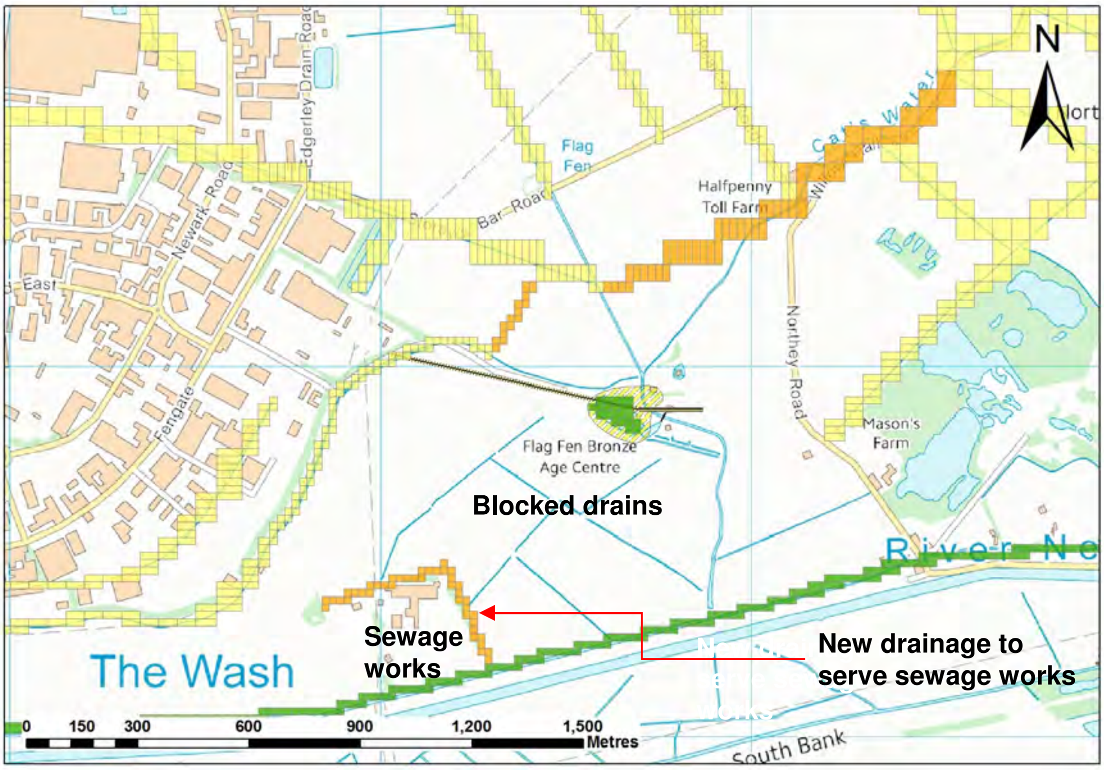
Figure 4-4 Drain Diversion Scheme: DIVERSION 2 (new, or deepened, drains in orange)



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4.2 Results of Scenario Modelling

The results of the transient modelling scenarios are illustrated in the hydrographs of Figure 4-5 to Figure 4-9. Note that where the baseline trace is not visible this is because it coincides with the PREL trace and locally also the DRYYR50 trace.

4.3 Implications of the Modelling Results

The modelling results suggest the following:

- The upper parts of the wooden structure at Flag Fen are typically located within (or even above) the zone of seasonal water table fluctuation, i.e. within Zone 2 (or Zone 1) in the three zone model of Chapman and Cheetham (2002). In this model, the best preservation of archaeological wood is in the zone of permanent saturation (Zone 3), below the minimum water table elevation. In the overlying zone of fluctuation (Zone 2) wood is generally subject to deterioration at the cellular level, although the macro-structure may be retained (Chapman and Cheetham, 2002). In the "dry" zone above the maximum water table level (Zone 1), archaeological wood is often subject to almost total deterioration of its structure (Chapman and Cheetham, 2002). The results of the present study therefore suggest that the hydrological conditions are sub-optimal for the long-term *in situ* preservation of the wooden platform and causeway at Flag Fen.
- The Large Mere may be fulfilling its function as an artificial recharge basin (Pryor, 1991 and 1992), maintaining higher groundwater levels beneath it. However, as noted in Section 3.10.1, the extent to which this is benefiting the Bronze Age platform is unclear. The location and extent of the platform are uncertain, and the Mustdyke - which is known to cut through the archaeology - is draining the ground adjacent to its channel. Also, the artificial recharge will not have any effect east of the Mustdyke, which will act as a hydraulic barrier to shallow groundwater flow.
- If the observed basal elevation of the eastern part of the Bronze Age structure is representative then, on average, the base of the archaeology is close to the base of the zone of water table fluctuation (base of Zone 2). The implication of this is that much of the archaeological wood located outside the immediate area covered by the Large Mere is within the zone of fluctuating groundwater levels and therefore potentially at risk of enhanced degradation (relative to Zone 3). Even beneath the Large Mere the artificial recharge may potentially allow degradation of the wood by introducing fresh water into the ground at a rate higher than natural recharge; however, an assessment of this would require detailed analysis and lies outside the scope of the present study.
- The main factor controlling groundwater levels in the Flag Fen area is artificial drainage. Climate seems to be less of an influence. This is consistent with the conclusions of Pryor (1992), who wrote "The archaeological site at Flag Fen is being excavated because all areas outside an artificial mere are being destroyed by drying-out. This gradual desiccation has followed from the lowering of the local ground water table by artificial drainage." (p.442) The Mustdyke is a particularly strong influence, as it is a deep ditch cutting through the archaeological remains at Flag Fen. It has long been known that drainage associated with the Mustdyke has resulted in drying of the adjacent peat, with implications for preservation of the archaeology (Pryor, 1992). Catswater Drain has less of an influence as the reach that runs alongside the Flag Fen causeway generally does not flow along its entire length (thereby reducing the drainage effect). However, it may still limit maximum groundwater levels.
- Hardstanding associated with the PREL development is unlikely to have a significant influence on groundwater levels at Flag Fen. By extension, wind farm developments (which involve only a small "footprint" of impermeable, or low permeability, structures) are unlikely to pose a significant threat to groundwater levels at Flag Fen.
- Blocking ditches to create a wetland southwest of Flag Fen could potentially raise groundwater levels in the vicinity of the causeway and platform. However, the drains concerned could not be accessed during the site visit, so were represented approximately in the model based on observation of surrounding drains and on observed groundwater levels. Further field investigations would be required to confirm the nature

of the drains concerned and to assess the potential for raising groundwater levels. This possibility could be further modelled in detail if required.

- The ditch diversion scenarios give the best results in terms of raising groundwater levels at Flag Fen. The results suggest that these scenarios could return much of the archaeology to the zone of permanent saturation. However, agreement would need to be reached with the Environment Agency and the IDB. Also, further more detailed studies would be required to inform the detailed design of any scheme. This would also need to include consideration of any flood risk associated with the works.

Figure 4-5 Scenario Results for BH3

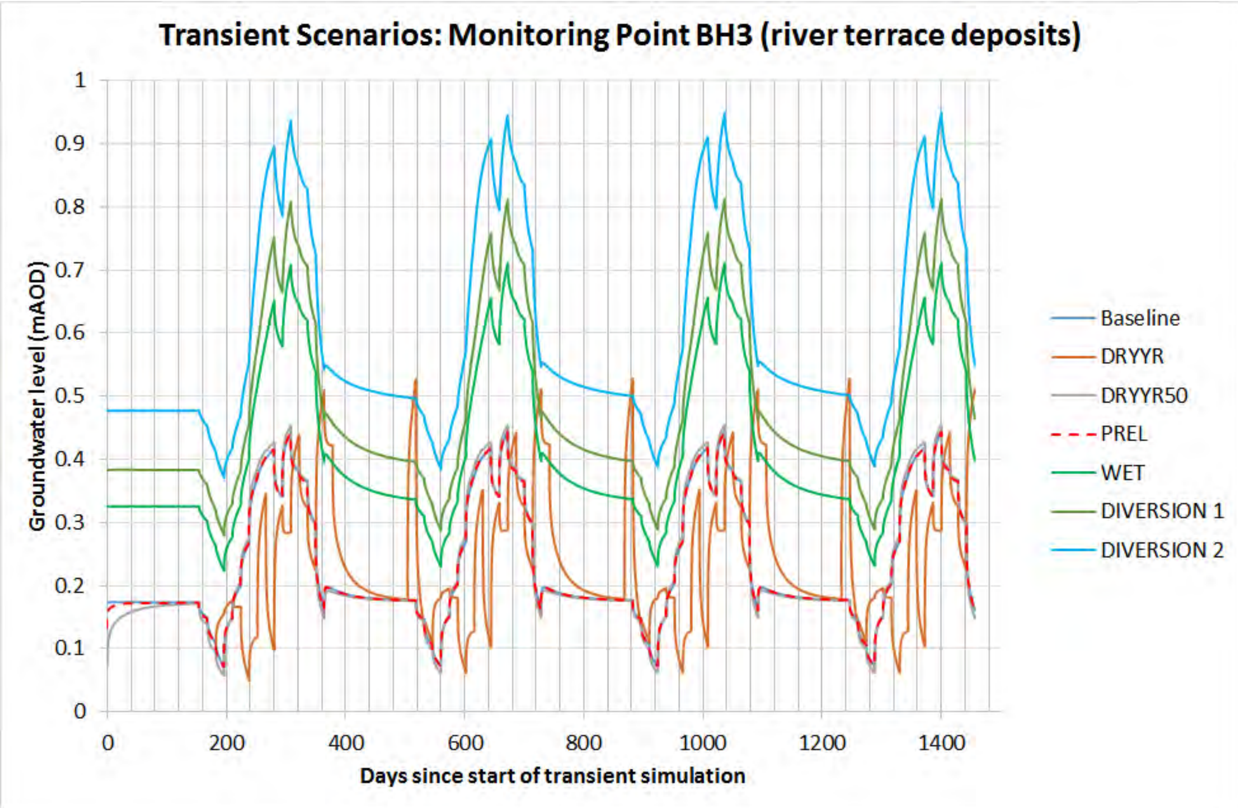


Figure 4-6 Scenario Results for DW03 (Archaeology top = top in the vicinity of DW03)

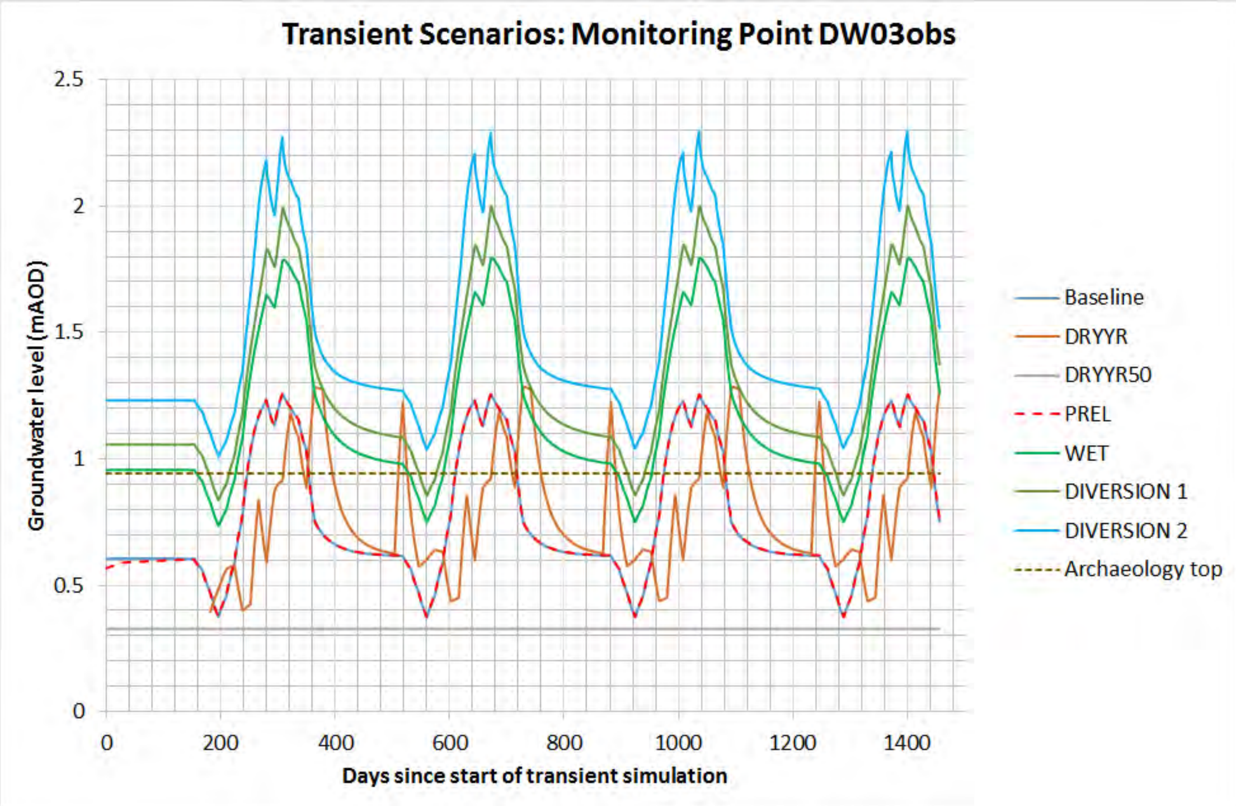


Figure 4-7 Scenario Results for FF_causeway (Archaeology top = top in the vicinity of FF_causeway)

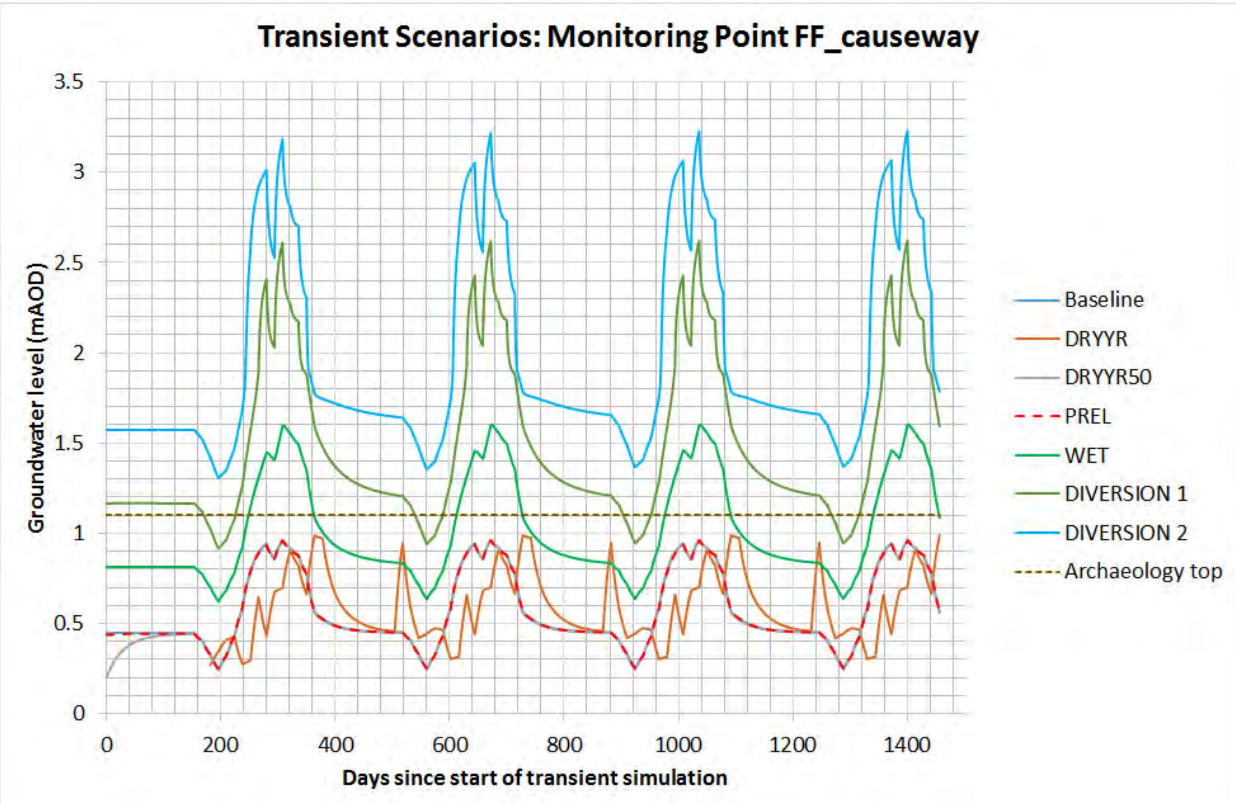


Figure 4-8 Scenario Results for FF_platform (Archaeology top = top in the vicinity of FF_platform)

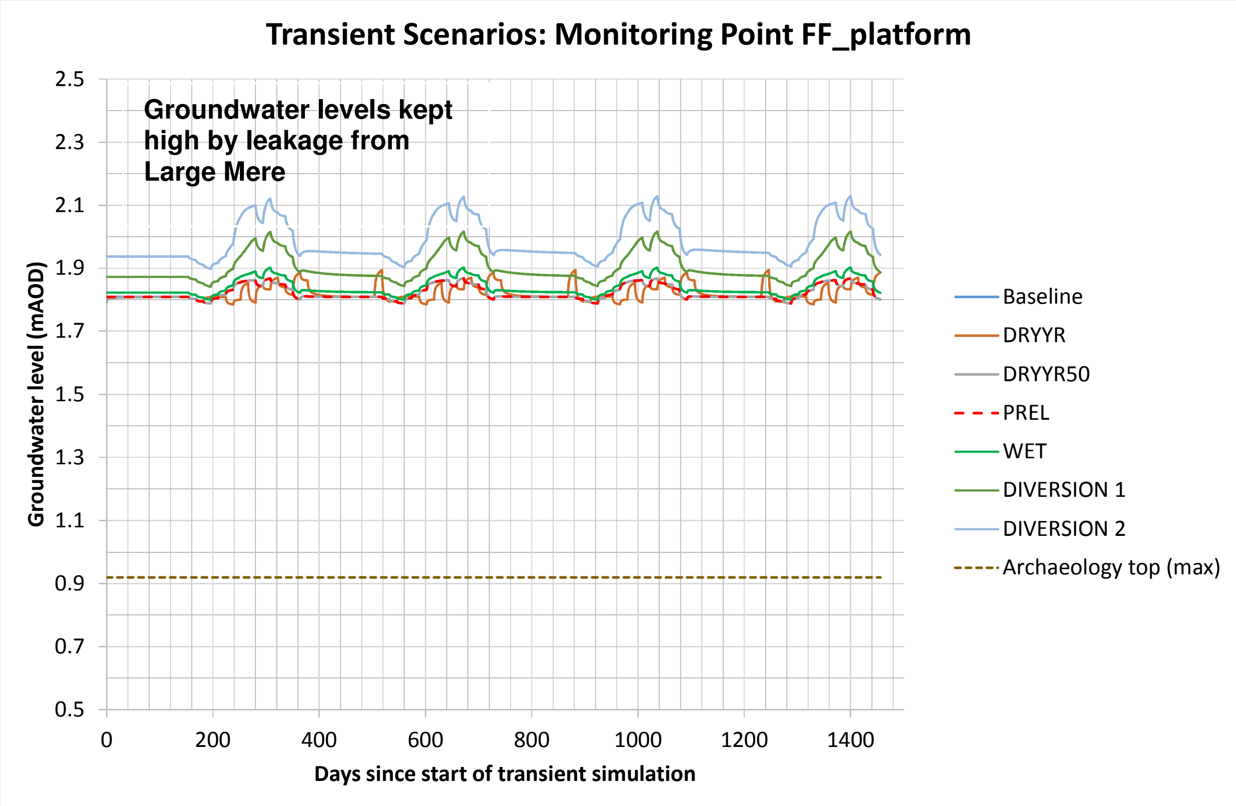
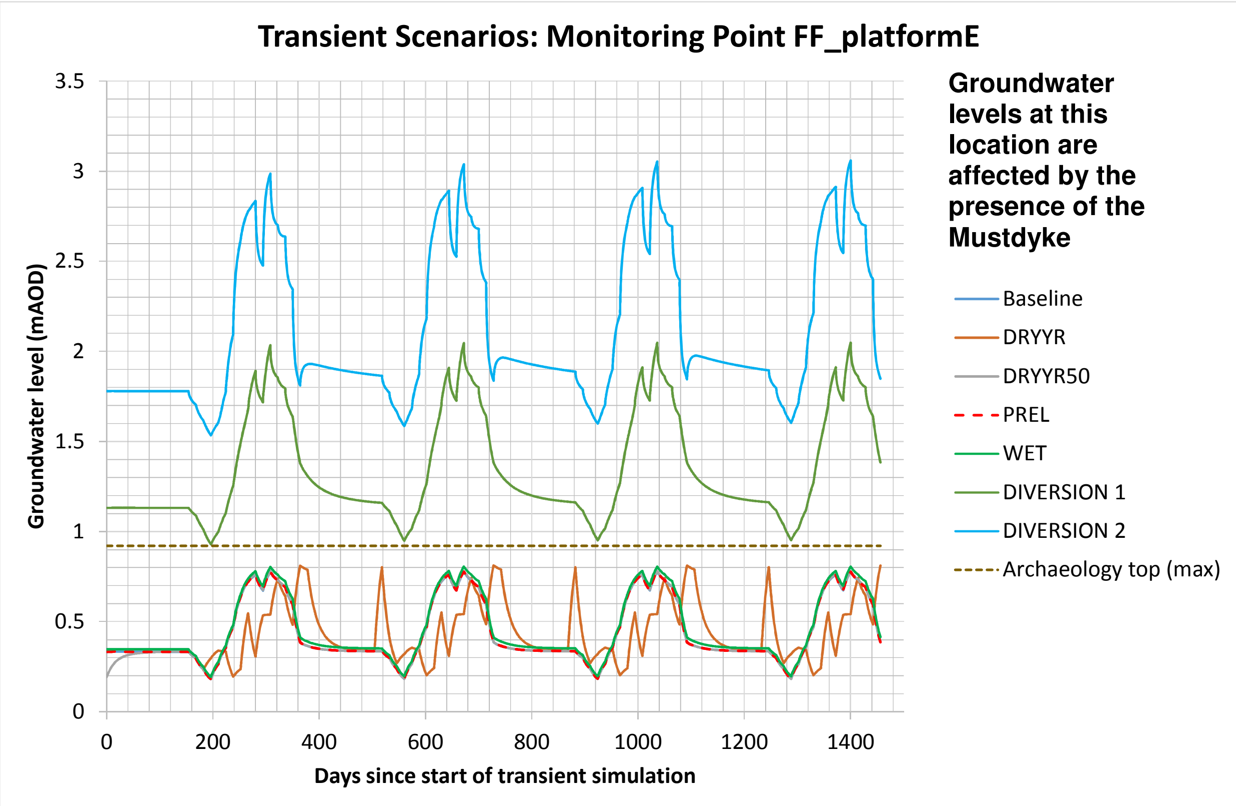


Figure 4-9 Scenario Results for FF_platformE (Archaeology top = top in the vicinity of FF_platformE)



5 Conclusions and Recommendations

5.1 Conclusions

Concern exists regarding the long-term viability of the archaeological remains of the Flag Fen basin near Peterborough, the principal archaeological site of which is the Bronze Age Scheduled Ancient Monument (SAM) timber platform and post alignment of Flag Fen. The delicate organic archaeological remains associated with the site are thought to be degrading as a result of desiccation of the local soil and underlying deposits, resulting from a lowering of the water table. Indeed, the Bronze Age timber structure at Flag Fen was discovered during the deepening of a major drainage ditch (the Mustdyke) in 1982, and a year later the effects of drying out were clearly evident in the ditch banks (Pryor, 1992).

This project has developed a hydrogeological conceptual model of the Flag Fen site and surrounding area, and has used this as the basis for a numerical groundwater model. The numerical model has been used to better understand the current situation (especially the relationship between groundwater levels and preserved organic archaeology) and also to explore potential future scenarios. Future scenarios considered include both external threats (climate change and development) and potential water level management schemes.

The low-lying fenland landscape is naturally wet, but has been drained artificially by a network of ditches, with water levels controlled by pumping stations. Across most of the area the Jurassic bedrock immediately beneath the site is dominated by low permeability mudstone and so forms an effective base to the shallow groundwater system in the overlying superficial deposits. The superficial deposits beneath Flag Fen consist of river terrace sand/gravel overlain by peat, with locally-developed alluvium and made ground. A low permeability clay-rich layer commonly separates the peat from the underlying river terrace deposits; this is best-developed in the eastern part of the area where it is referred to as the Barroway Drove Beds. It helps to maintain a vertical hydraulic gradient between the peat and the river terrace, with groundwater levels (heads) being higher in the peat.

The archaeological features of interest extend through the made ground and peat, and locally into the underlying river terrace deposits. Monitoring and modelling of groundwater levels in the superficial deposits suggest that the upper parts of the wooden structure at Flag Fen are typically located within (or even above) the zone of seasonal water table fluctuation, i.e. within Zone 2 (or Zone 1) in the three zone model of Chapman and Cheetham (2002). In this model, the best preservation of archaeological wood is in the zone of permanent saturation (Zone 3), below the minimum water table elevation. In the overlying zone of fluctuation (Zone 2) wood is generally subject to deterioration at the cellular level, although the macro-structure may be retained (Chapman and Cheetham, 2002). In the "dry" zone above the maximum water table level (Zone 1), archaeological wood is often subject to almost total deterioration of its structure (Chapman and Cheetham, 2002). The results of the present study therefore suggest that the hydrological conditions are sub-optimal for the long-term *in situ* preservation of the wooden platform and causeway at Flag Fen.

Modelling suggests that leakage from the Large Mere is maintaining high groundwater levels beneath the pond itself. However, the extent to which artificial recharge from the mere is benefiting the wooden platform structure is unclear, partly because the location and extent of the platform are uncertain (see Section 2.5.2), and partly because enhanced recharge and flushing by surface water may potentially affect the rate of degradation. Certainly the eastern part of the structure has been adversely affected by drainage as it is cut by the Mustdyke, a major drainage ditch. Furthermore, the influence of artificial recharge from the Mere will not extend to the east of the Mustdyke, which will act as a hydraulic barrier to shallow groundwater flow.

If the observed basal elevation of the eastern part of the Bronze Age structure is representative then, on average, the base of the archaeology is close to the base of the zone of water table fluctuation. The implication of this is that much of the archaeological wood located outside the area covered by the Large Mere is within the zone of fluctuating groundwater levels and therefore potentially at risk of enhanced degradation relative to wood in the underlying zone of permanent saturation.

The main factor controlling groundwater levels in the Flag Fen area is artificial drainage. Climate seems to be less of an influence. The Mustdyke is a particularly strong influence, as it is a deep ditch cutting through the archaeological remains at Flag Fen. Catswater Drain has less of an influence as the reach that runs alongside the Flag Fen causeway generally does not flow along its entire length (thereby reducing the drainage effect). However, Catswater is still likely to limit maximum groundwater levels.

One of the modelling scenarios investigated the potential impact of a nearby development (PREL Energypark) on groundwater levels in the area of the Bronze Age causeway and platform. This was to address the concerns of English Heritage that hardstanding associated with the development might reduce recharge to groundwater (through reduced infiltration) and thereby lower groundwater levels. The results of the modelling (which assume 70% hardstanding on the PREL site) suggest that hardstanding associated with the development is unlikely to have a significant influence on groundwater levels at the Flag Fen archaeological site.

English Heritage has also expressed concerns about the potential impact of any future wind farm developments in the area. Wind farms have not been modelled explicitly as part of this study, but some conclusions can nevertheless be drawn from the modelling results. Wind farms generally involve only a small "footprint" of impermeable, or low permeability, structures and so are likely to have less of an impact on groundwater recharge than a development like the PREL Energypark. Furthermore, wind farm access tracks and other hardstanding areas are generally designed to shed water to the surrounding ground, allowing infiltration. The model could potentially be re-run to investigate the impact of a wind farm close to Flag Fen. However, well-designed wind farms generally have mainly a visual impact, and their long-term hydrological effects are typically minor to insignificant.

The modelling work has allowed exploration of potential remediation measures to raise groundwater levels at Flag Fen and potentially help preserve the Bronze Age wooden structures. Blocking ditches to create a wetland southwest of Flag Fen could potentially raise groundwater levels in the vicinity of the causeway and platform. However, the drains concerned could not be accessed during the site visit, so were represented approximately in the model based on observation of surrounding drains and on observed groundwater levels. Further field investigations would be required to confirm the nature of the drains concerned and to assess the potential for raising groundwater levels. This possibility could be further modelled in detail if required.

The ditch diversion scenarios give the best results in terms of raising groundwater levels at Flag Fen. The results suggest that these scenarios could return much of the archaeology to the zone of permanent saturation (Zone 3 of Chapman and Cheetham, 2002). However, agreement would need to be reached with the Environment Agency and the IDB. Also, further more detailed studies would be required to inform the design of any scheme. This would also need to include consideration of any flood risk associated with the works.

Summary of Conclusions

This study suggests that much of the Bronze Age wooden structure of Flag Fen is located within the zone of seasonal groundwater level fluctuation and therefore potentially at risk of enhanced degradation relative to wood in the underlying zone of permanent saturation. Modelling results suggest that the area of the Large Mere may be an exception, with leakage from this artificial pond maintaining locally high groundwater levels. This was the intended purpose of the pond.

The main factor controlling groundwater levels at Flag Fen is artificial drainage. The Mustdyke, an open ditch cutting through the wooden structure, exerts a particularly strong influence. Numerical groundwater modelling has been used to investigate both potential future threats (development and climate change) and water level management options. Modelled groundwater levels are relatively insensitive to a lowering of groundwater recharge, whether a general reduction (dry year scenario) or a local reduction (nearby development with hardstanding reducing infiltration).

Water level management options investigated using the model include drain blockage and diversion, and the creation of a wetland close to Flag Fen. The modelling results suggest that drain blockage and diversion may have the potential to return much of the archaeology to the zone of permanent saturation. However, agreement would need to be reached with the Environment Agency and North Level IDB, and further more detailed studies would be required to inform the design of any scheme. These studies would need to include an assessment of any flood risk associated with the works.

5.2 Recommendations

The findings of this study suggest that the hydrological conditions at Flag Fen may put at risk the long-term *in situ* preservation and viability of the Bronze Age wooden structures. The following additional work is recommended to clarify the existing hydrological situation and also the potential effects of the mitigation/management options explored in this study:

- Discussion of any wetland creation and/or ditch diversion proposals with the Environment Agency and the IDB.
- Feasibility studies for any new wetland south of Flag Fen and for any ditch diversion scheme. This work would need to include consideration of potential impacts on flood risk in the area.
- Field investigation of the ditches south of Flag Fen (in the area which has been identified as being suitable to establish a wetland) - this would give more confidence in the modelling of these features and in the likely impact of drain blocking.
- Monitoring of groundwater levels. It is understood that there are water level dataloggers in boreholes on site (installed by Atkins), but that these have not been downloaded (and the data processed) for some time. It is recommended that monitoring be actively undertaken and also extended to include the ground beneath the Large Mere. This would help confirm whether or not the archaeology is saturated in this location.
- A water quality study to determine whether the chemical environment beneath the Large Mere differs from that in the saturated zone elsewhere on the Flag Fen site, and whether this may have implications for the preservation of archaeological wood.
- Archaeological investigations to further constrain the spatial distribution of the Bronze Age wooden structures at Flag Fen. It appears that past investigations have not always recorded the elevation (in mAOD or m below ground level) of archaeological wood encountered within trenches (H. Chapman, *pers. comm.*, 26th November 2014). Routine recording of elevations will form a database that can be readily compared to measured and modelled groundwater levels within the context of the three zone model (Chapman and Cheetham, 2002). GIS provides a powerful tool for analysing spatial archaeological and hydrological datasets.
- Consideration of the application of the methods employed here to other, similar, sites. The techniques routinely used for peatland (and other wetland) management and restoration are directly applicable to archaeological sites that depend on high groundwater levels for the preservation of organic archaeological material.

Appendices

A Maps

Map 1 Location of the Study Area

Map 2 Flag Fen Location Map

Map 3 Topography

Map 4 Bedrock Geology

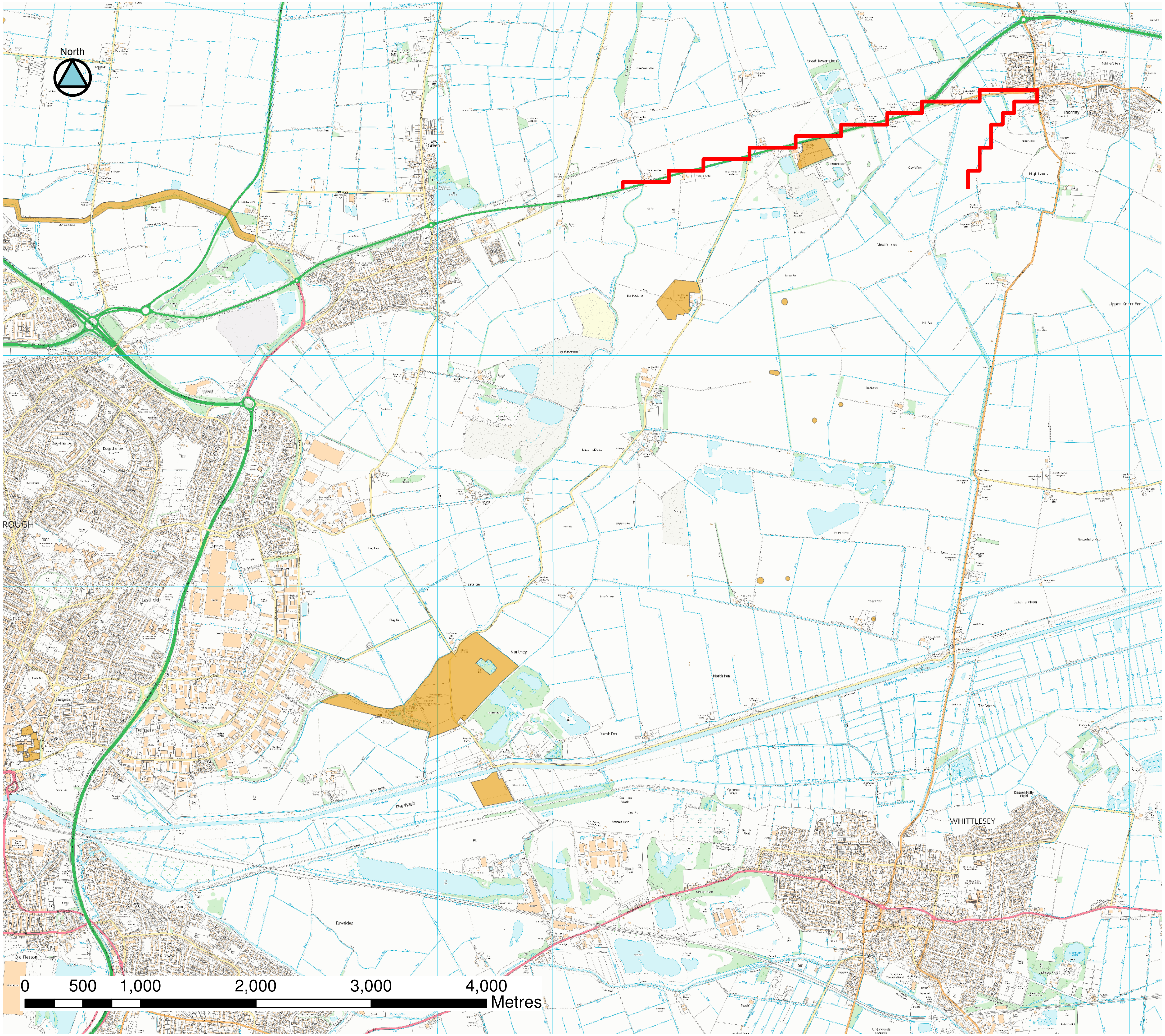
Map 5 Superficial (Drift) Geology

Map 6 Drainage

Map 7 Licensed Water Abstractions

Map 8 Groundwater Monitoring Boreholes at Flag Fen

Map 9 Archaeological Top Data Points



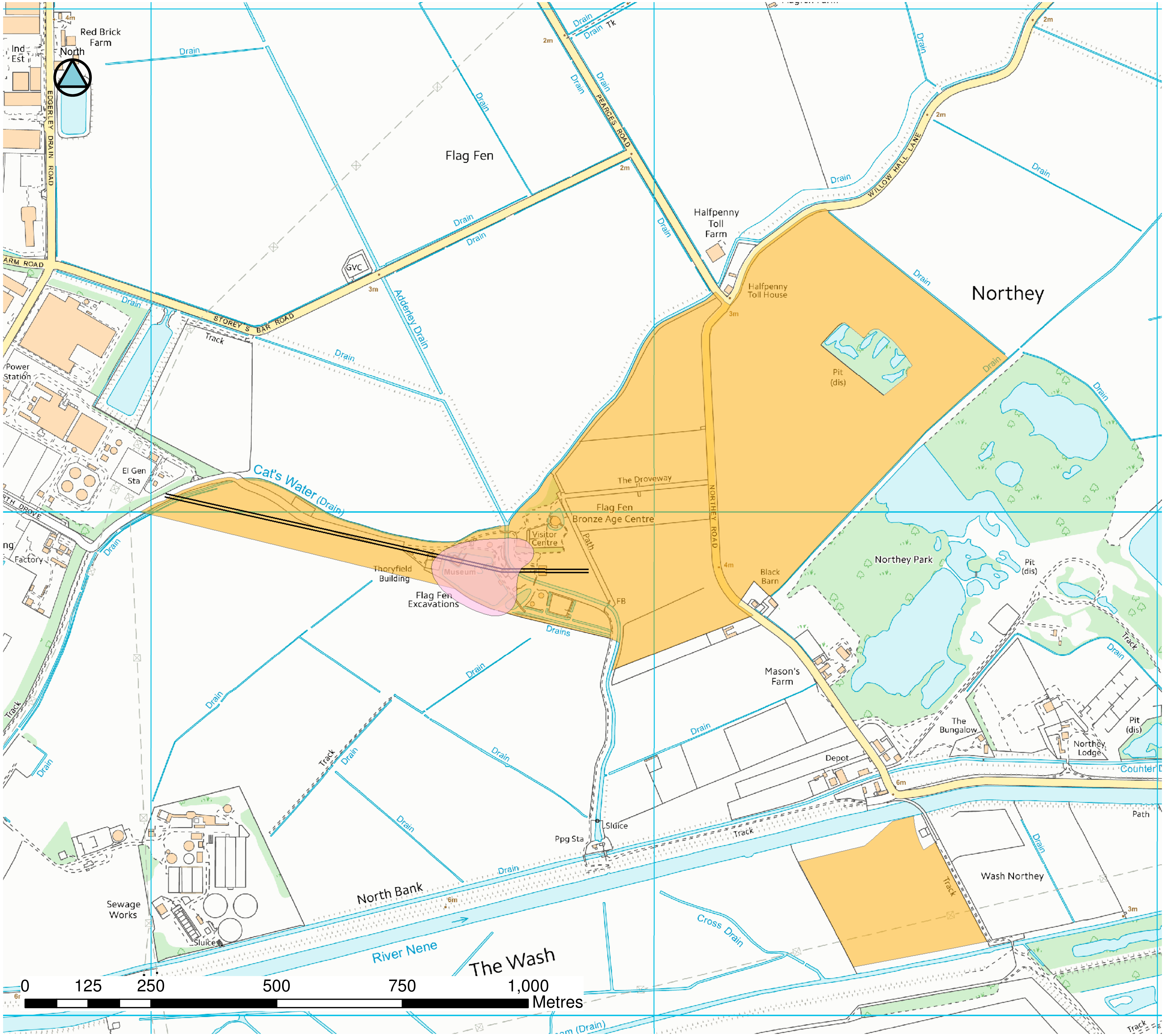
LEGEND

Model Area

Scheduled Monuments

JBA consulting

Map 1 Location of the study area



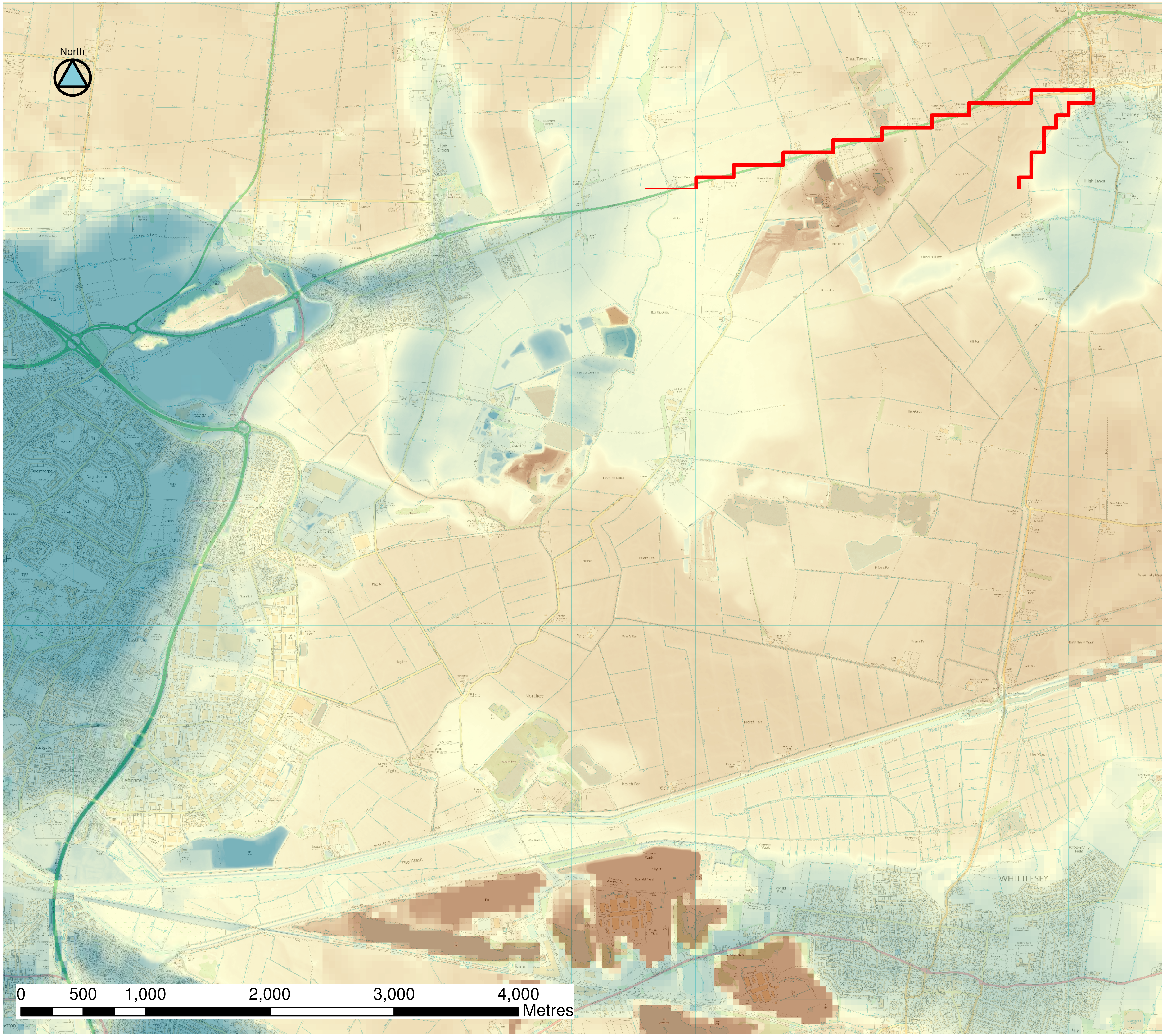
LEGEND

- Flag Fen Timber Platform
- Flag Fen Timber Causeway
- Scheduled Monuments

Location of timber platform and causeway based on that presented by Pryor and Bamforth (2010).

JBA consulting

Map 2 Flag Fen Location Map



LEGEND

Model Area

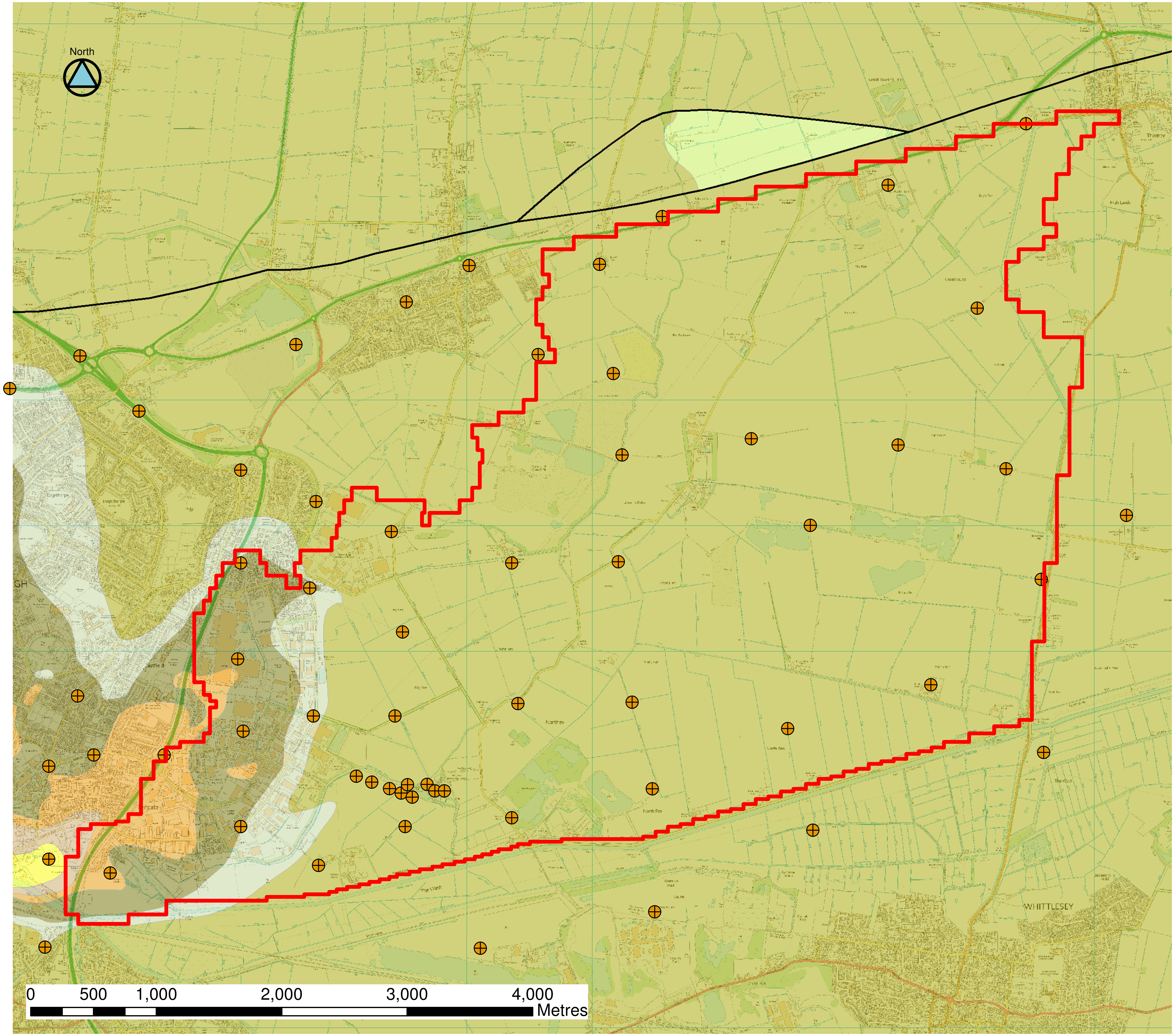
Topography

mAOD

High : 25.3377

Low : -26.9

Map 3 Topography



LEGEND

Model Area

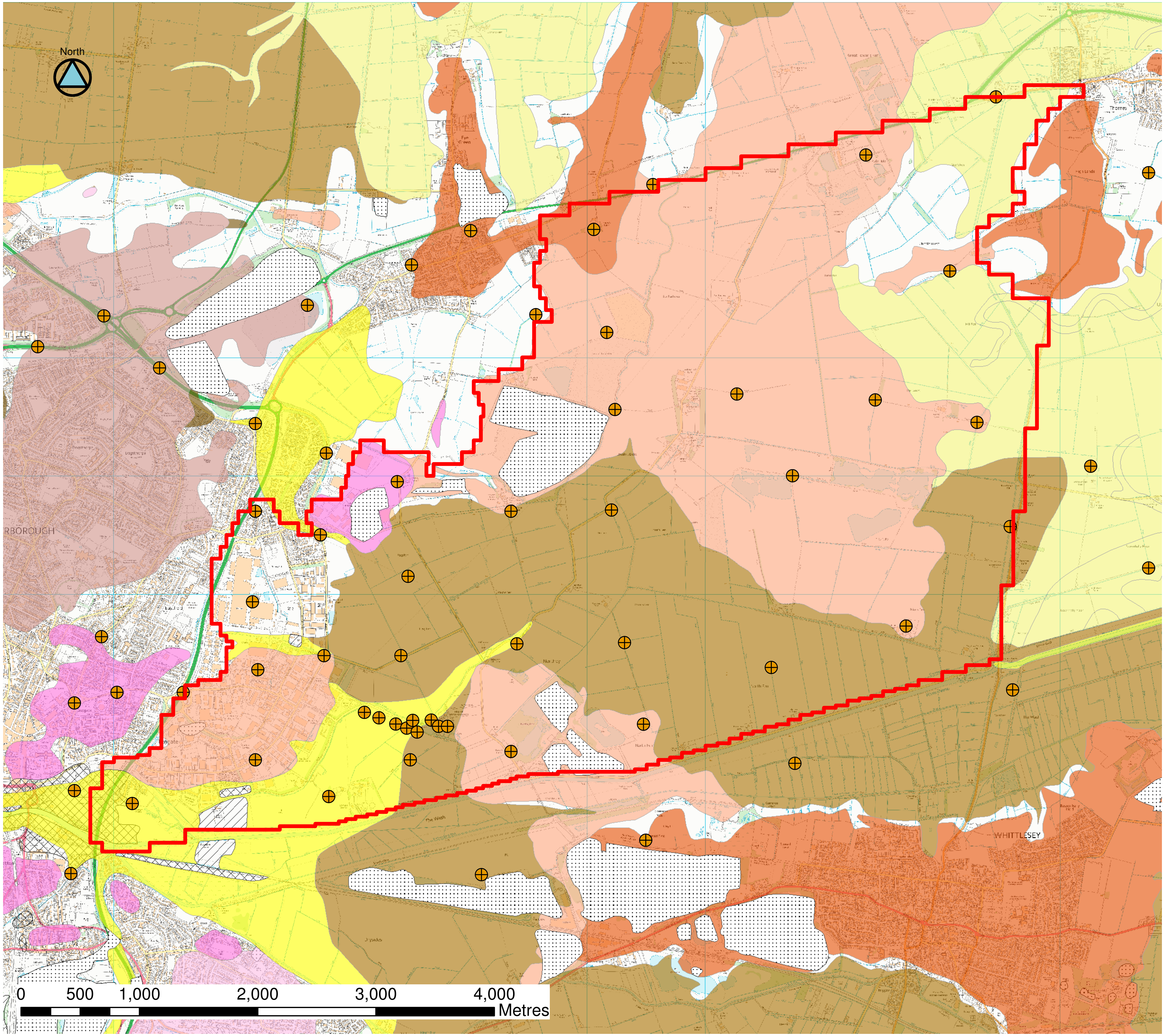
Borehole Records

Geology

Bedrock

- WEST WALTON FORMATION
- OXFORD CLAY FORMATION
- KELLAWAYS SAND MEMBER
- KELLAWAYS CLAY MEMBER
- CORNBRASH FORMATION
- BLISWORTH CLAY FORMATION
- BLISWORTH LIMESTONE FORMATION
- RUTLAND FORMATION

Map 4 Bedrock Geology



LEGEND

Model Area

Borehole Records

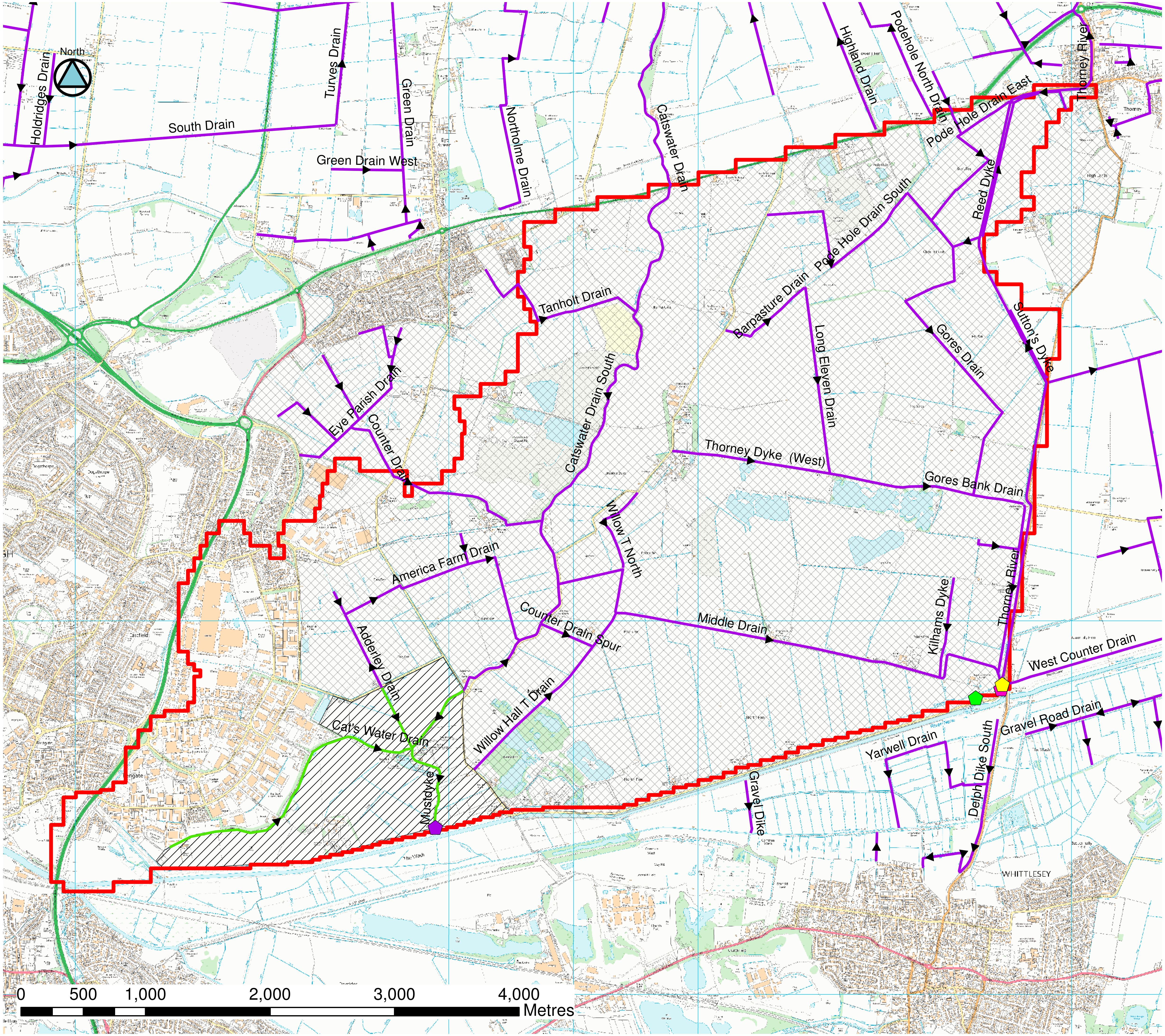
Geology

Superficial

- ALLUVIUM
- TIDAL FLAT DEPOSITS
- TIDAL FLAT DEPOSITS, 1
- PEAT
- RIVER TERRACE DEPOSITS (UNDIFFERENTIATED)
- RIVER TERRACE DEPOSITS, 1
- RIVER TERRACE DEPOSITS, 2
- RIVER TERRACE DEPOSITS, 3
- WOODSTON MEMBER
- MARCH GRAVELS MEMBER
- HEAD
- GLACIOFLUVIAL DEPOSITS, MID PLEISTOCENE
- TILL, MID PLEISTOCENE
- GLACIOLACUSTRINE DEPOSITS, MID PLEISTOCENE
- INFILLED GROUND
- MADE GROUND (UNDIVIDED)
- WORKED GROUND (UNDIVIDED)

JBA consulting

Map 5 Superficial (Drift) Geology



LEGEND

Pumping Stations

- Dog-in-a-Doublet (Anglian Water)
- Dog-in-a-Doublet New (North Level IDB)
- Dog-in-a-Doublet Old (North Level IDB)
- Padholme (EA)
- EA Controlled Drains
- North Level IDB Controlled Drains
- Model Area
- Padholme Catchment
- Dog-In-A-Doublet Catchment

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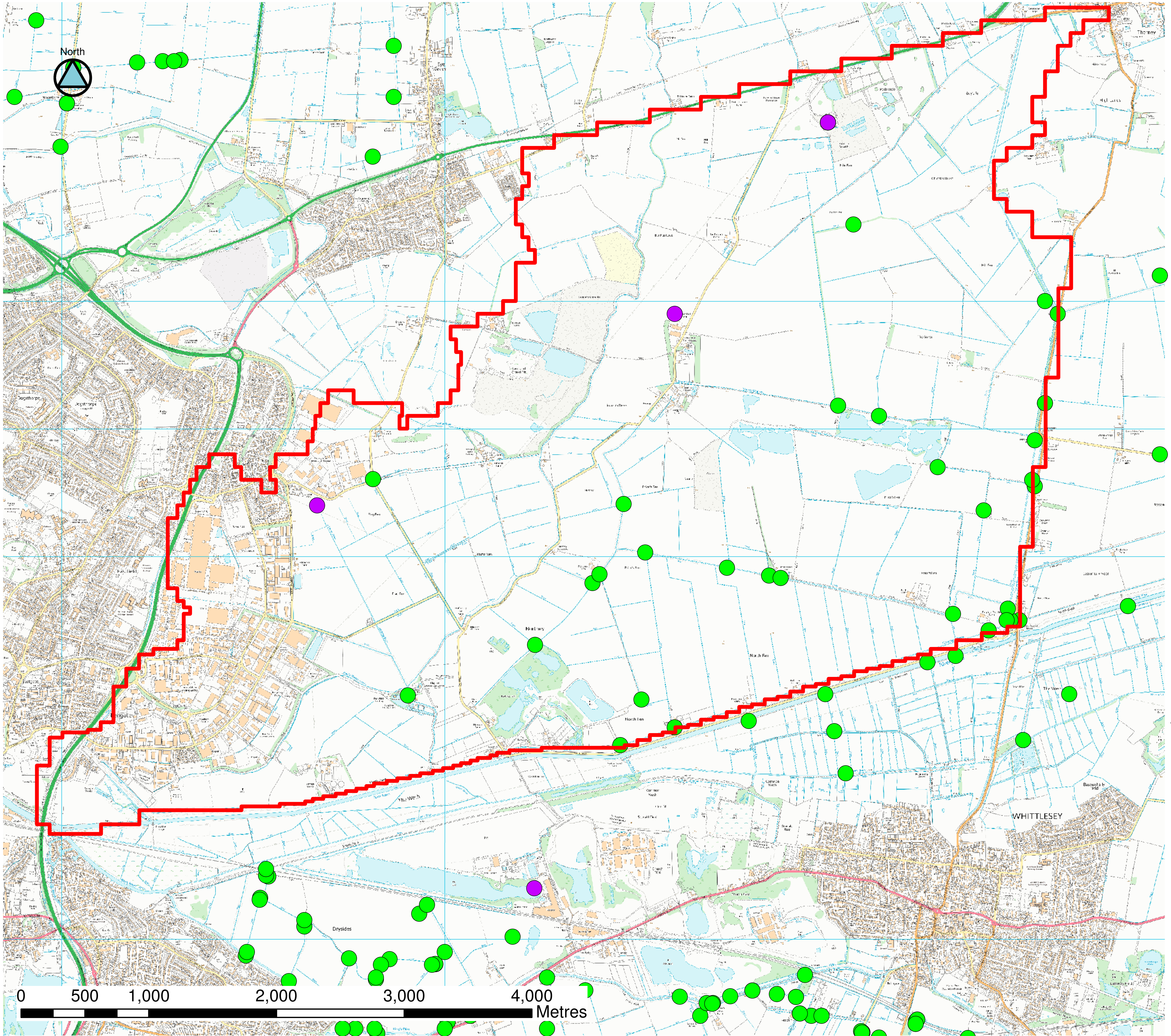
Map 6 Drainage



LEGEND

Model Area

Licensed Water Abstractions

Groundwater

Surfacewater

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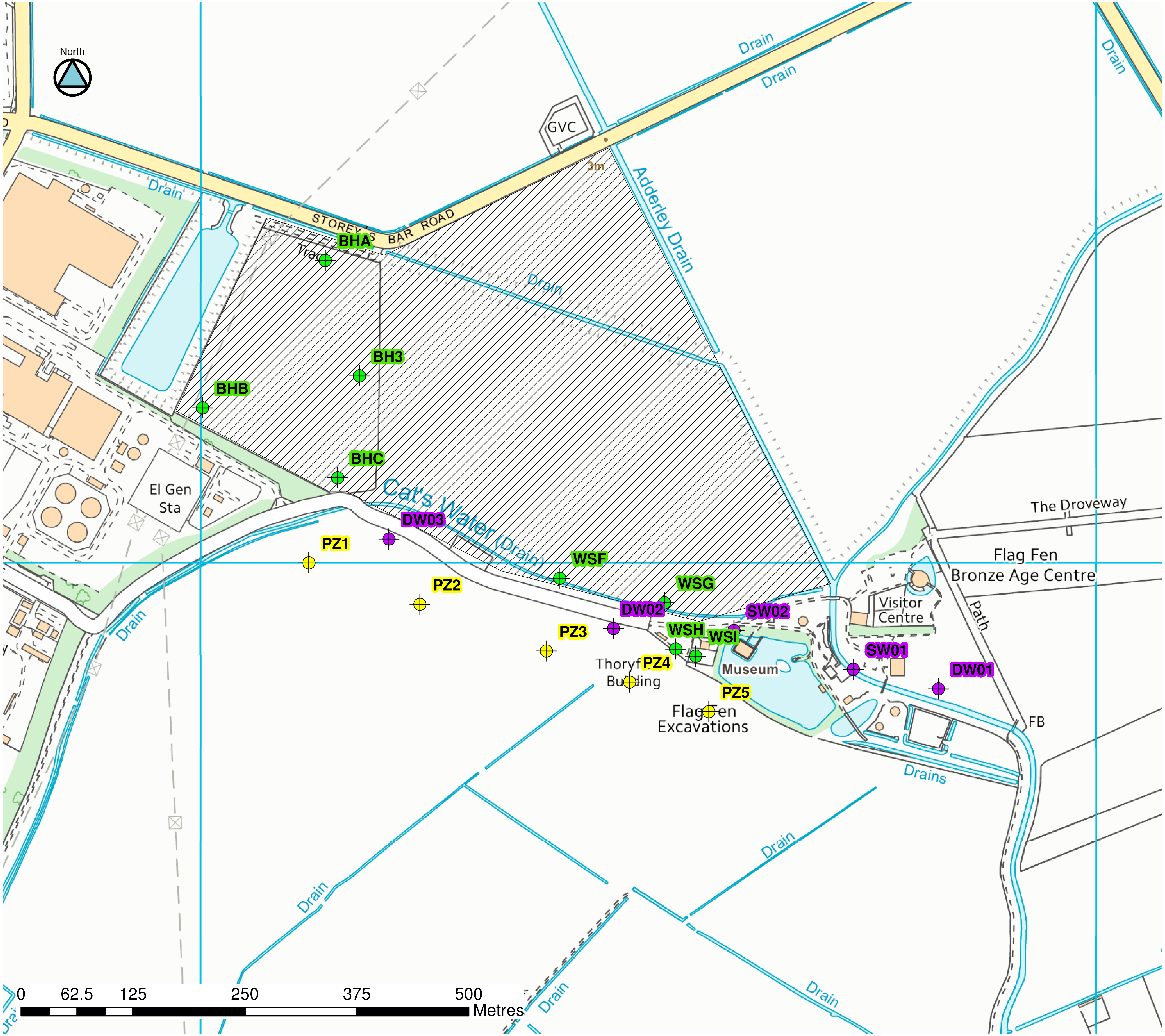
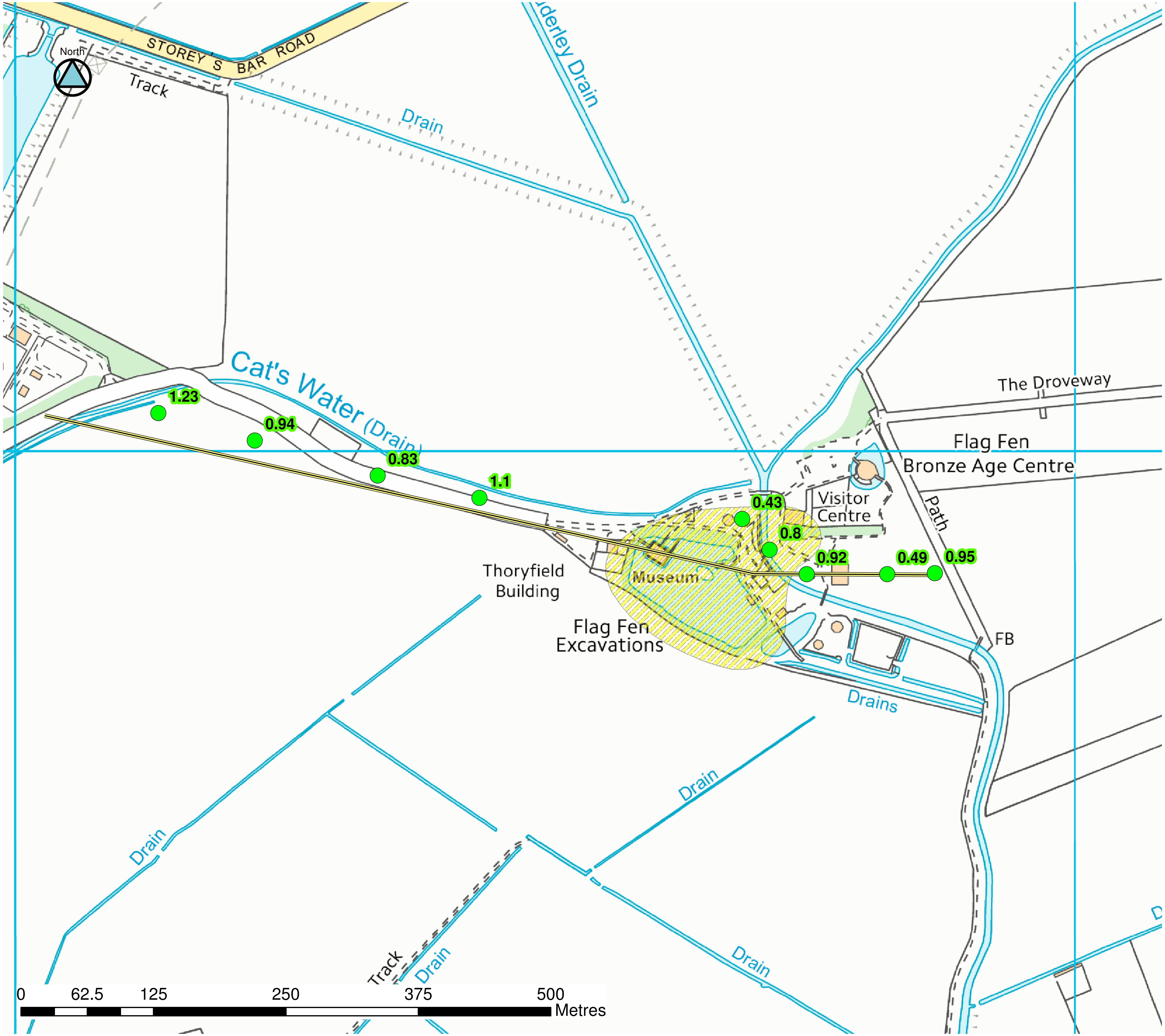
Map 7 Licensed Water Abstractions



LEGEND

- Atkins Boreholes
- Lillie and Cheetham Boreholes
- PREL Boreholes
- PREL Energypark proposed location

Map 8 Groundwater Monitoring Boreholes at Flag Fen



LEGEND

Tops of Preservation mAOD

Causeway

Platform

JBA consulting

Map 9 Archaeological Top Data Points

B Technical Details of the Numerical Modelling

B.1 General Approach

The three-dimensional transient (time-variant) flow of groundwater of constant density through an anisotropic porous medium in rectangular Cartesian Coordinates[1] is described by the following partial differential equation:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t}$$

Equation 1

where x,y,z are distances [L] parallel to the x, y and z axes respectively, K_{xx} = hydraulic conductivity [LT^{-1}] in x direction, K_{yy} = hydraulic conductivity [LT^{-1}] in y direction, K_{zz} = hydraulic conductivity [LT^{-1}] in z direction, W = source or sink [LT^{-1}], S_s = specific storage [dimensionless], h = hydraulic head [L] and t = time [T]. A derivation of this equation may be found in Anderson and Woessner (2002).

Given suitable boundary conditions (heads or flows at the boundaries of the system) and an initial condition (heads at t=0) the above equation can be solved to yield groundwater heads (and therefore flows) as a function of space and time. For steady-state problems heads do not change with time, and the right-hand-side of the equation is zero; in this case only boundary conditions are required.

For very simple problems, such as those involving one-dimensional flow through a homogeneous aquifer, the groundwater flow equation can be solved analytically to yield an equation expressing head as a function of space and/or time. However, many practical problems require modelling of heterogeneous anisotropic aquifer systems with complex three-dimensional geometry. In such cases, numerical modelling techniques are usually employed. These approximate the problem by dividing up ("discretizing") the model domain into discrete spatial grid cells or elements, and discrete time steps. This project uses the finite difference method, in which the porous medium is represented by a rectangular grid of cells and the space and time derivatives are approximated using finite differences (see Wang and Anderson, 1982). The result is a finite set of algebraic equations (with a version of the flow equation written for each cell or node) that can be represented in matrix form and solved simultaneously to yield the head in each cell for each time step.

Note that the flow equation in the form written above assumes that the groundwater has a constant density. This is a reasonable assumption for the shallow groundwater beneath Flag Fen and the surrounding area.

B.2 Numerical Modelling Code and Solver

The model was produced using the United States Geological Survey's (USGS's) open source numerical modelling code MODFLOW (McDonald and Harbaugh, 1984; McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996a and 1996b; Harbaugh *et al.*, 2000). The version of MODFLOW employed for this project was MODFLOW2000 (Harbaugh *et al.*, 2000).

MODFLOW uses the finite difference method to solve the partial differential equation describing groundwater flow. Application of the finite-difference method leads to matrix equations that can be solved by direct or by iterative methods. In iterative approaches an initial estimate of the solution is repeatedly refined so that successive solutions approach the true solution. Solution convergence is assumed when the difference in results (e.g. difference in calculated heads) between successive iterations is less than a user-specified convergence criterion.

A number of automated solvers are available for use with MODFLOW. For this project the matrix equations were solved using the Preconditioned Conjugate-Gradient 2 (PCG2) solver, which uses iteration (Hill, 1990). The settings used for PCG2 were: 3,000 maximum outer iterations, 25 maximum inner iterations, head change criterion (for convergence) 0.001 m, residual criterion for convergence = 1, relaxation parameter = 1, matrix preconditioning method = Cholesky, maximum bound on eigenvalue = 2, solver printing option = "Print All", PCG2 summary data

[1] As written, the equation assumes that the coordinate axes are aligned parallel to the principal directions of K anisotropy and that the z axis is oriented vertically, i.e. parallel to the direction in which gravity acts.

printed every five iterations, damping factor = 1. The solver was set to converge if the convergence criteria were met for 9999 outer iterations.

B.3 Resaturation of Dry Model Cells

MODFLOW2000 has options for resaturation of dry cells (the original version of MODFLOW allowed cells to dry out, but not to become wet again). Whether a dry cell becomes resaturated or not depends on the heads in neighbouring cells. MODFLOW has a number of settings that allow the user to control the way in which resaturation operates, including how often (during the solution process) MODFLOW checks to see if any cells should be re-wetted. For this project the following resaturation options were selected: wetting factor = 1, wetting threshold = 0.1, head assigned to dry cells = -1×10^{30} m, wetting iteration interval = 20, wetting equation number = 0 and rewetting option = "Use 4 Surrounding Nodes and Node Below Dry Cell".

B.4 Graphical User Interface

A number of Windows-based Graphical User Interfaces (GUIs) are available to aid with the pre-processing of input data for MODFLOW and also the presentation and analysis of modelling results. This project used Groundwater Vistas, a popular and widely used interface (Groundwater Vistas Version 6.53, Build 8; ESI, 2011).

B.5 Discretization of Space and Time

The numerical model described in this report has the following grid properties:

- Four layers
- 146 rows and 194 columns
- 113,296 cells (of which 44,495 are defined as active flow cells)
- Variable grid spacing due to refinement around the area of interest: 100 m to 20 m
- National Grid coordinates in bottom left-hand corner of grid: 518000, 296000
- Dimensions of model area: width = 12,000 m, height = 9,000 m.

The transient versions of the model have the following temporal discretization scheme:

- An initial steady-state stress period (3650 days' duration; single time step) to obtain initial groundwater levels.
- 104 fortnightly stress periods, each of 14 days' duration and each composed of 14 individual time steps. The model simulates four identical annual cycles; this is to allow the model to "settle" and ensure that there is no progressive change in groundwater level from year to year.

Note that the 14 time steps in any given stress period are not of equal length, and therefore do not represent days. Within a stress period, the time steps form a geometric progression, and the spacing of time steps is determined by the time step multiplier, which is defined as the ratio of the length of each time step to that of the preceding time step (McDonald and Harbaugh, 1988). Typical values for the time step multiplier lie in the range 1.2 to 1.5, with $\sqrt{2}$ (approximately 1.4) often being a good choice (Anderson and Woessner, 2002). For the purposes of this project a value of 1.4 was specified.

The point of having time steps within a stress period increase as a geometric progression is that short time steps are required early on in order to represent properly the rapid changes in heads and flows that may follow a sudden change in stress. The reader is referred to Anderson and Woessner (2002) for more information on the discretization of time in numerical groundwater models.

B.6 Hydraulic Properties

Hydraulic conductivity

Average hydraulic conductivity values for multilayered units were initially estimated by calculating equivalent horizontal and vertical hydraulic conductivities using the following formulae that can be used to represent an n-layered aquifer system (each layer assumed to be homogeneous and isotropic) as a single anisotropic layer with horizontal hydraulic conductivity K_x (=K_y) and vertical hydraulic conductivity K_z (Freeze and Cherry, 1979):

$$K_x = K_y = \sum_{i=1}^{n} \frac{K_i d_i}{d}$$

Equation 2

$$K_z = \frac{d}{\sum_{i=1}^{n} \left(\frac{d_i}{K_i} \right)}$$

Equation 3

where K_x = K_y = equivalent horizontal hydraulic conductivity (m/d), K_z = equivalent vertical hydraulic conductivity (m/d), K_i = hydraulic conductivity of individual aquifer layer i (m), d_i = thickness of layer i (m), and d = total thickness of the n layers (m). Approximate layer thicknesses were used. The degree of anisotropy was modified during calibration until the vertical head gradient represented by the targets was matched as closely as possible.

Table B- 1 Hydraulic Conductivity Zones

Zone	Unit	Material	Model Kxy [m/d]	Model Kz* [m/d]	Realistic range of Kxy [m/d]	Source
1	Made/ infilled ground		1.32	1.32	1 x 10^{-4} to 100	7
2	Alluvium	Clay, silt, sand and gravel	0.132	0.0132	0.001 to 10	7
3	NOT USED		1.32	0.132		
4	Peat	Peat	0.66	0.0066	0.1 to 10	Assumed equivalent to silt to clean sand (refs 1, 2, 3 and 6)
5	Barroway Drove Beds	Clay and silty clay	0.00132	0.000132	1 x 10^{-5} to 0.01	7
6	River terrace	Sand/gravel	10.56	1	1 to 100	7
7	March gravels	Sand/gravel	10.56	1	1 to 100	7
8	West Walton Formation	Mudstone and siltstone with subordinate fine-grained sandstone and argillaceous limestone	0.00132	0.000132	3.8 x 10^{-6} to 3.7 x 10^{-1}	Based on similar Rutland Formation
9	Oxford Clay	Mudstone with local calcareous nodules	0.000132	1.32 x 10^{-5}	1 x 10^{-5} to 1 x 10^{-3}	7
10	Kellaways Sand	Sandstone and siltstone with interbeds of sandy/silty mudstone	0.00132	0.000132	2.8 x 10^{-6} to 6.1 x 10^{-1}	4 and 5
11	Kellaways Clay	Mudstone with local thin siltstones/ sandstones and calcareous nodules	0.000132	1.32 x 10^{-5}	1 x 10^{-5} to 1 x 10^{-2}	7
12	Cornbrash	Limestone	0.0066	0.00066	8.64 x 10^{-4} to 8.64 x 10^{-3}	Based on similar Blisworth Limestone
13	Blisworth Clay	Mudstone	0.000132	1.32 x 10^{-5}	1 x 10^{-5} to 1 x 10^{-3}	7
14	Blisworth Limestone	Limestone with thin marls and	0.0066	0.00066	8.64 x 10^{-4} to 8.64 x 10^{-3}	4

		mudstones				
15	Rutland Formation	Mudstone and siltstone	0.00132	0.000132	3.8×10^{-6} to 3.7×10^{-1}	5
16	Alluvium overlying peat	Clay, silt, sand, gravel and peat	1	0.1	Initial estimation from averaging	
17	Peat overlying Barroway Drove Beds	Clay, silty clay and peat	1	0.1	Initial estimation from averaging	
18	Quarry lake	Open water	1320	1320	High value	
19	Peat over Barroway Drove Beds (Layer 2)		0.00132	6.6×10^{-5}	Initial estimation from averaging	
20	Alluvium over peat (Layer 2)		0.001	0.0001	Initial estimation from averaging	

Sources:

1. Freeze and Cherry (1979)
2. Newson (1987)
3. Heathwaite (1994)
4. Mather *et al.* (1998)
5. Jones *et al.* (2000)
6. Bromley *et al.* (2004)
7. Brassington (2007)

*For anisotropic materials, Kz generally taken as 0.1(Kxy). However, multiplication factors lower than 0.1 were used when averaging K values between aquifer/aquitard layers.

Figure B- 1 Hydraulic Conductivity Zones (Layer 1)

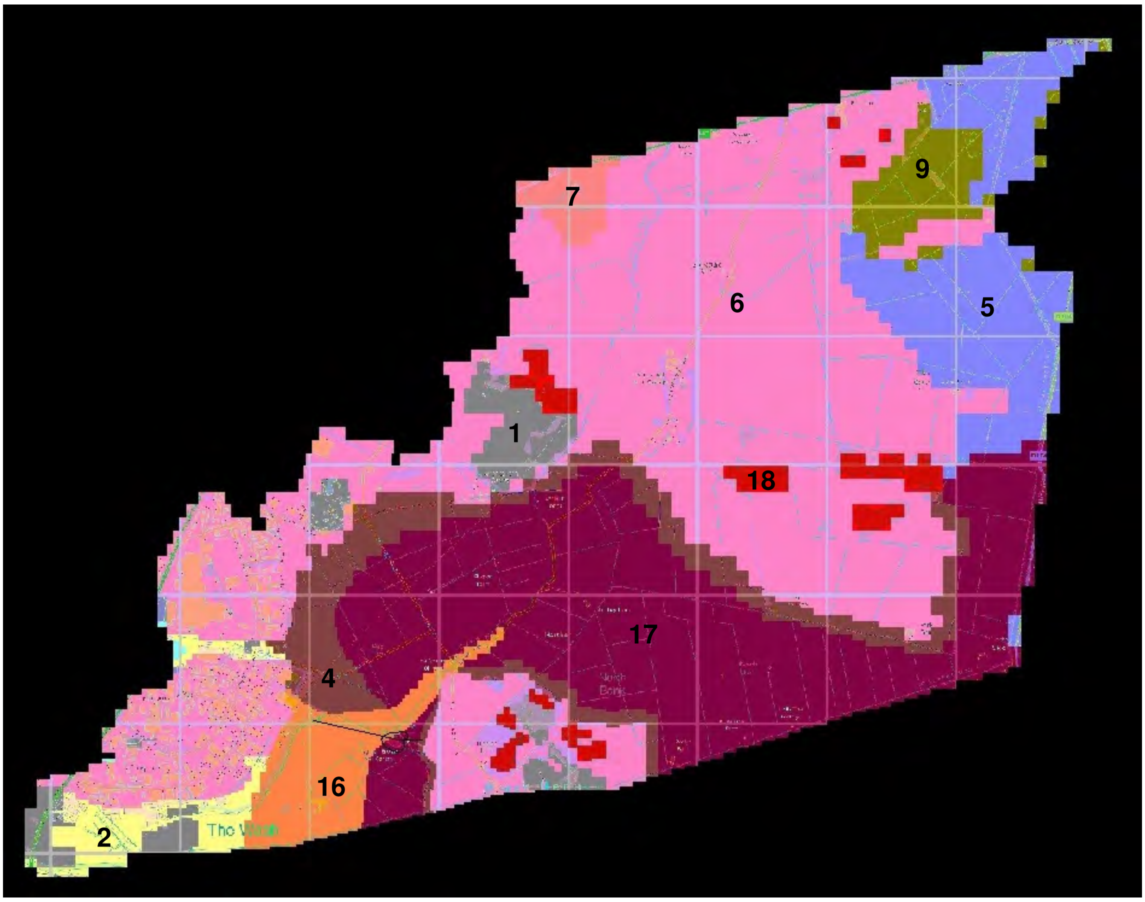


Figure B- 2 Hydraulic Conductivity Zones (Layer 2)

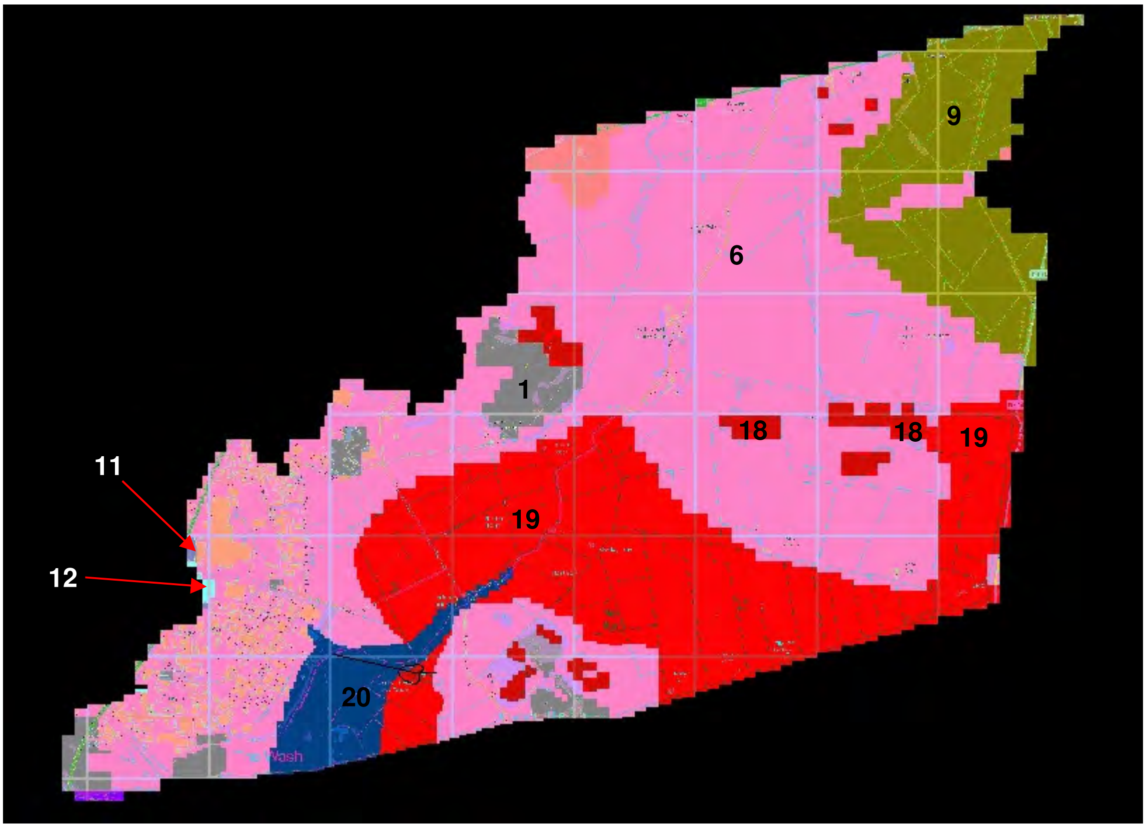


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Figure B- 3 Hydraulic Conductivity Zones (Layer 3)

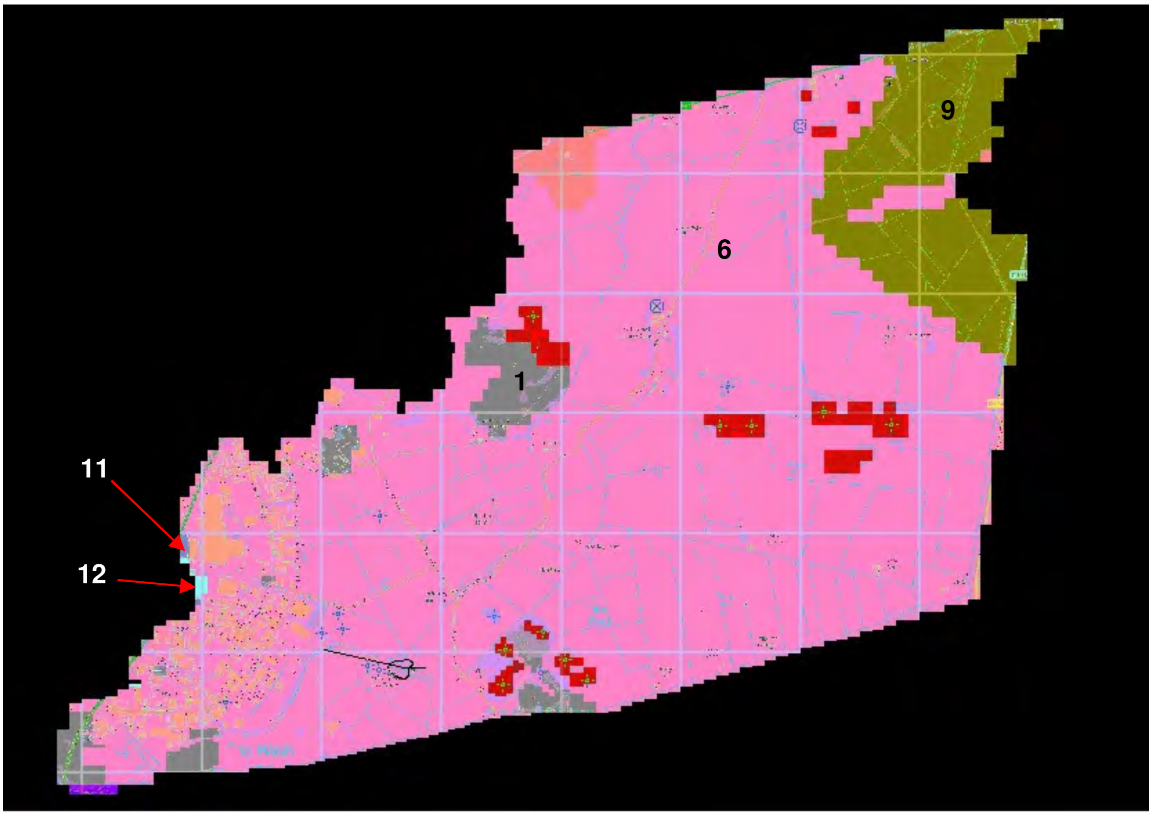

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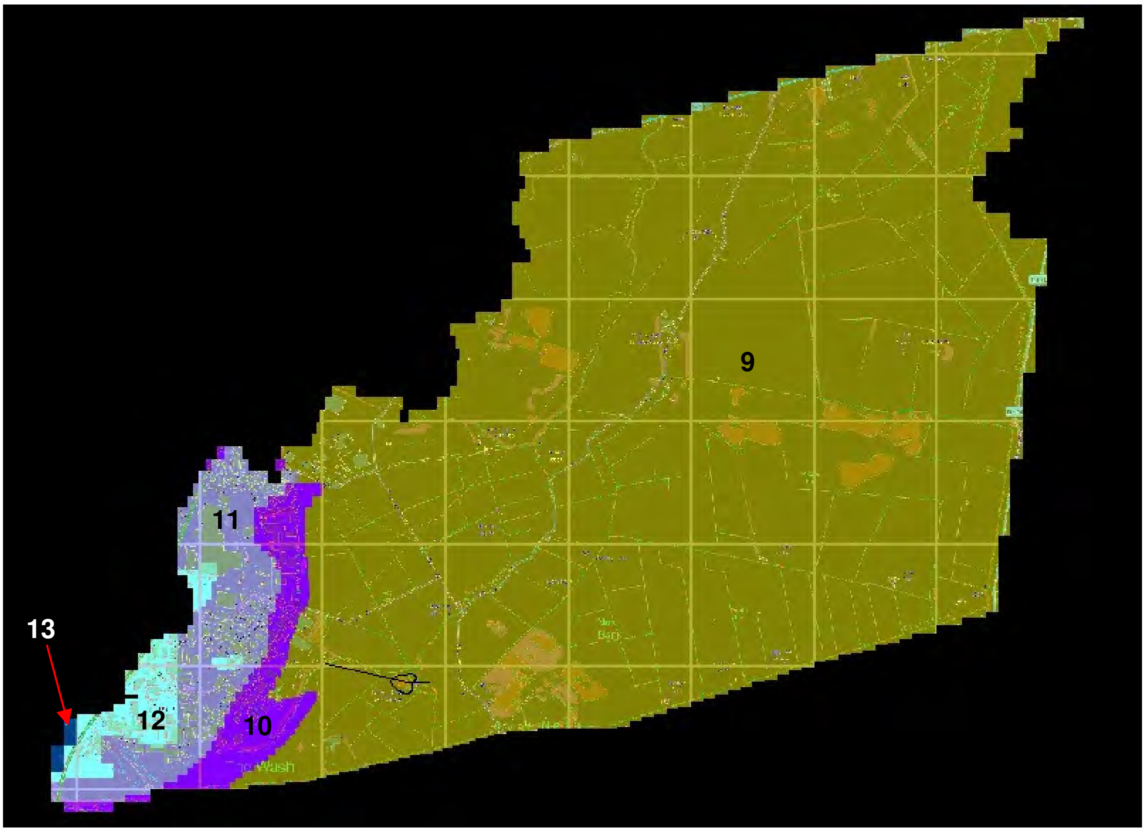
Figure B- 4 Hydraulic Conductivity Zones (Layer 4)



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Storage Properties

For the purposes of the transient modelling, storage properties were defined as follows:

Table B- 2 Storage Zones

Zone	Unit	Material	Specific storage (Ss)	Specific yield (Sy)	Porosity (not used)
1	Made/infilled ground		0.001	0.1	0.4
2	Alluvium	Clay, silt, sand and gravel	0.0005	0.08	0.4
3	NOT USED		0.0005	0.1	0.4
4	Peat	Peat	0.0005	0.015	0.4
5	Barroway Drove Beds	Clay and silty clay	0.000333333	0.05	0.4
6	River terrace	Sand/gravel	0.000166667	0.25	0.4
7	March gravels	Sand/gravel	0.000166667	0.25	0.4
8	West Walton Formation	Mudstone and siltstone with subordinate fine-grained sandstone and argillaceous limestone	5×10^{-5}	0.01	0.4
9	Oxford Clay	Mudstone with local calcareous nodules	5×10^{-5}	0.01	0.4
10	Kellaways Sand	Sandstone and	5×10^{-5}	0.12	0.4

		siltstone with interbeds of sandy/silty mudstone			
11	Kellaways Clay	Mudstone with local thin siltstones/ sandstones and calcareous nodules	5×10^{-5}	0.01	0.4
12	Cornbrash	Limestone	5×10^{-5}	0.14	0.4
13	Blisworth Clay	Mudstone	5×10^{-5}	0.01	0.4
14	Blisworth Limestone	Limestone with thin marls and mudstones	5×10^{-5}	0.14	0.4
15	Rutland Formation	Mudstone and siltstone	5×10^{-5}	0.01	0.4
16	Alluvium overlying peat	Clay, silt, sand, gravel and peat	0.0005	0.015	0.4
17	Peat overlying Barroway Drove Beds	Clay, silty clay and peat	0.0005	0.015	0.4
18	Quarry lake	Open water	0.0005	0.95	0.99
19	Peat over Barroway Drove Beds (Layer 2)		0.0005	0.05	0.4
20	Alluvium over peat (Layer 2)	Not defined as a storage zone (areas of K zone 20 are assigned to storage zone 6)			

Sources:
1. Freeze and Cherry (1979)
2. Brassington (2007)
*For anisotropic materials, Kz generally taken as 0.1(Kxy). However, multiplication factors lower than 0.1 were used when averaging K values between aquifer/aquitard layers.

The distribution of storage zones coincides with the hydraulic conductivity zones (the zone numbers are the same for K and for storage), with the exception of K Zone 20, for which the storage is assigned to Zone 6.

Note that the peat has a very low specific yield, about 1.5%. This may reflect the importance of fractures and macropores in controlling effective groundwater storage; it may also reflect the presence of significant volumes of clay (e.g. as lenses and interbeds) within the peat sequence.

B.7 Recharge

For the steady-state model, recharge was initially estimated as:

Zone 1 (main model area): 0.0002 m/d, corresponding to about 12 or 13% of long-term average rainfall.

Zone 2 (urban areas): 0.0001 m.d, i.e. 50% of main recharge.

Zone 3 (outcrop area of Barroway Drove Beds): 0 m/d (approximating very low recharge to clay-rich superficial deposits).

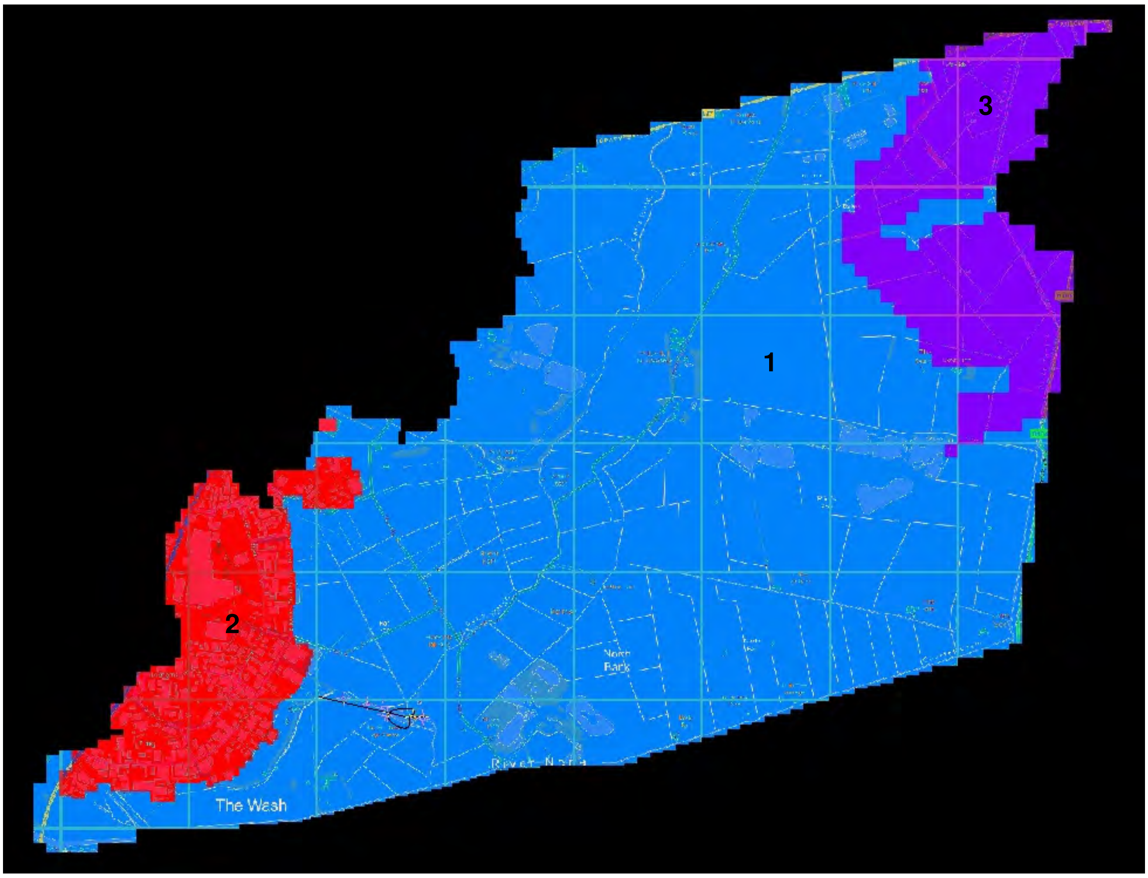
These recharge rates were refined during model calibration. The final values in the calibrated steady-state model were:

Zone 1: 0.000225 m/d, corresponding to about 13 to 15% of long-term average rainfall.

Zone 2: 9.92647 x 10-5 m/d

Zone 3: 0 m/d.

Figure B- 5 Recharge Zones



For the transient model, recharge was varied as shown in Figure 2-7.

Recharge from the Large Mere

The following abstraction returns for the Flag Fen surface water abstraction (Section 2.5.3) were used to estimate the rate of leakage of the Large Mere to ground: 16,180 m^3/yr (2008) and 6,248 m^3/yr (2009). The rate of leakage is estimated as:

$$Leakage = Abstraction + (Rain - Evap).(Area)$$

where Leakage = rate of leakage from the mere [L^3/T], Abstraction = rate of abstraction [L^3/T], Rain = rainfall [L/T], Evap = rate of open water evaporation [L/T] and Area = area of the Large Mere [L^2]. It is assumed that the inputs are the surface water abstraction and the rainfall, and that water is lost to a combination of leakage and evaporation.

For 2008:

Abstraction = 16,180 m^3/d

Area of Large Mere = 8,217 m^2

MORECS rainfall = 665 mm/yr = 5,464.305 m^3/yr over Mere area

MORECS average open water evaporation = 827 mm/yr = 6,795.459 m^3/yr over Mere area

Rainfall - evaporation = -1,331.15 m^3/yr

Leakage = 16,180 - 1331.15 = 14,848.85 m^3/yr = 40.68 m^3/d

For 2009:

Abstraction = 6,248 m^3/d

Area of Large Mere = 8,217 m^2

MORECS rainfall = 535.6 mm/yr = 4,401.025 m^3/yr over Mere area

MORECS average open water evaporation = 864.9 mm/yr = 7,106.883 m^3/yr over Mere area

Rainfall - evaporation = -2,705.86 m^3/yr

Leakage = 6,248 - 2,705.86 = 3,542.142 m^3/yr = 9.70 m^3/d

B.8 Boundary Conditions

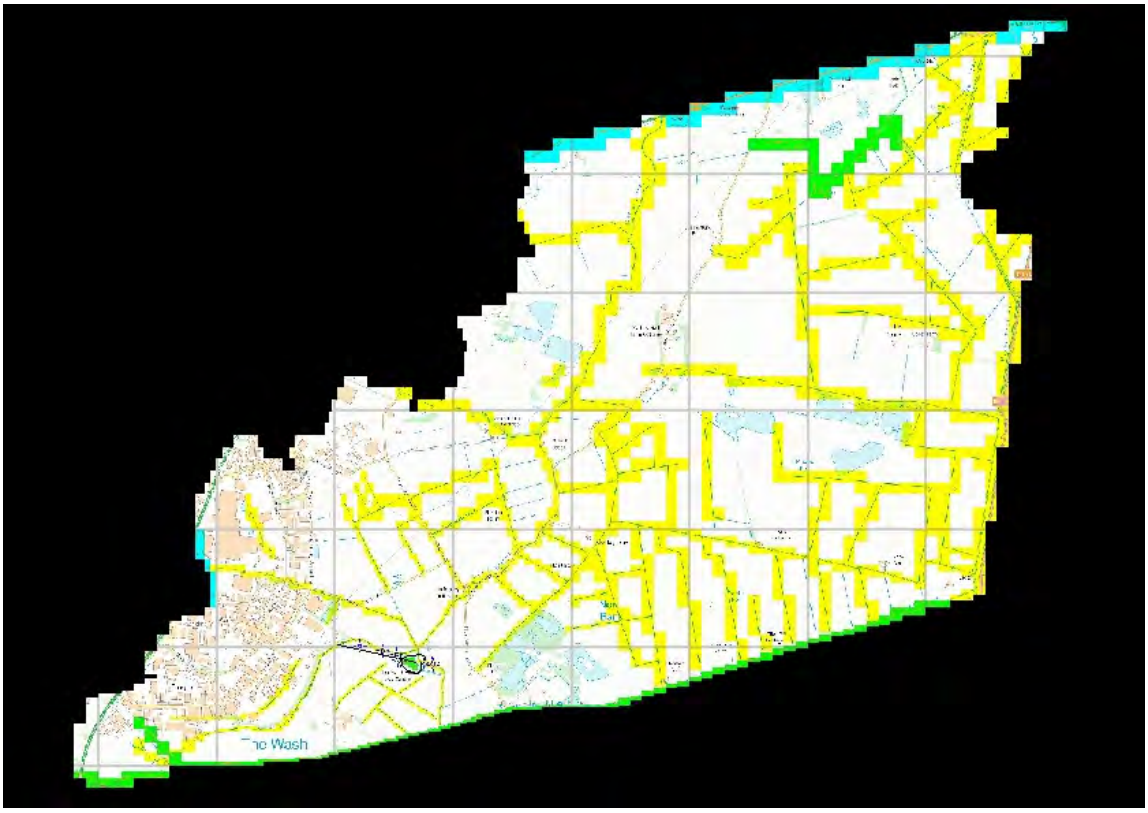
Table B- 3 summarises the parameter settings for the various boundary conditions. The figures that follow the table show the spatial distribution of boundary conditions in each model layer.

Table B- 3 Boundary Conditions

Location	Layer	Boundary Type	Explanation
Northern edge of model	1	**General head boundary (Reaches 3 to 6):** Head = 1.6 to -0.51 mAOD at a distance of 1000 m with K = 0.1 m/d and saturated thickness = 1.5 m.	Model edge represents an approximate surface water drainage divide. The general head boundary allows some flow of groundwater across the boundary (e.g. it allows a large groundwater abstraction close to the northern edge of the model area to draw water from beyond the surface water catchment boundary).
	2	**General head boundary (Reaches 3 to 6):** Head = 1.6 to -0.51 mAOD at a distance of 1000 m with K = 10 m/d and saturated thickness = 6 m.	As above.
	3	**General head boundary (Reaches 3 to 6):** Head = 1.6 to -0.51 mAOD at a distance of 1000 m with K = 10 m/d and saturated thickness = 6 m.	As above.
	4	**General head boundary (Reaches 3 to 6):** Head = 1.6 to -0.51 mAOD at a distance of 1000 m with K = 0.1 m/d and saturated thickness = 10 m.	As above.
Southern edge of model	1	**River boundary (Reach 102 in SW):** Stage = 3 mAOD (managed level); bottom elevation = 2 mAOD; width = 33 m; bed thickness = 1 m; K = 0.01 m/d. **River boundary (Reaches 14 and 65):** Stage = 1.49 to -1.19 mAOD; bottom elevation = 0.49 to -2.69 mAOD; width = 5 to 8 m; bed thickness = 0.5 m; K = 0.01 m/d.	River Reach each 102 (south-western corner of the model) represents the River Nene. River Reaches 14 and 65 represent a drainage ditch immediately north of the River Nene. At its western end, this boundary extends into the interior of the model domain.
	2		
	3		
	4	Part of River Reach 14 extends into Layer 4.	
Eastern edge of model	1	**Drain boundary (Reaches 52, 53, 54, 55, 57, 58, 61, 62, 64)** with some short stretches of **no-flow boundary.**	The drain cells represent the Thorney River (or the drain immediately west of this) and also some other ditches along the north-eastern edge of the model. The no-flow boundaries represent the outer edges of the permeable superficial geology units represented in the model.
	2		
	3		
	4		
Western edge of model	1	Mostly a **no-flow boundary.** **General head boundary (Reaches 104, 105 and 106):** Head = 3 mAOD at a distance of 65 to 260 m with K = 1 m/d and saturated thickness = 1 m/d.	No-flow boundary represents the up-gradient edge of the permeable superficial deposits. General head boundary defined locally to represent a drainage ditch immediately west of the model area.
	2		
	3		
	4		
Interior of model (and locally at the	1	**Drain and River boundaries (various reaches):** Stages estimated in the field or based	Drain boundaries used to represent drainage ditches. River boundaries used to represent
	2		

margins)		(typically) on ground level minus 1.5 m. Widths estimated in the field, measured from the OS map (if width represented) or assumed to be 2 m. Default K = 0.01 m/d and bed thickness = 0.5 m, but for some reaches these values were adjusted during calibration. K was allowed to increase to 10 m/d. For rivers, bed elevation was based on field estimation or an assumed depth (e.g. 1 m). River Nene: stage set at 3 m based on information supplied by the IDB. Bed thickness estimated at 1 m, reflecting greater width of this watercourse. **Large Mere (River Reach 999):** stage = 1.96 mAOD (based on monitoring), depth assumed to be 1 m, bed thickness taken as 0.5 m and bed K as 0.005 m/d (reflecting silt/clay lining).	the River Nene, the Large Mere and also those drains with the potential to supply water to the ground. Wells (analytical elements) used to represent groundwater abstractions.
	3	As above, but with **wells** (analytical elements)	
	4	Very few drain and river cells present as most watercourses are assumed not to penetrate the bedrock.	
K = hydraulic conductivity			

Figure B- 6 Boundary Conditions (Layer 1)



Drain cells = yellow, River cells = green, General Head Boundary cells = pale blue.
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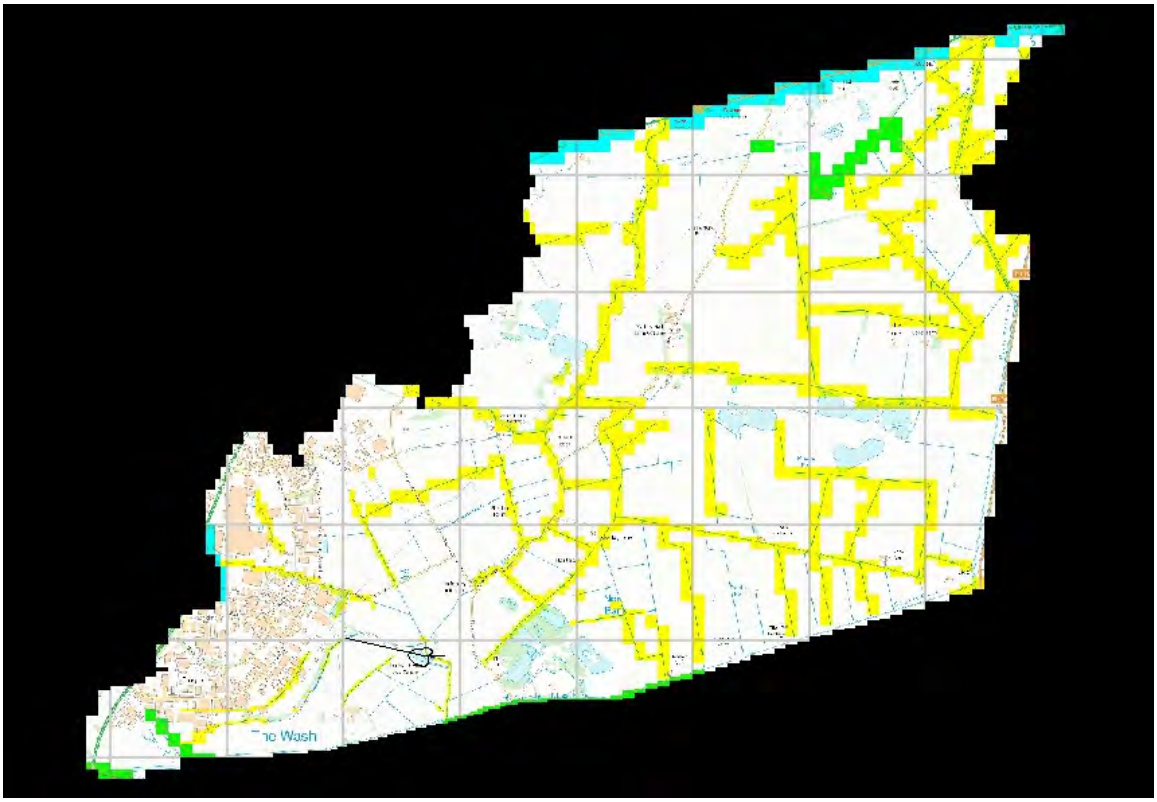
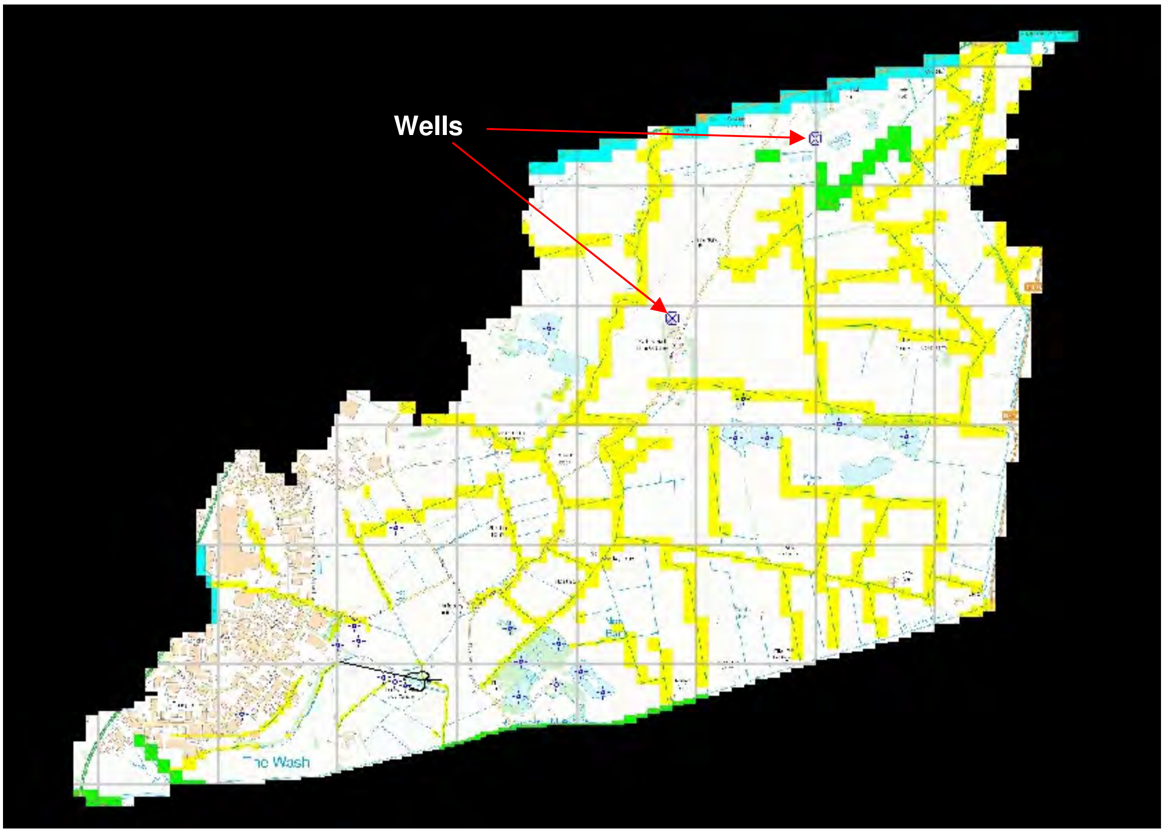
Figure B- 7 Boundary Conditions (Layer 2)



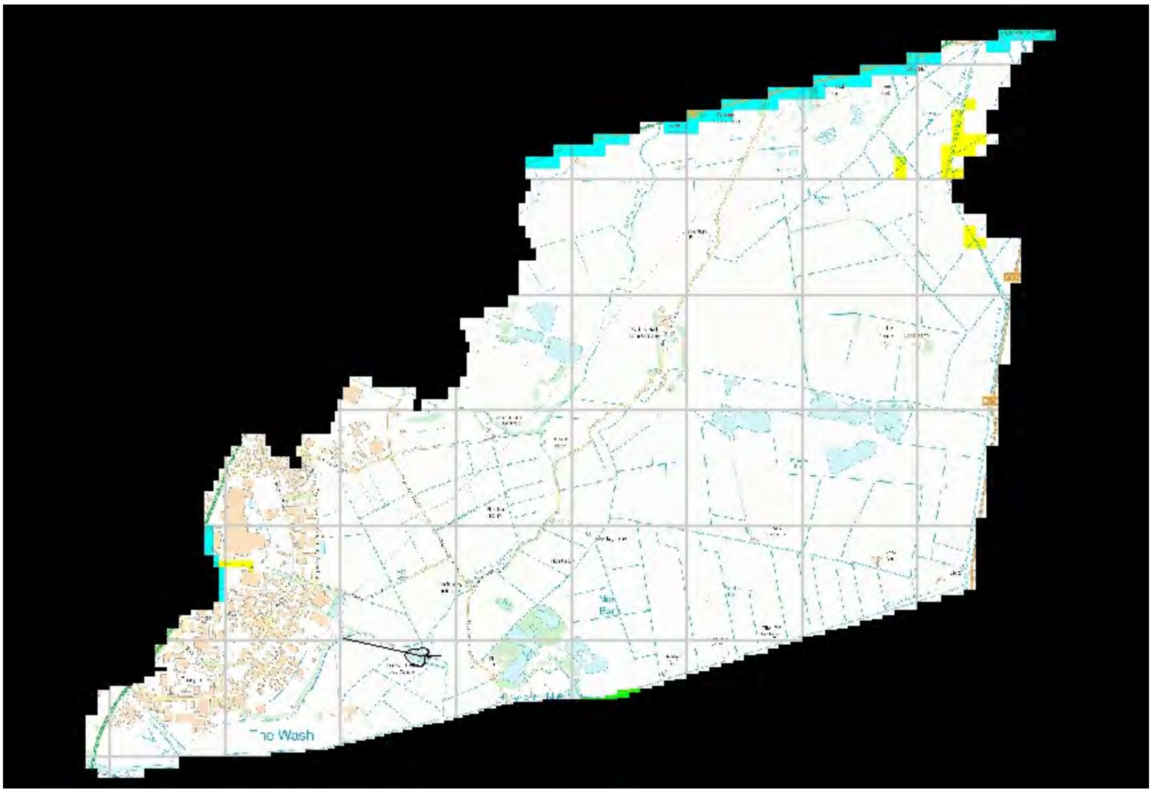
Drain cells = yellow, River cells = green, General Head Boundary cells = pale blue.

Figure B- 8 Boundary Conditions (Layer 3)



Drain cells = yellow, River cells = green, General Head Boundary cells = pale blue.

Figure B- 9 Boundary Conditions (Layer 4)



Drain cells = yellow, River cells = green, General Head Boundary cells = pale blue.
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B.9 Model Calibration Statistics

Model Calibration Targets

Two types of target were used to calibrate the model: head targets and a single flux target (estimated leakage rate from the Large Mere into the ground).

Table B- 4 Head calibration targets

Easting	Northing	Name	Layer	Target (mAOD)
522490	300150	TF20SW200	3	-1.39
521200	298600	TL29NW185	3	1.6
522386.1	298901.7	PZ3	3	0.03
522479.1	298867.1	PZ4	3	-0.02
522567.6	298834	PZ5	3	0.01
522830	298864	DW01	1	0
522211	299026	DW03	1	0.35
522139.1	299337.9	BHA	3	0.23
522002.2	299173.2	BHB	3	-0.06
522177.5	299208.9	BH3	3	-0.17
522530.6	298903.9	WSH	1	0.89
522401.1	298983	WSF	1	0.36
522518.2	298955.6	WSG	1	0.52

522553	298896	WSI	1	0.79
523516.8	298741.5	NPL1	3	0.6
523532.9	299035	NPL2	3	0.7
524033.8	298948.8	NPL4	3	0.6
524220.7	298776.5	NPL5	3	0.6
523849.5	299185.5	NPL3	3	0.55
523829.1	298844.2	NPL6	3	0.6
523439.2	299314.5	NPL7	3	0.7
526435.7	300591.6	PFL1	3	0.6
526194.4	301018.6	PFL2	3	0
526758	300910.7	PFL3	3	-0.5
525589.8	300898.9	PFL4	3	0.4
525327.9	300901.5	PFL5	3	0.4
525388.7	301227	PFL6	3	0.7
523767.3	301816	Tholt	3	0.7
522748	298883	TPit2	1	0.47
522823	298883	TPit3	1	0.49

The leakage rate from the Large Mere is described above under "Recharge from the Large Mere". A target range was derived, namely 10 to 40 m^3/d.

Model Calibration Statistics (Baseline Steady Model)

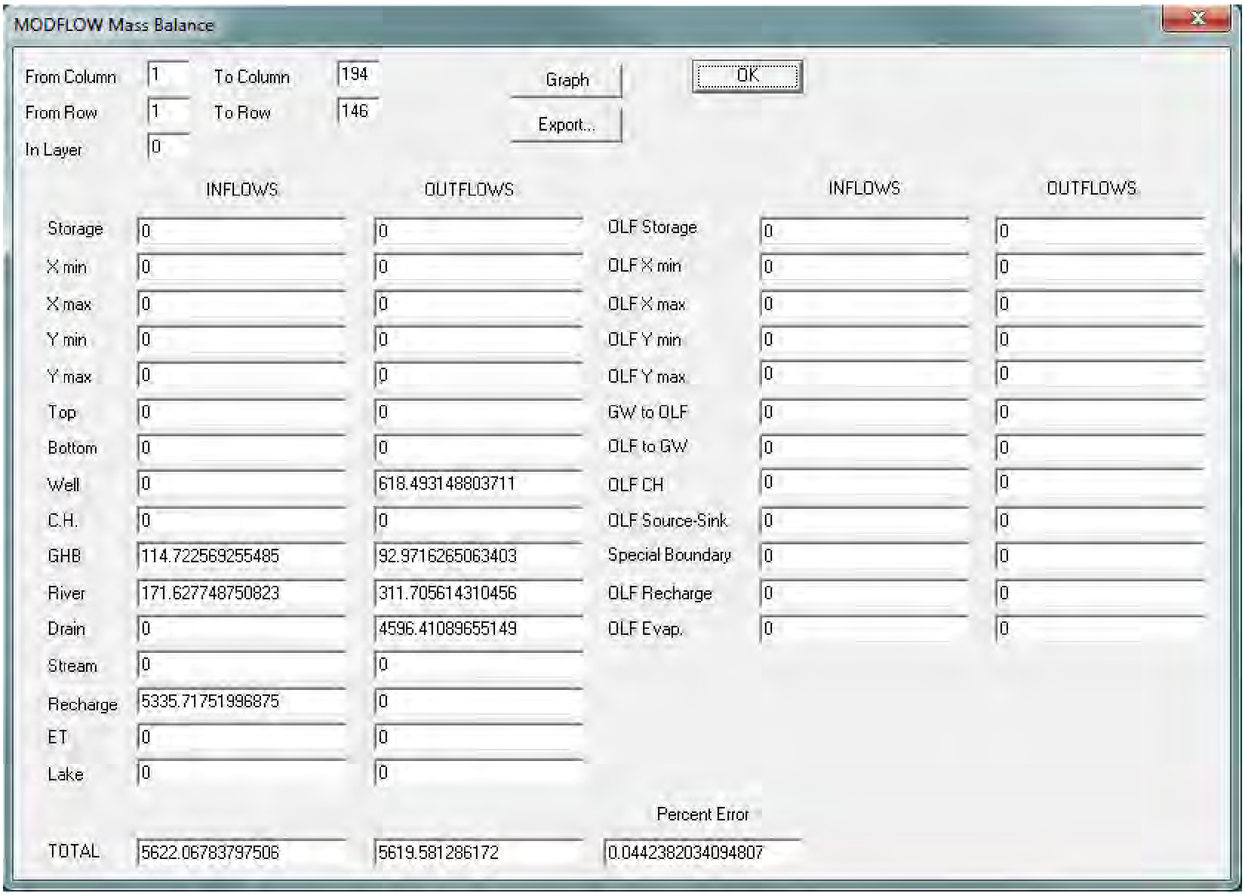
The main calibration statistics for the steady-state baseline model are as follows:

- Residual mean = -0.02 m
  - The residual mean is calculated as the sum of residuals (positive and negative) divided by the total number of residuals. It should be close to zero for a good calibration, as positive and negative residuals cancel one another out.
- Residual standard deviation = 0.24
  - The residual standard deviation is a measure of the overall spread of residuals.
- Absolute residual mean = 0.21 m
  - The absolute residual mean is calculated using absolute (positive) values only and is a measure of average error in the calibration.
- Sum of squared residuals = 1.72
  - The sum of squared residuals is calculated by squaring all residuals and adding them together. It is a useful optimisation parameter for comparing different calibrations (e.g. during sensitivity analysis) and for determining which is best.
- Minimum residual = -0.50 m
- Maximum residual = 0.36 m
- Number of observations = 29.

B.10 Mass Balance for Calibrated Steady-state Model

Figure B- 10 shows the mass balance (water balance) calculated for the calibrated baseline model. The flows are expressed as volumetric flow rates in cubic metres per day. The modelled leakage rate from the Large Mere is not separately itemised within the table, but is 25.83 m^3/d. This lies within the target range of 10 to 40 m^3/d.

Figure B- 10 Mass Balance for the Calibrated Baseline Model (screen capture from Groundwater Vistas v6)



B.11 Model Scenarios

The set-up for the model scenarios is described in the main text. In the drain diversion scenarios, properties for new drain reaches (stage, width, etc.) were based on those of the drains to which they were connected. Blocked drains were represented simply by deleting the relevant drain boundaries from the model. The new drain adjacent to the sewage works (Reach 1003) was given the following properties: stage = 1.67 to 0.35 mAOD, width = 2 m, bed thickness = 0.5 m, bed K = 0.01 m/d.

C Glossary of Hydrogeological Terms

C.1 Glossary

The definitions given here are based on Freeze and Cherry (1979), Shaw (1994), Fetter (2001) and Anderson and Woessner (2002). Terms in **black bold** are defined elsewhere in the glossary.

ANALYTICAL METHODS - Solution of the **groundwater flow equations** using the methods of calculus.

AQUICLUDE - A low **permeability** layer of rock or sediment that cannot transmit a significant quantity of water under ordinary **hydraulic gradient**s.

AQUIFER - A saturated permeable layer of rock or sediment that can transmit significant quantities of water under ordinary **hydraulic gradient**s.

AQUITARD - A low **permeability** layer of rock or sediment that permits slow **groundwater** seepage.

BOUNDARY CONDITIONS - Mathematical statement of the conditions satisfied at the boundary of a region in which a differential equation (or set of such equations) is to be solved. The **groundwater flow equations** are differential equations. Boundary conditions for such equations take the form of heads or flows specified along the boundaries of the groundwater flow system.

CAPILLARY FRINGE - The zone, immediately above the **water table**, in which the **pores** are completely filled with water. The water is drawn up from the main **saturated zone** by capillary forces (this is analogous to water being drawn up a narrow capillary tube).

CONFINED AQUIFER - An aquifer overlain by a low **permeability layer** (confining bed). **Groundwater** in the aquifer may be under pressure so that the water level in a well or borehole penetrating the aquifer rises above the top of the aquifer.

DARCY'S LAW - An empirical law describing fluid flow through a **porous medium** (Darcy, 1856); in one dimension it can be written as:

$$Q = -KA\frac{dh}{dl}$$

where Q = **discharge** [L^3/T], K = hydraulic conductivity [L/T], A = cross-sectional area of flow [L^2], h = hydraulic head [L] and l = distance along the flow path [L].

DISCHARGE - Fluid flow expressed as the volume of fluid passing a given point per unit time, e.g. cubic metres of water per second. In general the units are [L^3/T].

EVAPOTRANSPIRATION - The sum of evaporation and transpiration (transpiration being the release of water vapour from pores in the leaves of plants). Potential evapotranspiration is the evapotranspiration that would occur under given climatic conditions if there were an unlimited supply of soil moisture. If the soil moisture is not unlimited, then the actual evapotranspiration is less than the potential.

FIELD CAPACITY - The maximum amount of water that an unsaturated soil can hold against gravity, expressed as a fraction of the total volume.

GROUNDWATER - Subsurface water in the saturated zone.

GROUNDWATER FLOW EQUATIONS - Differential equations that describe the flow of groundwater through a **porous medium**. They may be steady-state (time invariant) or transient (time variant) and may be written for one, two or three spatial dimensions.

HYDRAULIC CONDUCTIVITY - The proportionality constant, K, in **Darcy's Law**. Its value depends on the intrinsic **permeability** of the **porous medium** and also on the properties of the fluid.

$$K = k\frac{\rho g}{\mu}$$

where K = hydraulic conductivity [L/T], k = intrinsic permeability [L^2], ρ = density [M/L^3], g = acceleration due to gravity [L/T^2] and μ = viscosity [M/(LT)].

HYDRAULIC GRADIENT - The rate of change of **hydraulic head** with distance in a given direction. In general, groundwater flows down the hydraulic gradient in the direction of decreasing hydraulic head. However, the flow direction is also influenced by anisotropy (variation with direction) in **hydraulic conductivity.**

HYDRAULIC HEAD - **Groundwater** has mechanical energy due to its elevation and pressure (groundwater velocities are generally very low, so kinetic energy can be neglected). The mechanical energy per unit weight is referred to as the hydraulic head. This is measured in units of length [L] and is equal to the level that the water can raise itself above a datum. Roughly speaking, the head is the level to which water will rise in a well.

Technically, the total (static) head, h [L], is the sum of the elevation head, z [L], and the pressure head, ψ [L]:

$$h = z + \psi = z + \frac{P}{\rho g}$$

where P = pressure [$M/(LT^2)$], ρ = density [M/L^3] and g = acceleration due to gravity [$L/(T^2)$].

HYDROGEOLOGY - The study of underground, or **subsurface, water.**

INITIAL CONDITIONS - For a transient groundwater model, the initial distribution of heads in the system. Solution of a transient modelling problem requires specification of both **boundary conditions** and initial conditions.

MODFLOW - A computer code (McDonald and Harbaugh, 1988) that uses finite difference methods to solve the **groundwater flow equations.**

NUMERICAL METHODS - Solution of the **groundwater flow equations** using numerical techniques (e.g. finite difference methods).

PERMEABILITY - The ability of a **porous medium** to transmit fluid. The higher the permeability, the easier it is for fluid to pass. A permeable medium allows fluid to pass; an impermeable medium is a barrier to fluid flow.

PIEZOMETER - A narrow-diameter well that is used to measure **hydraulic head**. It consists of either an open-ended pipe or a pipe with a short well screen through which water can enter.

PORES - Void spaces, or holes, within a rock, sediment or other solid material.

POROUS MEDIUM - A rock, sediment or other material containing void space through which water (and/or another fluid) can flow.

POTENTIOMETRIC SURFACE - An imaginary surface that represents the level to which water will rise in **piezometers** penetrating a particular aquifer horizon.

RECHARGE - Water that infiltrates into the ground, percolates downwards, and reaches the **water table**, thereby replenishing the aquifer.

SATURATED ZONE - Beneath the **water table** all the interconnected **pores** are filled with water, and the rock or sediment is referred to as being saturated. This is the saturated zone; it is also known as the phreatic zone.

SOIL MOISTURE DEFICIT - The amount of water needed to restore a soil to **field capacity.**

SUBSURFACE WATER - Water present beneath the ground surface. The water occupies holes, or **pores**, within sediments and rocks.

UNCONFINED AQUIFER - An aquifer that is not confined; it has a water table.

UNSATURATED ZONE - The zone, above the **water table** and **capillary fringe**, in which the pores are partly filled with water and partly filled with air. It is also known as the vadose zone.

WATER TABLE - The surface in a **porous medium** at which the pore water pressure is equal to atmospheric pressure. The water table is commonly thought of as the top of the saturated zone, but the capillary fringe is also saturated and may have a significant thickness in porous media with small pores (and therefore strong capillary action). The definition in terms of pressure is therefore more accurate.

D Elevations of Archaeological Wood

D.1 Elevations of Archaeological Wood

The table overleaf contains the archaeological elevation data used in this study. Scores given in the table are defined as follows:

Wood preservation score: 1 = Poor, 2 = Moderate and 3 = Good.

Data quality score:

1 = Good (no better data available; unlikely to be improved upon in the near future)

2 = Data with known deficiencies (to be replaced as soon as third parties re-issue)

3 = Based on major assumptions (data value deduced by the project team from experience or related literature/data sources)

4 = Educated guess (no data sources available or yet found).

ID	Trench	Material	Wood preservation score	Length of timber (m)	Upper level of preservation (mAOD)	Upper level good preservation (mAOD)	Lower level of preservation (mAOD)	Depth range (m)	Data source	Data qualilty score	Wood preservation description	X_COORD	Y_COORD
DV_T1_D1001	T1 2012	Timber	n/a	n/a	0.73		0.51	0.22	DigVentures	2		522868	298885
DV_T1_D0162	T1 2012	Timber	1	0.37	0.67		0.3	0.37	DigVentures	2		522868	298885
DV_T1_D0166	T1 2012	Timber	3	0.48	0.83		0.35	0.48	DigVentures	2		522868	298885
DV_T1_D003	T1 2012	Timber	2		0.73		0.1	0.63	DigVentures	2		522868	298885
DV_T1_D002	T1 2012	Timber	3	0.52	0.72		0.2	0.52	DigVentures	2		522868	298885
DV_T1_D006	T1 2012	Timber	2	0.43	0.61		0.18	0.43	DigVentures	2		522868	298885
DV_T1_D008	T1 2012	Timber	2	0.33	0.55		0.22	0.33	DigVentures	2		522868	298885
DV_T1_D0167	T1 2012	Timber	2	0.39	0.65		0.26	0.39	DigVentures	2		522868	298885
DV_T1_D0163	T1 2012	Timber	2	0.42	0.95		0.53	0.42	DigVentures	2		522868	298885
DV_T1_D0171	T1 2012	Timber	n/a		0.73		0.63	0.1	DigVentures	2		522868	298885
DV_T1_D0168	T1 2012	Timber	1	0.07	0.56		0.49	0.07	DigVentures	2		522868	298885
DV_T1_D0166	T1 2012	Timber	1	0.18	0.77		0.59	0.18	DigVentures	2		522868	298885
DV_T1_D0165	T1 2012	Timber	1	0.075	0.525		0.45	0.075	DigVentures	2		522868	298885
DV_T1_D0164	T1 2012	Timber	2	0.23	0.75		0.52	0.23	DigVentures	2		522868	298885
DV_TP2_D0084	TP2 2012	Timber	3	0.95	0.34		0.61	0.95	DigVentures	2		522747	298884
DV_TP2_D0123	TP2 2012	Timber	4	0.58	0.85		-0.27	0.58	DigVentures	2		522747	298884
DV_TP2_D0124	TP2 2012	Timber	3	0.42	0.82		-0.4	0.42	DigVentures	2		522747	298884
DV_TP2_D0125	TP2 2012	Timber	4	1.42	0.92		0.5	1.42	DigVentures	2		522747	298884
DV_TP2_D0126	TP2 2012	Timber	3	0.42	0.74		-0.32	0.42	DigVentures	2		522747	298884
DV_TP2_D0127	TP2 2012	Timber	2	0.195	0.63		-0.435	0.195	DigVentures	2		522747	298884
DV_TP2_D0128	TP2 2012	Timber	4	1.065	0.72		0.345	1.065	DigVentures	2		522747	298884
DV_TP2_D0129	TP2 2012	Timber	3	0.464	0.76		-0.296	0.464	DigVentures	2		522747	298884
DV_TP2_D0130	TP2 2012	Timber	2	0.24	0.54		-0.3	0.24	DigVentures	2		522747	298884
DV_TP2_D0131	TP2 2012	Timber	3	0.115	0.52		-0.405	0.115	DigVentures	2		522747	298884
DV_TP2_D0135	TP2 2012	Timber	3	0.18	0.58		-0.4	0.18	DigVentures	2		522747	298884
DV_TP2_D0146	TP2 2012	Timber	4	0.365	0.32		0.045	0.365	DigVentures	2		522747	298884
DV_TP2_D0148	TP2 2012	Timber	4	0.74	0.47		0.27	0.74	DigVentures	2		522747	298884
DV_TP3_D0025	TP3 2012	Timber	2	1.042	0.43	0.35	0.612	1.042	DigVentures	2		522686	298936
DV_TP3_D0035	TP3 2012	Timber	3	0.62	0.41	0.35	0.21	0.62	DigVentures	2		522686	298936
DV_TP3_D0138	TP3 2012	Timber	3	0.71	0.38	0.35	0.33	0.71	DigVentures	2		522686	298936
DV_TP3_D0149	TP3 2012	Timber	3	0.85	0.3	0.35	0.55	0.85	DigVentures	2		522686	298936
DV_TP3_D0159	TP3 2012	Timber	3	0.96	0.31	0.35	0.65	0.96	DigVentures	2		522686	298936
EAA_DYKE10_Platform	DYKE10	Bronze Age Platform	n/a		0.65		0	0.65	EAA 59, Figure 66, page 95			522712	298907
EAA_DYKE10_ Timber	DYKE10	Bronze Age Causeway	n/a		0.8		-0.6	1.4	EAA 59, Figure 66, page 95		Assumed from image in fig 66 but no direct reference to causeway in text.	522712	298907
			unscored		0.92				Henry Chapman			522748	298884
			unscored		0.49				Henry Chapman			522823	298884
			unscored		1.1				Henry Chapman			522438	298956
			unscored		0.829999				Henry Chapman			522342	298977
			unscored		0.939999				Henry Chapman			522226	299010
			unscored		1.235				Henry Chapman			522135	299036

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