Norwich Western Link

Environmental Statement

Chapter 12: Road Drainage and the Water Environment

Appendix 12.5: River Wensum Crossing – Groundwater Modelling Report

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Glossary of Abbreviations and Defined Terms

Term	Definition
Aquifer	Underground layer of water-bearing permeable rock, rock fractures or unconsolidated materials (gravel, sand, or silt).
Borehole	A hole that is drilled into the ground in order to determine the ground conditions; investigate the presence of contamination; obtain samples of soil for analysis; and allow monitoring of groundwater and ground gas. Typically installed with inert HDPE piping
Catchment	The total area which drains to a specific point on a watercourse.
Conceptual site model (CSM)	A representation of the characteristics of the site in diagrammatic or written form that shows the possible pollutant linkages between contaminants, pathways, and receptors.
Contaminant	A substance that is in, on or under the land and that has the potential to cause harm or to cause pollution to the water environment.
Controlled waters	Controlled waters are rivers, streams, estuaries, canals, lakes, ponds, ditches, and groundwater as far out as the UK territorial limit These are fully defined in Section 104 of the Water Resources Act 1991.
Groundwater	Water found underground in the cracks and spaces in soil, sand, and rock. It is stored in and moves slowly through geologic formations of soil, sand and rocks called aquifers.

Term	Definition
Groundwater Body	Defined by UK Technical Advisory Group (UKTAG) as an aquifer that is capable of supplying 10 m^3/d or 50 people (on a continuous basis). Such aquifers have future resource value which must be protected.
Groundwater Dependent Terrestrial Ecosystems	Based on SSSI outlines from Natural England, filtered to include only those sites with wetland vegetation communities listed in UK
Hydrogeology	Is the area of geology that deals with the distribution and movement of groundwater in the soil and rocks of the Earth's crust
Hydrograph	A graph showing the rate of flow (discharge) versus time past a specific point in a river, channel, or conduit carrying flow.
Hydrology	The study of the movement, distribution, and management water on Earth’s surface.
Nitrate Vulnerable Zone	Area designated as being at risk from agricultural nitrate pollution.
Principal Aquifer	Layers of rock or drift deposits that have high intergranular and / or fracture permeability - meaning they usually provide a high level of water storage. They may support water supply and / or river base flow on a strategic scale. In most cases, principal aquifers are aquifers previously designated as major aquifers
Proposed Scheme	All works associated with the proposed development of the Site

Term	Definition
Secondary A Aquifer	Permeable layers capable of supporting water supplies at a local rather than strategic scale, and in some cases forming an important source of base flow to rivers. These are generally aquifers formerly classified as minor aquifers.
Secondary (Undifferentiated) Aquifer	Assigned in cases where it has not been possible to attribute either category A or B to a rock type. In most cases, this means that the layer in question has previously been designated as both minor and non-aquifer in different locations due to the variable characteristics of the rock type.
Site of Special Scientific Interest (SSSI)	A Site of Special Scientific Interest (SSSI) in Great Britain or an Area of Special Scientific Interest (ASSI) in the Isle of Man and Northern Ireland is a conservation designation denoting a protected area in the United Kingdom and Isle of Man. A SSSI (or ASSI) usually describes an area of particular interest to science due to the rare species of fauna or flora it contains - or even important geological or physiological features that may lie in its boundaries.
Special Area of Conservation (SAC)	A Special Areas of Conservation (SACs) is a strictly protected site designated under the EC Habitats Directive.
Source Protection Zone (SPZ)	Areas which show the level of risk to the source of groundwater from contamination. SPZ 1 (Inner zone) is based on a 50-day travel time of pollutant to source with a 50 metres default minimum radius. SPZ2 (outer zone) is based on a 400-day travel time of pollutant to source with 250 or 500 metres minimum radius around the source depending on the amount of water abstracted. SPZ 3 (total catchment) area around a source within which all the groundwater ends up at the abstraction point.

Term	Definition
Surface water flood risk	Risk of flooding from overland flow resulting from rainfall events which cannot be contained within drainage systems.
Temporary Works Platform	The term to refers to the temporary platform across the floodplain used to construct the viaduct. It will cross the River Wensum by means of a temporary bailey bridge.
Tributaries	Smaller watercourses which drain to a large watercourse
Water Environment	A term used to describe the water environment that also has legal definitions within UK legislation. This includes groundwater, surface water (e.g. rivers, streams, and lakes), estuarine and coastal waters.
Water Framework Directive (WFD)	Originally a European Union directive which commits member states to achieve good qualitative status of all water bodies (post Brexit converted into UK legislation). The purpose of the Water Framework Directive is to establish a framework for the protection of inland surface waters, estuaries, coastal waters, and groundwater.
Water Table (Groundwater Table)	The level below which the ground is saturated with water. This is the surface where water pressure is equal to atmospheric pressure.

1 Introduction

1.1 Project background

1.1.1 The Norwich Western Link Road (NWL 'The Proposed Scheme') is a highway scheme linking the A1270 Broadland Northway from its junction with the A1067 Fakenham Road to the A47 trunk road near Honingham.

1.1.2 The Proposed Scheme would cross the River Wensum and its flood plain by means of a viaduct. The Proposed Scheme would also cross four minor roads by means of overpass or underpass bridges. The Proposed Scheme would include ancillary works such as provision for non-motorised users, necessary realignment of the local road network and the provision of environmental mitigation measures.

1.2 Groundwater Background

1.2.1 The purpose of this document is to carry out a conceptual and numerical modelling study of the groundwater system underlying the proposed River Wensum Viaduct.

1.2.2 This model was used to assess the impact of the River Wensum bridge foundations on groundwater flow and levels in the area adjacent to the River Wensum Special Area of Conservation.

1.2.3 An initial numerical model was developed in 2021, which was subsequently updated in 2023 to account for a revised viaduct design and additional ground investigation and 2022 monitoring data.

1.2.4 In addition, the model has been used to assess the potential impacts of future salt spreading for de-icing purposes of the bridge on groundwater and surface water quality.

1.2.5 Considerations are also given to impacts of required alterations to local ground conditions as part of the Temporary Works Platform construction on the water environment.

1.3 Brief and Objectives

1.3.1 The purpose of the conceptual and numerical model study is to assess the potential impact of the implementation of the River Wensum piles (below ground structures) associated with the proposed viaduct design on the groundwater flow conditions. Potential impacts include diversion of groundwater flow, local groundwater level rise including increased risk of groundwater flooding and changes to the vertical connectivity between the deeper regional aquifer (Chalk aquifer) and the superficial deposits aquifer with its links to surface water features within the Special Area of Conservation. This report will help to evaluate bridge foundation detailed design options and feed into other technical reports (e.g. Water Framework Directive (WFD) assessment and flood risk assessments). Whilst other below ground structures which are not explicitly modelled are included in the Proposed Scheme design, the majority of these are expected to be smaller, located in less sensitive areas or of temporary use only. The impact to groundwater surface water connectivity resulting from the construction of the Temporary Works Platform, whilst not explicitly modelled due to its shallow nature, has also been considered (please refer to Section 4 for further detail).

1.3.2 The groundwater flow model was also used as the basis for a contaminant transport model, developed to assess the impact that salt spreading on the River Wensum Viaduct may have on the surrounding water environment.

1.4 Data Sources

1.4.1 The main sources of information for this study were:

- Rain gauge data was obtained from https://environment.data.gov.uk; the Salle online logger was used (**Ref 8, 9, 10 and 11**).
- Detailed topographical survey carried out by WSP between August and September 2019 along the proposed river crossing at the time.

- Surface water elevations survey at 8 points across the River Wensum and adjacent local drains near the viaduct area, measured on December 12th, 2022.
- BGS Map 161 (**Ref 3**) was used to obtain information about the main geological units on site and create the different hydraulic zones in the numerical model.
- A total of 63 boreholes, 25 BGS boreholes from Mapapps2.bgs.ac.uk (2021) (**Ref 21**) and 38 ground investigation boreholes from Norfolk Partnership Laboratory (2020) (**Ref 24**) and Leech (2022) (**Ref 17, 18 and 19**) investigations have been used to assist with creating the numerical model (**Sub Appendix A: Borehole Information** (Document reference 3.12.05a)).
- Hydraulic conductivity data was obtained from a combination of Particle Size Distribution data completed by WSP, magic.defra.gov.uk.co.uk (2024) (**Ref 20**) and Domenico and Schwartz (1990) (**Ref 6**).
- Information on the regional groundwater resource model (Norwich, Wensum and Tud Area numerical model) and groundwater abstractions were provided by the Environment Agency.
- Information on regional groundwater levels in the Chalk were obtained from the Hydrogeological map of Northern East Anglia Sheet 2 (1981) (**Ref 14**).
- Groundwater level information obtained from 10 boreholes on 13th December 2022 was provided by NCC's monitoring team.

1.5 Report Structure

1.5.1 To present the methodology and the main results associated with the conceptual and numerical model study, the report has been organised into the following Sections:

- Section 2 summarises the hydrogeological information compiled within the area of interest and presents the associated conceptual model.
- Section 3 gives the main characteristics of the viaduct design.
- Section 4 discusses potential impacts associated with construction of the Temporary Works Platform on surface water and groundwater flow.
- Section 5 explains how the conceptual model has been transformed into a numerical model.
- Section 6 presents the numerical model calibration and the sensitivity analysis.
- Section 7 presents the predictive scenarios results, showing the potential impact of the piles on the groundwater system and the list of important model limitations.
- Section 8 presents the contaminant transport model, developed to assess the impact that salt spreading on the River Wensum Viaduct may have on the surrounding environment.
- Section 9 provides the conclusions of the study.

1.6 Limitations

1.6.1 Numerical groundwater models are tools to help assess environmental impacts or to inform engineering designs. They are set up to meet the modelling objectives and are not intended to be a copy of real conditions. Simplification and limitations due to the variable nature of ground conditions and groundwater flow are necessary.

1.6.2 Ground investigation data are snapshots of local conditions but are commonly used to develop conceptualisation of hydrogeological conditions. For this conceptual model and numerical model set up and calibration third party information has been used, and for its accuracy WSP cannot be held responsible.

1.6.3 Model assumptions were chosen to create conditions which allow the model objectives to be met and the model to be calibrated, based on the author's conceptual understanding of the site developed according to available information. In order to better understand uncertainties in the model, sensitivity analysis and qualitative assessments are used to validate the assessment outputs and increase confidence in model predictions.

2 Hydrogeological setting and conceptual model

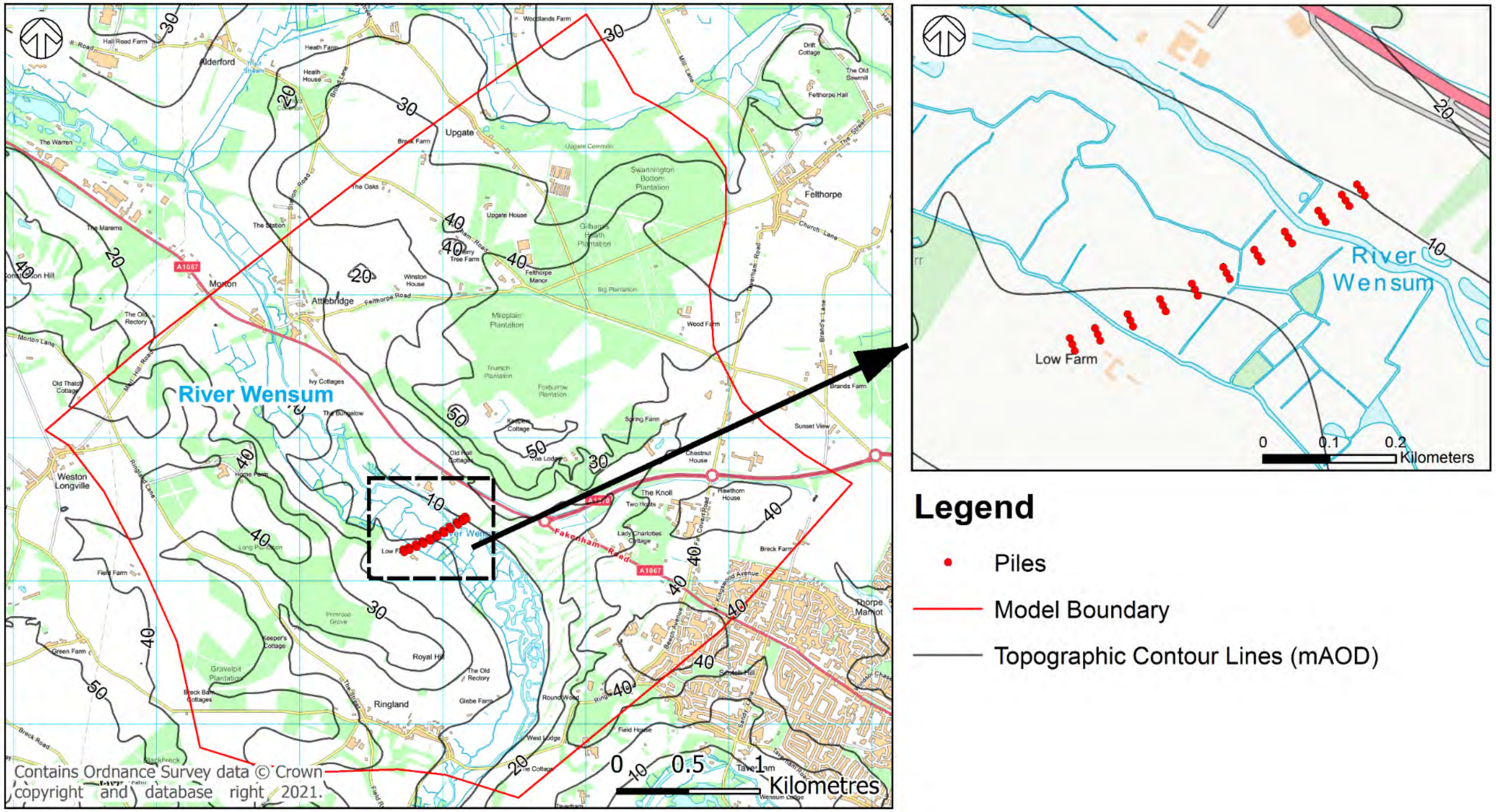
2.1 Location of the Study Area

2.1.1 The groundwater flow at the proposed River Wensum crossing is connected to a regional groundwater and surface water flow system, i.e., in order to describe and model local groundwater flow conditions, a wider Study Area needs to be considered. This wider catchment area or area of interest is unrelated to the Proposed Scheme Study Areas defined as part of the Environmental Statement as it is purely driven by modelling specific requirements.

2.1.2 **Figure 2.1** presents the viaduct location, within the wider Study Area used for the hydrogeological assessments. The Study Area and model boundary has been established based on the hydrogeological map, which is presented in detail in Section 2.5, and has been considered to be an adequate size and shape to allow numerical groundwater flow modelling to be undertaken which is dependent on the regional hydrogeological setting.

2.1.3 The data available within the Study Area has been compiled, reviewed and interpretated such as presented in the following sub-sections.

Figure 2.1 Location of the viaduct piles and wider study are (model boundary)

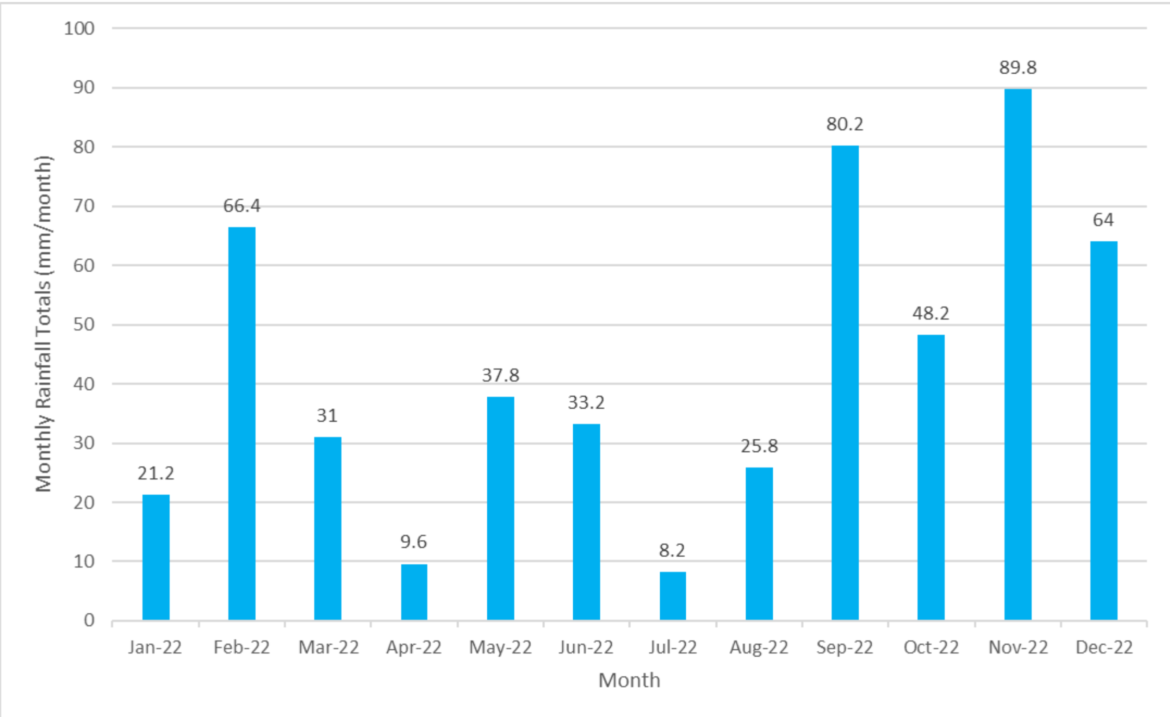


2.2 Climate

2.2.1 The climate at Norwich is generally warm and temperate with significant amounts of rainfall all year round (**Ref 4**).

2.2.2 Precipitation data from the Environment Agency's weather station Salle Rain Gauge Station, located approximately 9km to the north of the viaduct area, has been compiled. This is the closest Environment Agency weather station to the Study Area. The monthly precipitation between January 2022 and December 2022 for this station was obtained from (**Ref 11**) and values are presented in **Figure 2.2**. The rainfall varies between approximately 8mm in July 2022 and 90mm in November 2022, with a total precipitation of 515mm in 2022. The long-term annual average rainfall rate for Norwich is approximately 719mm/year (based on data collected between 1999 and 2019. This suggests that following a relatively dry year regional groundwater levels may have been relatively low at the end of 2022, in contrast to higher surface water levels following the particularly wet November.

Figure 2.2 Precipitation data at the Salle weather station (Ref 11)



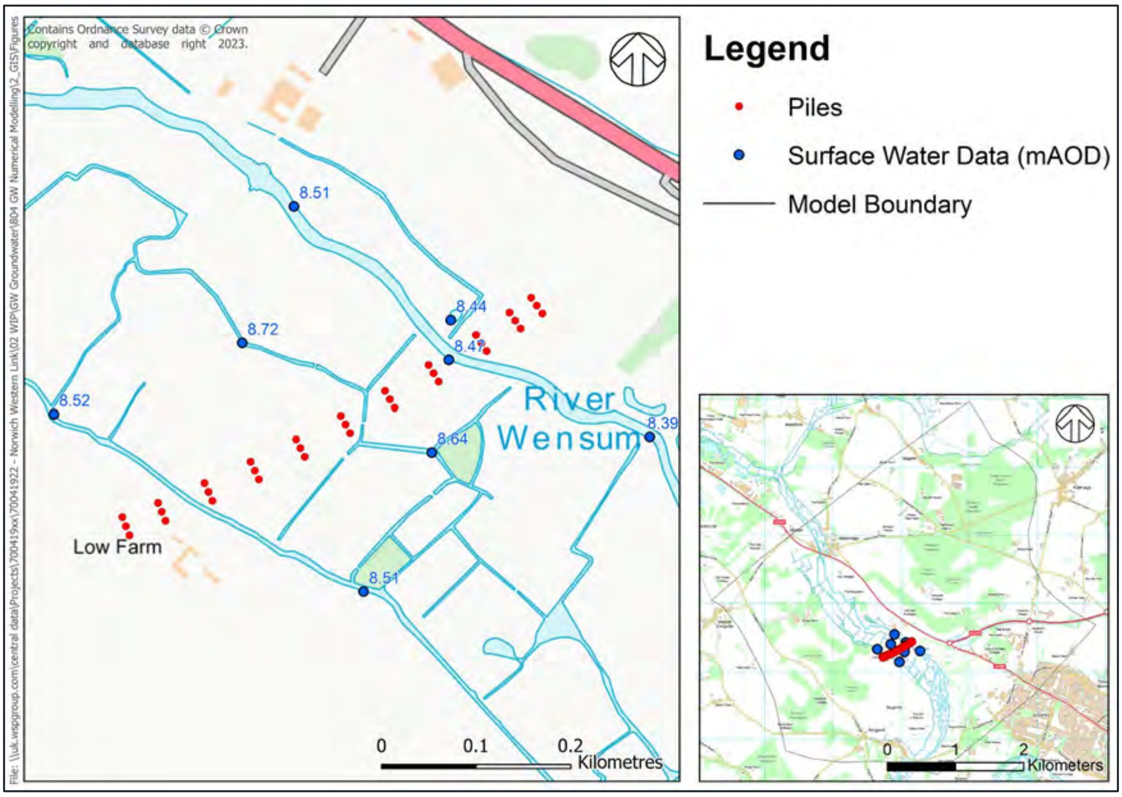
2.3 Topography and Hydrology

2.3.1 **Figure 2.1** shows the OS map and topographical contour lines. Within the wider Study Area, the topography generally slopes from the southwest and northeast towards the River Wensum. According to the detailed topographical survey, within the main area of interest (i.e. close to the location of the proposed River Wensum Viaduct) the ground elevation varies between approximately 40mAOD next to the Spring Hill and 9mAOD near the River Wensum.

2.3.2 The River Wensum represents the main hydrological feature (**Figure 2.3**) in the area of interest. The Wensum flows from the north west to the south east and is approximately 12m wide (according to the OS map).

2.3.3 River elevations at 8 points across the river and adjacent local drains near the proposed viaduct area, were measured on December 12th, 2022, as shown on **Figure 2.3**. The river gradient was relatively shallow and showed a decrease in the river stage of approximately 0.12m over the 471m of the hydrological survey.

Figure 2.3 Location of surface water survey points around the proposed viaduct



2.3.4 In addition to the River Wensum, a dense drainage system associated with the river floodplain can be observed on the OS map and five measurements of drain water level elevation were obtained. Drain water level elevations were similar to those measured in the River Wensum, suggesting a good hydraulic connectivity between shallow groundwater and surface water features throughout the valley floor.

2.4 Geology

Superficial and bedrock geology

2.4.1 **Table 2.1** presents the main geological units within the Study Area and **Figure 2.4** and **Figure 2.5** show the locations of the superficial and bedrock units, respectively. The superficial deposits cover most of the Study Area and include: Head Deposits, Alluvium, River Terrace Deposits, and the Sheringham Cliffs Formation (**Figure 2.4**). The bedrock geology across the site consists mostly of undifferentiated deposits of the White Chalk Subgroup and some of the Wroxham Crag Formation to the east (**Figure 2.5**).

Table 2-1 Geological units (information from Ref 3)

Formation	Geological Period	Description
Head	Holocene	Head deposits comprise of poorly sorted, subangular to sub-rounded sand, gravels, and clay with local lenses of clay, silt, and peat present.
Alluvium	Holocene	The Alluvium is situated adjacent to the River Wensum towards the northern end of the highway scheme. BGS Lexicon indicates that the Alluvium comprises of clay, silt, and sand, and has a gravelly base.
River Terrace Deposits	Middle-late Pleistocene	These deposits are also situated adjacent to the rivers at each end of the Proposed Scheme. The River Terrace Deposits mostly comprise of sand and gravels with local lenses of clay, silt, or peat according to the BGS definition.

Formation	Geological Period	Description
Sheringham Cliffs Formation	Middle Pleistocene	This formation can be found across most of the Proposed Scheme. Lee et al. (2014) (**Ref 16**) indicates that this formation consists of a sequence of thick glaciogenic lithofacies. The units within this formation vary in composition from fine-grained sands, laminated silts, clays, and gravels, where the formation tends to coarsen upwards
Wroxham Crag Formation	Early-middle Pleistocene	This formation consists mostly of sand and gravel, with some silt and clay.
White Chalk Subgroup	Cretaceous	The White Chalk Subgroup comprises of chalk with flints, marl seams and nodular chalk. BGS Map Sheet 161 indicates a maximum thickness of up to 270 metres (Upper and Middle Chalk) for the White Chalk Subgroup.

Figure 2.4 Geological Map: Surface deposits (Ref 3)

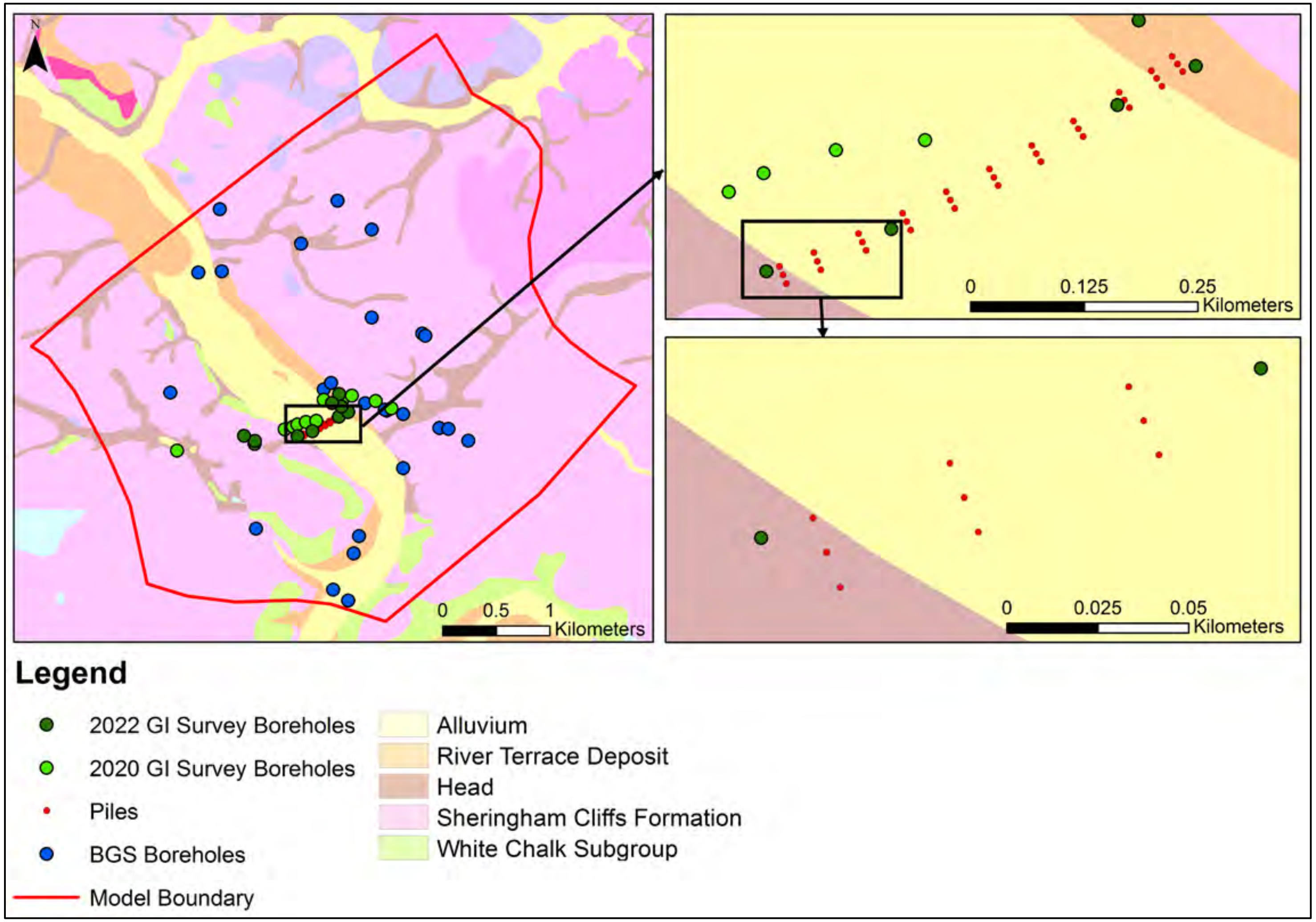
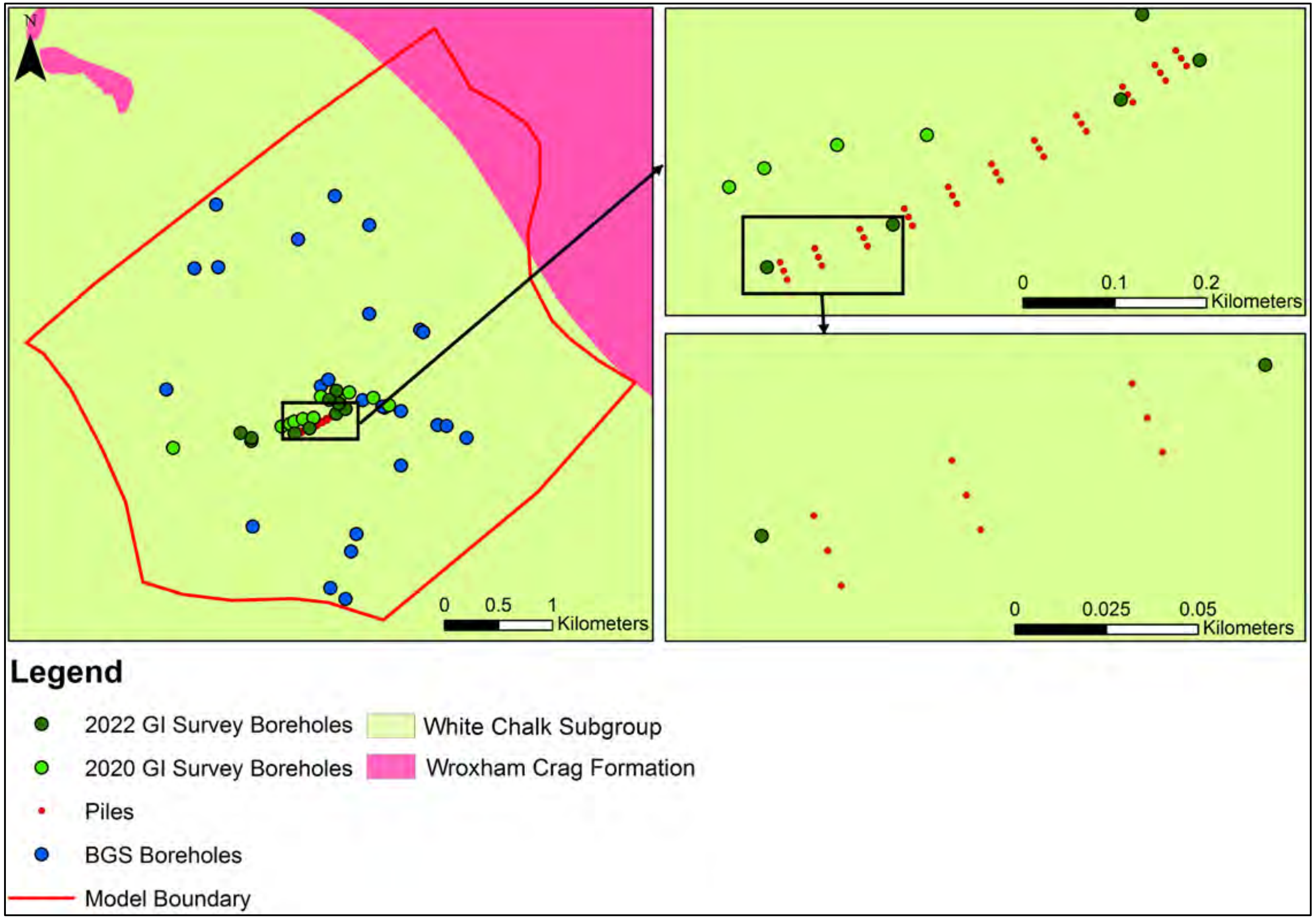


Figure 2.5 Geological map: Bedrock (British Geological Survey, 1975)



Borehole logs

2.4.2 A total of 63 boreholes with a log and geological descriptions have been identified within the Study Area, where the location of these boreholes is presented in **Figure 2.4** and **Figure 2.5**. The available borehole logs come from the British Geological Survey (BGS) (25 boreholes, **Ref 21**), from a ground investigation (GI) survey (**Ref 25**) carried out during August 2020 (28 boreholes) and from a second ground investigation survey (**Ref 17, 18 and 19 and 22**) undertaken throughout 2022 (10 boreholes). The maximum drilled borehole depths within the Study Area varies between approximately 20m to 60m. A summary of the borehole characteristics (completion date, coordinates, elevation, screen position, etc.) is available in **Sub Appendix A: Borehole Information** (Document reference 3.12.05a).

2.4.3 The borehole logs indicate that the thickness of the superficial deposits can range from 0.2m (Borehole TG11SW157, approximately 850m south-east of the proposed viaduct) to 33.2m (Borehole TG11NW054, approximately 2000m north of the proposed viaduct) within the model boundary. The White Chalk Subgroup underlies the superficial deposits. None of the borehole logs intercept the bottom elevation of this subgroup, however, BGS map sheet 161 indicates that the total thickness of the White Chalk Subgroup could be up to 270m (**Ref 3**).

2.5 Hydrogeology

Aquifer types and Properties

2.5.1 The Head Deposits, the Alluvium, the River Terrace Deposits and The Sheringham Cliffs Formation are all mostly Secondary A Aquifers, where a Secondary A Aquifer is defined as permeable layers capable of supporting water supplies at a local scale (**Ref 20**). Towards the south, the Sheringham Cliffs Formation is designated as a Secondary B Aquifer, where this is defined as an aquifer with low permeability layers which may store and yield limited amounts of groundwater from fissures and thin permeable layers (**Ref 20**).

2.5.2 The White Chalk Subgroup generally has a high permeability, predominantly through fracture flow and is used for groundwater abstraction in the region. The Chalk is designated by the Environment Agency (EA) as a Principal Aquifer (**Ref 20**). A Principal Aquifer is defined as layers of rock that have high intergranular and / or fracture permeability with high levels of water storage, where the aquifer tends to support water supply and / or river base flow on a strategic scale.

2.5.3 **Table 2.2** summarises the main geological units present on site in addition to ranges of hydraulic conductivities deduced from Particle Size Distribution tests obtained during the Norfolk Partnership Laboratory (2020) ground investigation and literature review (**Ref 1 and Ref 6**).

Table 2-2 Hydraulic conductivity

Formation	Description	Aquifer Designation	Horizontal hydraulic conductivity (K_h)(m/d)
Head Deposits	Poorly sorted and poorly stratified units with subangular to sub-rounded sand, gravel, and clays.	Secondary A Aquifers and Secondary B Aquifers	0.078 - 518.40 (**Ref 6**)
Alluvium	Consists of soft to firm consolidated, compressible silty clay, but can contain layers of silt, sand, peat, and basal gravel.	Secondary A Aquifers	0.017 - 25.92 (**Ref 6**) 0.89 (deduced from 1 PSD test)

Formation	Description	Aquifer Designation	Horizontal hydraulic conductivity (K_h)(m/d)
River Terrace Deposits	Sand and gravel, locally with lenses of silt, clay, or peat.	Secondary A Aquifers	0.078 - 518.40 (**Ref 6**)
Sheringham Cliffs Formation	Sand units vary between orange, light brown, brown, light grey and grey in colour and fine to coarse subangular to sub-rounded sand with grey silt.	Secondary A Aquifers, Secondary B Aquifers	0.078 - 43.20 (**Ref 6**) 1.6 – 80 (deduced from 59 PSD tests)
White Chalk Subgroup	Chalk with flints. With discrete marl seams, nodular chalk, sponge-rich and flint seams throughout	Principal Aquifer	0.01 – 10.00 (Reed et al., 2017)

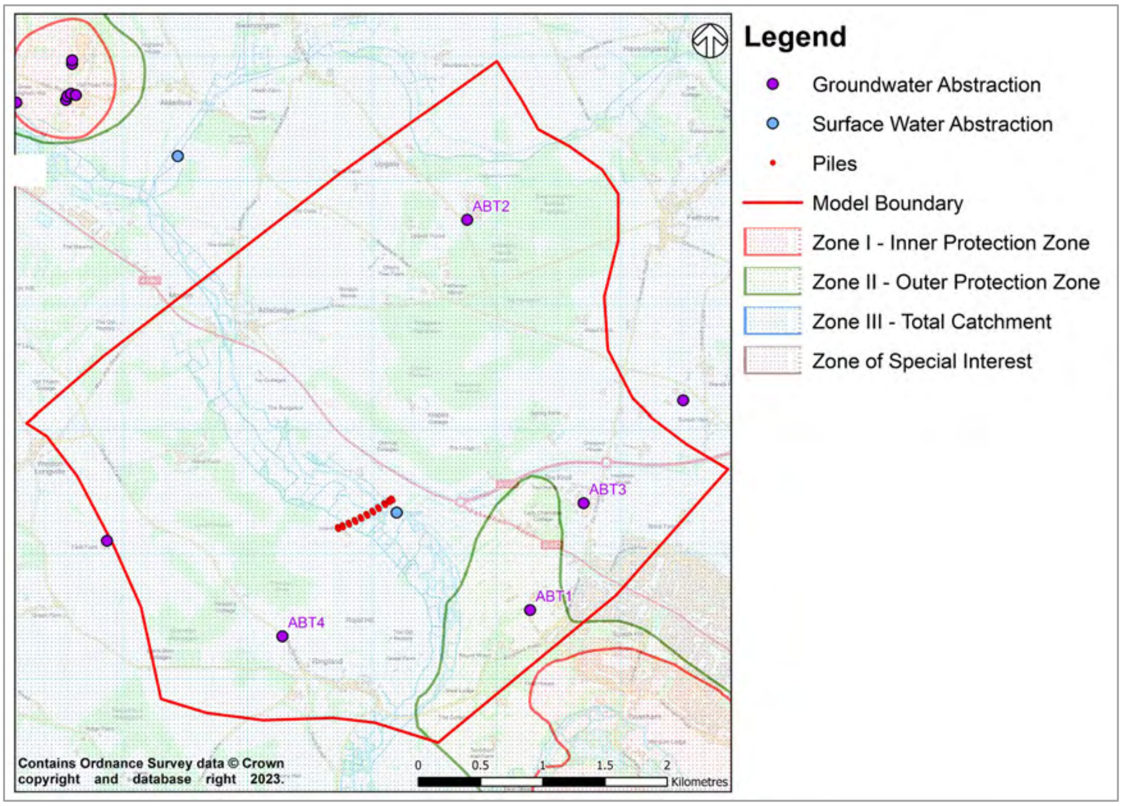
Table Notes: Hydraulic conductivity ranges interpreted from hydraulic conductivity ranges of unconsolidated sedimentary materials given by Domenico and Schwartz (1990) (**Ref 6**), Reed et al. (2017) (**Ref 26**) and Particle Size Distribution tests (PSD) completed by Norfolk Partnership Laboratory (2020) (**Ref 24**).

2.5.4 The groundwater system, because of its deposition mechanism, is expected to be anisotropic (especially the superficial deposits) and a ratio between the vertical hydraulic conductivity (Kv) and horizontal hydraulic conductivity (Kh) of 1:10 can be assumed reasonable.

2.6 Groundwater abstraction

2.6.1 The majority of the Study Area is located within a total catchment Source Protection Zone (SPZ) 3 (**Figure 2.6**), where a total catchment SPZ 3 is defined as the area around a source within which all groundwater recharge is presumed to be discharged at the source. The outer protection SPZ 2 is located within the Study Area towards the southeast, where this is defined by a 400-day travel time from a point below the water table. The inner SPZ 1s are situated just outside the Study Area towards the northwest and southeast. These inner SPZ 1s are defined as having a 50-day travel time from any point below the water table to the source and has a minimum radius of 50m (**Ref 20**).

Figure 2.6 Source protection zones and private abstractions



2.6.2 A total of 4 private abstraction boreholes have been identified within the Study Area and the location of these boreholes are presented in **Figure 2.6**. The total licensed pumping rate is approximately 617m^3/d, which has been deduced from data provided by the Environment Agency (received from Environment Agency April 2023). **Figure 2.6** also shows an unlabelled abstraction adjacent to the piles, where this abstraction targets surface water from the River Wensum.

Table 2-3 Abstraction boreholes within Study Area, as shown on figure 2.6

Name	Purpose	Target	Licensed Annual Yields (m^3/year)	Licensed Daily Yields (m^3/day)
ABT1	Industrial, Commercial and Public Services	Chalk Aquifer	13,636	37.36
ABT2	Agriculture	Chalk Aquifer	10,000	27.40
ABT3	Agriculture	Chalk Aquifer	2,300	6.30
ABT4	Agriculture	Chalk Aquifer	199,389	546.27

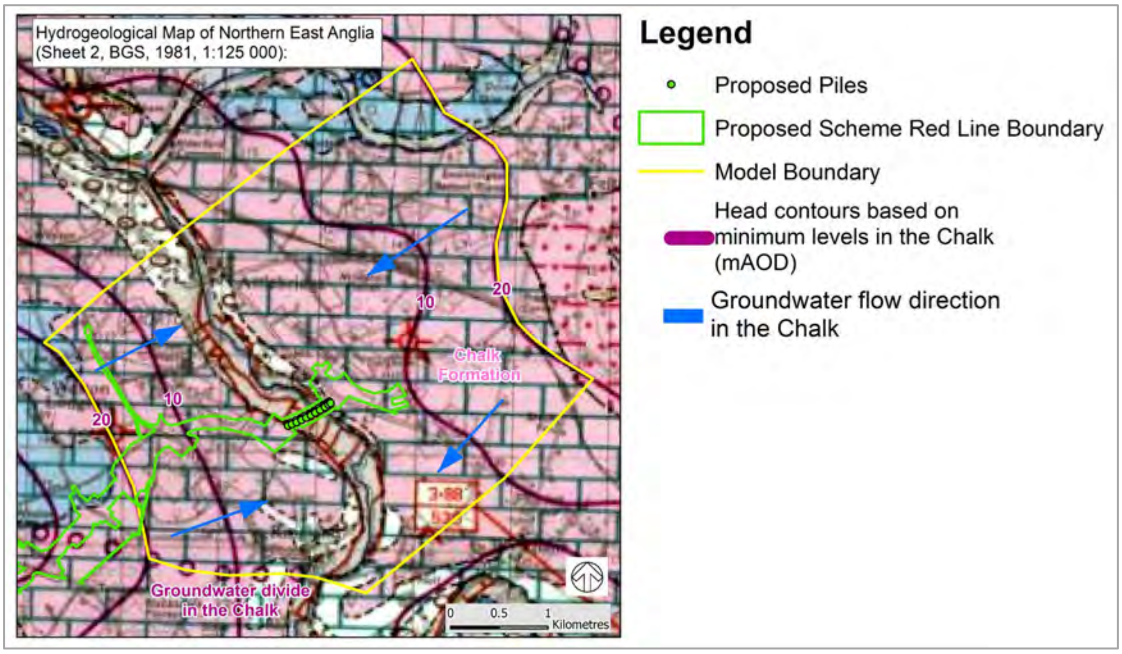
2.7 Groundwater levels

2.7.1 The Hydrogeological Map of Northern East Anglia (**Ref 14**) has been used in a first instance to understand the regional hydrogeological system which led to the definition of the Study Area. As presented in **Figure 2.7**, the map shows groundwater head contours associated with the Chalk aquifer based on minimum levels.

2.7.2 The boundaries of the Study Area and the numerical model have been defined based on the hydrogeological map and follow the 20mAOD groundwater level elevation to the northeast and southwest, a groundwater divide to the south and flow lines to the north and southeast. The 20mAOD groundwater contour is considered to be sufficiently distant from the area of interest such that any groundwater level inaccuracy at the boundary is unlikely to influence the groundwater modelling results on site.

2.7.3 Within the proposed viaduct and surrounding area, the piezometric map associated with the Chalk shows a general groundwater flow from the southwest and northeast towards the River Wensum, with groundwater levels below 10mAOD near the river. In the valley, where the River Wensum is located, the Chalk is expected to be in hydraulic continuity with shallow groundwater in the superficial deposits. Along the valley, generally the groundwater is assumed to discharge from the Chalk to the superficial deposits and part of it is expected to form the river baseflow.

Figure 2.7 1:125 000 Hydrogeological map of North East Anglia (Ref 14) with annotations



2.7.4 Groundwater level data near the River Wensum was initially recorded as part of a ground investigation undertaken during October 2020 to the north of the proposed viaduct, where most of the boreholes had nested dual piezometers targeting the shallow superficial deposits and the deeper chalk bedrock separately. In most cases, the groundwater levels were found to be similar between the deep and shallow piezometers, with either no difference in levels or a difference of up to a few centimetres with levels in the superficial deposits being slightly higher than those in the Chalk (indicating a local downwards gradient).

2.7.5 Additionally, a groundwater level monitoring campaign was carried out by NCCs monitoring team within the area of the proposed viaduct recording groundwater monitoring data between January 2022 to February 2023. For the purpose of this study only December 2022 data was used in the model as this data was recorded the day after the surface water level data and can therefore be used for comparison. **Table 2.4** summarise the boreholes monitored, their characteristics and groundwater levels recorded on December 13th, 2022.

Table 2-4 Groundwater levels monitoring network during December 13th, 2022

Name	X	Y	Ground elevation (mAOD)	Screen From (mAOD)	Screen to (mAOD)	Monitored unit	Groundwater depth (mbgl)	Groundwater elevation (mAOD)
BH210d	614081	315394	9.20	9.46	22.14	White Chalk Subgroup	0.41	8.79
BH210s	614081	315394	9.20	9.46	22.14	River Terrace Deposits	0.77	8.43
BH221	613831	315254	8.89	8.99	20.70	White Chalk Subgroup	0.17	8.72
BH226	613718	315233	11.50	12.1	19.99	River Terrace Deposits	2.69	8.81
BH231	613306	315141	25.08	24.79	22.52	White Chalk Subgroup	16.19	8.89
BH260	613308	315168	24.63	26.01	23.45	White Chalk Subgroup	15.79	8.84

Name	X	Y	Ground elevation (mAOD)	Screen From (mAOD)	Screen to (mAOD)	Monitored unit	Groundwater depth (mbgl)	Groundwater elevation (mAOD)
BH233	613205	315202	29.67	31.11	26.11	White Chalk Subgroup	20.89	8.78

2.7.6 As presented in **Table 2.4** one borehole (BH210) consists of nested piezometers meaning that both the superficial deposits (s) and the Chalk (d) are monitored at a same location. The monitoring boreholes are also presented in **Figure 2.8** and **Figure 2.9**, along with conceptual piezometric maps associated with the superficial deposits and the Chalk respectively which have been deduced from the December 2022 monitoring data (**Sub Appendix A: Borehole Information** (Document reference 3.12.05a)) and the general hydrogeological understanding of the site area including knowledge gained from the 2020 monitoring.

Figure 2.8 Piezometric map associated with the superficial deposits (December 13th, 2022)

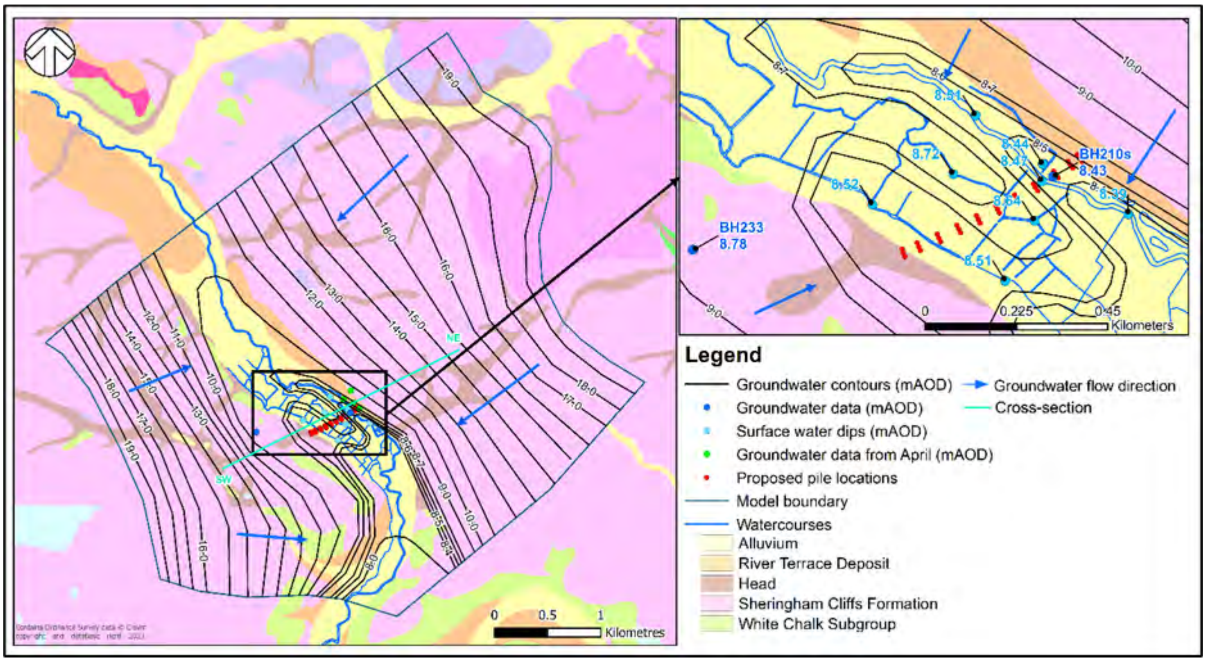
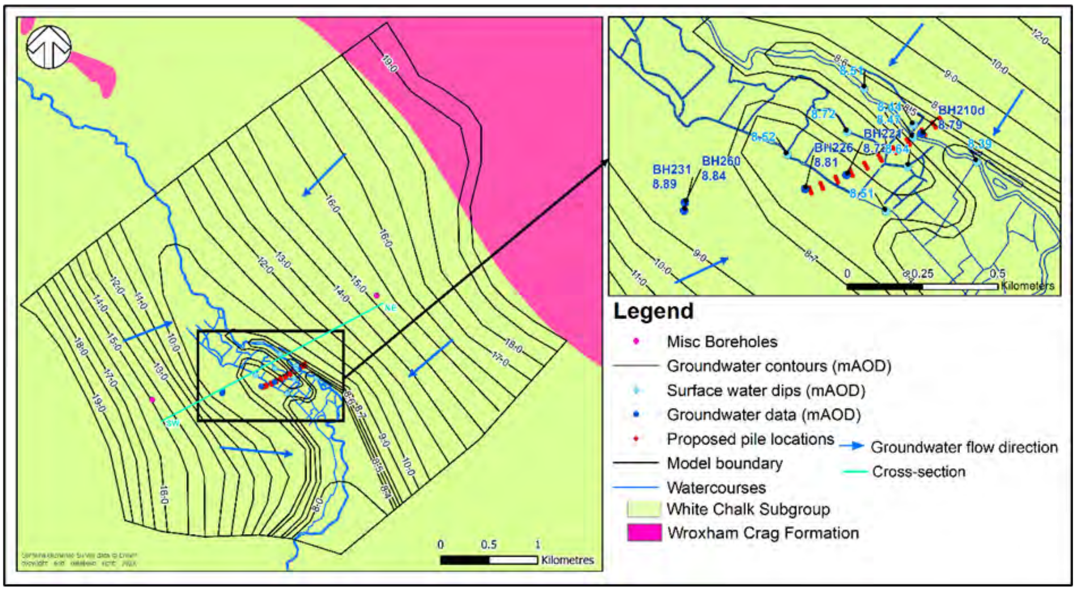


Figure 2.9 Piezometric map associated with the Chalk (December 13th, 2022)



2.7.7 As presented in **Table 2.4** and **Figure 2.9**, the groundwater levels are shallow in the floodplain area, and during the December 2022 monitoring round were found to be generally less than 1m below ground surface, with levels at ground level in the case of BH226 and BH210. Further away from the floodplain, the Chalk groundwater levels were deeper with values of 16.19mbgl in BH231 and 15.79mbgl in BH260.

2.7.8 **Table 2.5** shows the change in groundwater levels in the shallow and deep piezometers in borehole BH210 between July and December 2022, where the shallow piezometer targets the superficial deposits, and the deep piezometer targets the Chalk. The data suggests that the vertical head gradient fluctuates, for example in July and November the head in the deeper piezometer is less than the shallow piezometer, suggesting groundwater is moving from the superficial deposits into the Chalk. Other times of the year (e.g., September and December) the head in the deeper piezometer is greater than the shallow piezometer, indicating an upward flow gradient. Although the groundwater systems in the superficial deposits and in the Chalk are not in complete equilibrium, the measured hydraulic gradients together with the geological descriptions indicate substantial vertical groundwater connectivity between the hydrogeological units and the surface water features.

Table 2-5 Groundwater levels from BH210 shallow (s) and deep (d) between July and December 2022

Name	Elevation (mAOD)	Water Level (mAOD) 19/07/2022	Water Level (mAOD) 23/08/2022	Water Level (mAOD) 23/09/2022	Water Level (mAOD) 20/10/2022	Water Level (mAOD) 14/11/2022	Water Level (mAOD) 13/12/2022
BH210s	9.20	8.60	Not applicable	8.60	8.34	8.38	8.43
BH210d	9.20	8.53	8.75	8.79	8.34	7.83	8.79

2.7.9 The piezometric maps presented in **Figure 2.8 and Figure 2.9** have been deduced from the groundwater and surface water level data and indicate a similar behaviour for both groundwater systems (in the superficial deposits and in the Chalk), showing a general groundwater flow towards the River Wensum and the drainage system associated with its floodplain. The superficial deposits are expected to be in direct connection with the river and the drainage system, influencing the groundwater levels in the vicinity of these surface water features. There is generally a good correlation between the monitored groundwater levels in the Chalk and the head contours associated with the Hydrogeological Map of North East Anglia (**Figure 2.7**).

2.7.10 The hydraulic gradient is low to flat in the floodplain area, as presented in **Figure 2.9**. It has not been possible to assess the hydraulic gradient further away from the viaduct area considering the lack of groundwater monitoring points, but regional groundwater flow conditions are considered sufficiently well understood for the purpose of this study making use of information from the hydrogeological map and the EA's regional groundwater model (**Ref 26**).

Hydrogeological Conceptual Site Model

2.7.11 The wider Study Area consists of two main aquifers: the superficial deposits (upper aquifer) and the Chalk (regional aquifer). The upper aquifer consists mostly of the Sheringham Cliffs Formation, the River Terrace Deposits, and the Alluvium. These formations have similar compositions but with varying proportions and thicknesses of sand, silt, and clay, although it has not been possible to identify a clear difference between the formations in the borehole logs. The Alluvium is expected to have a greater proportion of fine material in comparison and the River Terrace Deposits are expected to comprise mainly coarse sediments. Regarding the regional aquifer (Chalk), it is expected that the upper part of the Chalk is more fractured and weathered than the deeper part, such as described by Allen et al. (1997) (**Ref 1**), although it was not possible to verify this assumption in the borehole logs. A weathered zone with a thickness of 5m has been assumed in the numerical model.

2.7.12 The hydraulic conductivity of the superficial deposits is expected to vary from a few m/d to several tens of m/d, depending on the strata and its content in fines particles. The hydraulic conductivity of the weathered upper part of the White Chalk is expected to be higher than its more compact lower part but is highly dependent on fractured zones.

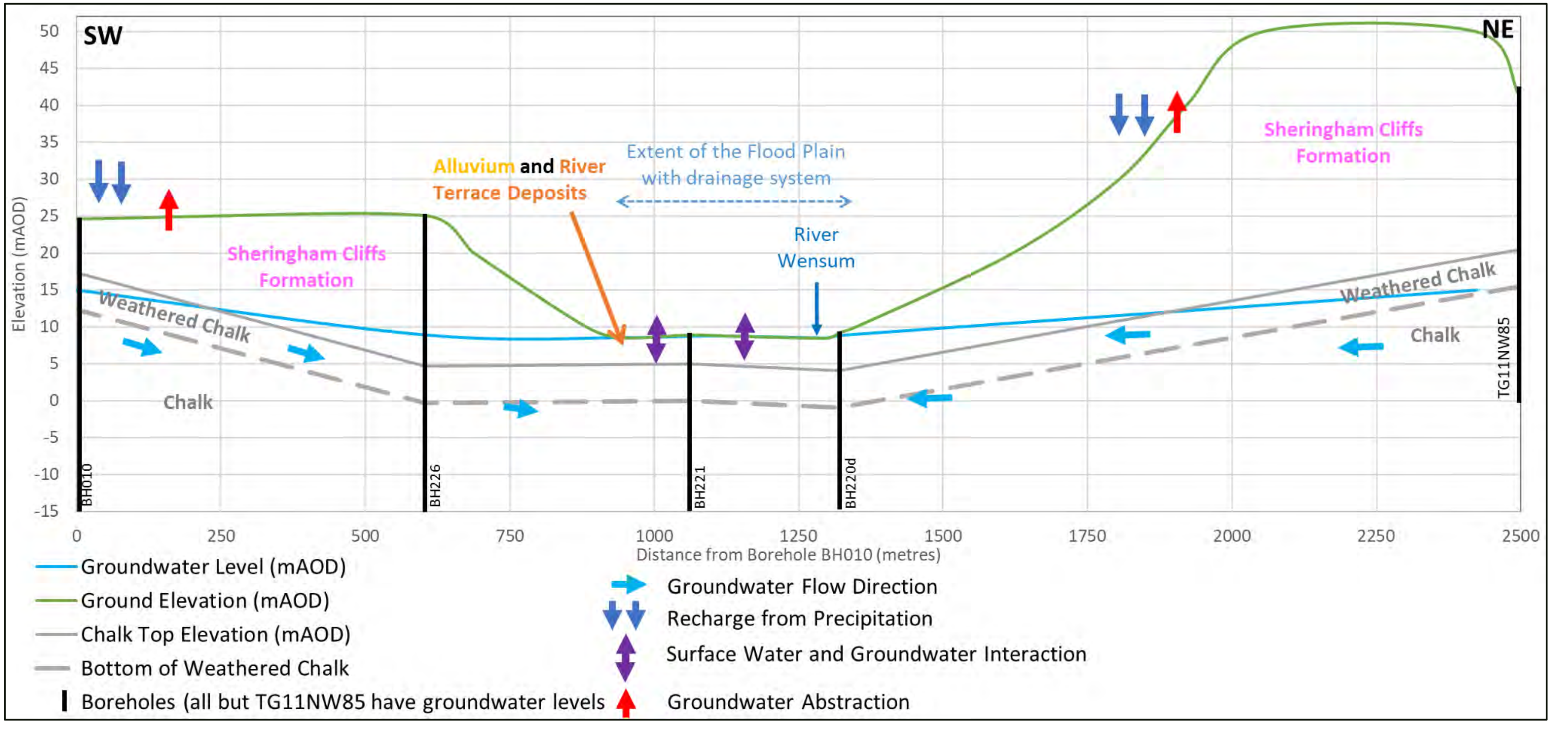
2.7.13 The system is expected to be recharged by the infiltration of a portion of the precipitation, through the unsaturated zone.

2.7.14 The main groundwater receptor for both main aquifers is the River Wensum and the drainage system associated with its floodplain. Groundwater flow is expected to be predominantly horizontal and intergranular in the upper aquifer, whereas it is expected to occur predominantly through fractures in the Chalk aquifer. The groundwater gradient in the flood plain is very low, and almost flat between the river and drainage system. Groundwater abstractions also act as groundwater sinks.

2.7.15 Both aquifers seem to be hydraulically well connected and vertical flow is expected to occur between them, especially in the River Wensum valley. The Chalk aquifer is expected to provide important baseflow to the River Wensum under low surface water flow conditions, whereas, as observed during the October 2020 and July and November 2022 monitoring round, there are times where surface water and connected shallow groundwater levels are higher than the deep groundwater levels which leads to temporary loss of surface water into the ground (groundwater recharge). This connectivity between surface water, shallow and deep groundwater forms an important buffer system for the River Wensum flows.

2.7.16 **Figure 2.10** presents a schematic hydrogeological conceptual model of the Study Area.

Figure 2.10 Schematic hydrogeological conceptual site model (for the purpose of this figure, only the groundwater levels associated with the Chalk have been considered)

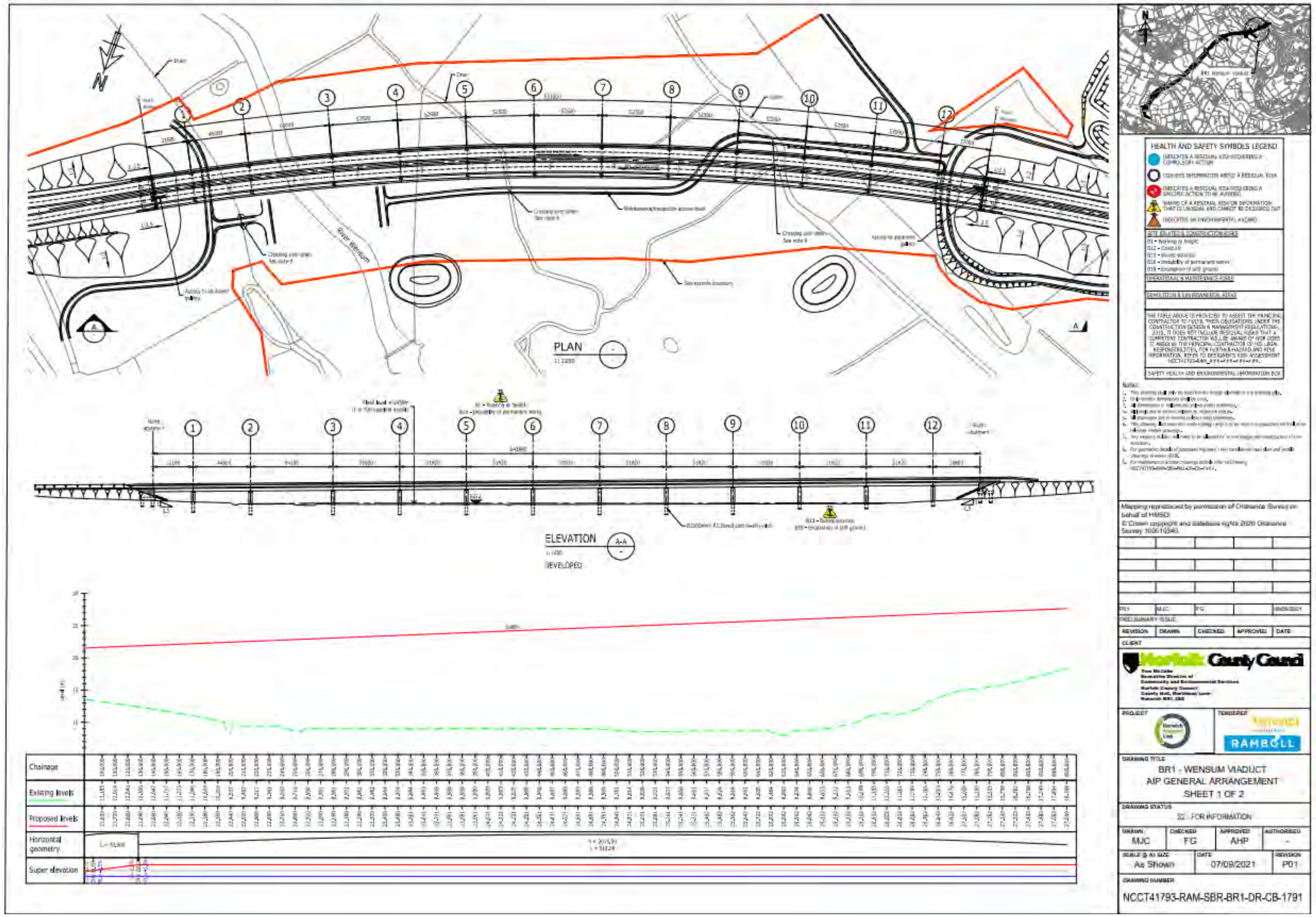


3 Viaduct design

3.1.1 The main characteristics of the proposed River Wensum Viaduct foundation design are presented in **Figure 3.1**. Below ground, the proposed viaduct design consists of 12 rows with 3 piles in each row. Each pile is expected to have a diameter of approximately 2.1m and a depth of approximately 50m.

3.1.2 The pile material is expected to be of very low hydraulic conductivity and is therefore going to lower the overall hydraulic conductivity of the ground within the viaduct area. When the hydraulic conductivity of the ground decreases, it is more difficult for the groundwater to flow through it and the groundwater level may consequently rise locally. There is therefore a risk that the implementation of the piles could generate an increase in groundwater levels in the viaduct area.

Figure 3.1 Proposed River Wensum Viaduct foundation design

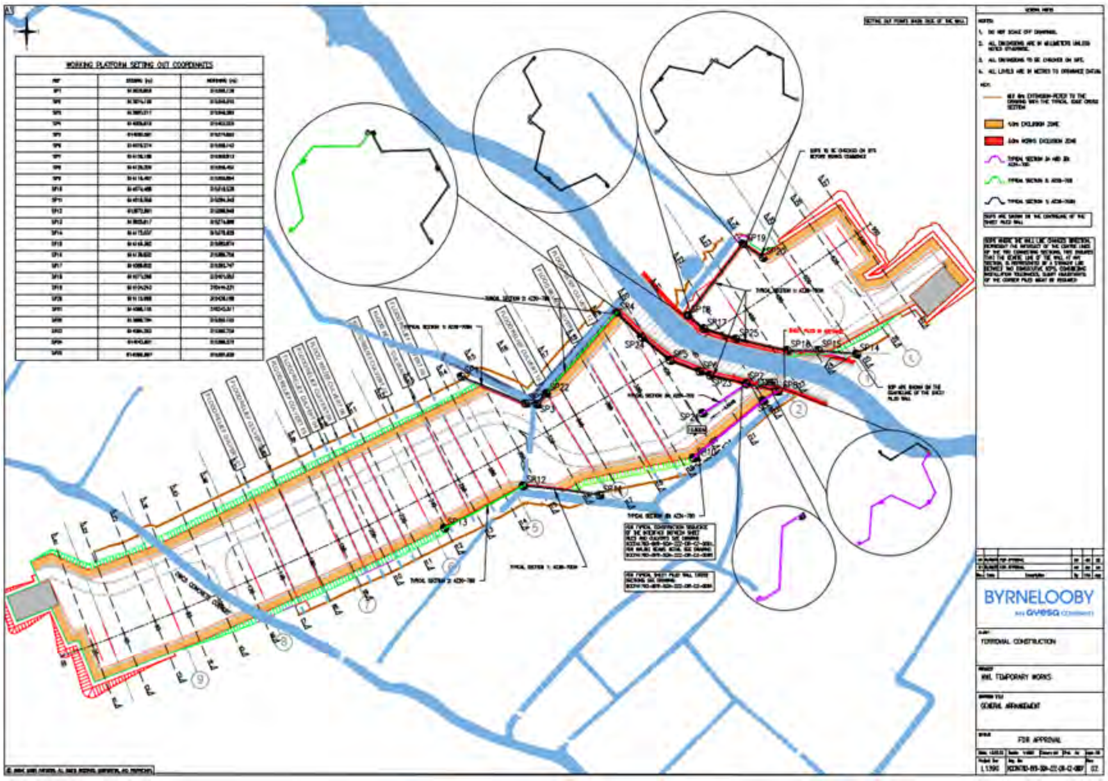


4 Temporary Works Platform

4.1 Overview of Temporary Works Platform

4.1.1 During the construction stage a Temporary Works Platform would be required to enable the construction of the viaduct over the River Wensum. This extends across the floodplain of the River Wensum. The platform would be up to two metres thick (below current ground level) and is raised above the current ground level to mitigate against surface water flooding. Where soft peaty soil has been identified below ground surface this is expected to be removed and replaced by the engineered fill material to improve the stability of the platform (material type 6A when below groundwater). Engineered fill type 6A is a granular material and is defined as a selected and well-graded granular fill, which primarily consists of crushed stone particles with a size of 500mm, and is the only aggregate that can be used underwater (**Ref 33**). A plan showing the proposed design of the Temporary Works Platform is included below as Figure X.1. The platform design aims to avoid surface water pathways as these have been found to be fundamental for the local groundwater level control. Where avoidance of such a feature was not possible, the existing surface water drainage channel (Water Course 5) is expected to be culverted to maintain hydraulic connection. Additional culverts are included in the design for flood protection purposes which are not discussed as part of this document (Appendix 2: Flood Risk Assessment (Document reference 3.12.02)). Sections of deep sheet piling would be required during construction, but sheet piles are designed to be removed at the end of the construction stage. The objective of this section is to assess the potential impact the Temporary Works Platform elements may have on surface water and groundwater levels, flow, and hydraulic connectivity across the platform area.

Figure 4.1 Proposed Temporary Works Platform general arrangement



4.2 Local Ground and Water Conditions

4.2.1 The soil survey (**Ref 30**) undertaken at the location of the proposed Temporary Works Platform in 2022 indicated two main types of soil were present in the area. This included a peat loam or a loamy peat subsoil (where organic matter ranged between 12% and 36.7%) and the second is a soil where there is no peat present. Peat (a soil with over 50% organic matter content) was not detected. **Figure 4.2** shows the distribution by depth of these soil types. The peaty soil was shown to be localised and variable in thickness, generally being surrounded by sand and gravel.

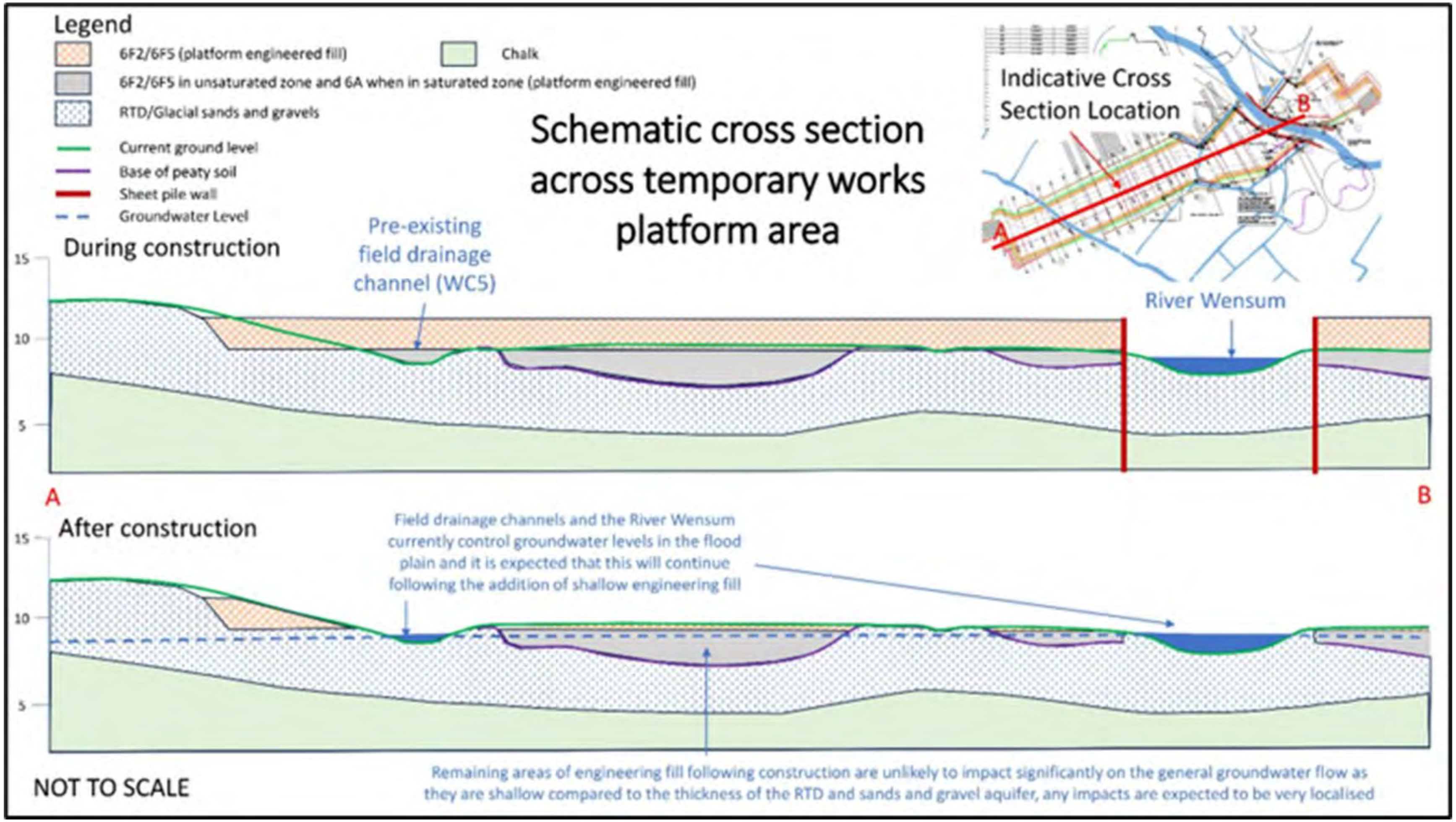
Figure 4.2 Soil distribution at the location of the proposed Temporary Works Platform (Ref 30)

4.2.2 Figures 2.8 and 2.9 show groundwater level contour plots describing the groundwater regime in the superficial deposits and the chalk bedrock respectively. Groundwater levels and surface water levels within the River Wensum floodplain are at similar levels, suggesting a high degree of connectivity. The surface water levels average at 8.53 mAOD across the flood plain and the River Wensum on 12th December 2022 (Figure 2.3) and the groundwater levels in BH210s, which targets the superficial deposits within the flood plain, average at 8.47 mAOD across 5 data points (Table 2.5). The flood model produced for the proposed Norwich Western Link (**Ref 31**) and the low flows derived from the Costessey gauge (**Ref 32**) were used to derive River Wensum mean levels, which are at 8.5 mAOD at the proposed viaduct location and where the river bed level are between 7.16 and 7.30 mAOD. This suggests a general connection between groundwater and surface water across the floodplain since all levels are similar (small variations exist due to the timing and location of data). As described in Section 2.7, surface water and groundwater form a substantial buffer system influencing the river flow and groundwater levels. It is fundamental to avoid that this buffer system deteriorates, that means the hydraulic connectivity between these water resources needs to be maintained or enhanced to protect the water environment and related habitats.

4.3 Conceptual Site Model

4.3.1 A schematic conceptual cross section of the Temporary Works Platform during and after construction is presented in Figure 4.3 below. As described above the River Wensum and the drainage channels control groundwater levels across the floodplain. Following the addition of the engineered fill, the groundwater is expected to remain connected to surface water levels in the River Wensum and associated drainage channels. After construction the majority of the fill would be removed to return ground levels to their previous elevation. The remaining areas of engineered fill below the ground surface, after construction, is not expected to impede surface water and groundwater interaction due to the granular nature of the material.

Figure 4.3 Schematic cross section across Temporary Works Platform area



4.4 Potential Impacts from Temporary Works Platform

4.4.1 Potential impacts associated with the Temporary Works Platform are summarised in **Table 4-1**.

4.4.2 During construction, the engineered fill associated with the Temporary Works Platform is not expected to impact surface water and groundwater flows, due to the permeable nature of the material used in the saturated zone. Impacts to groundwater and surface water in this phase are expected to be localised, minor and temporary. Additional drainage is included in the design to mitigate against any groundwater rise caused by the sheet pile walls associated with the Temporary Works Platform, and all sheet pile walls would be removed after construction.

4.4.3 After construction the remaining areas of engineered fill below ground surface are thought to be unlikely to have a significant impact on groundwater levels and flow in the flood plain. As represented in Figure 4.3 the remaining fill is shallow compared to the thickness of the sand and gravel superficial aquifer and its granular properties ensure good hydraulic connectivity laterally and vertically (Figures 4.2 and 4.3). Any impacts on groundwater and surface water as a result of the Temporary Works Platform are therefore expected to be localised and minor, and it was therefore not felt necessary to represent the Temporary Works Platform when constructing the numerical groundwater model.

Table 4-1 Potential impacts to groundwater from the Temporary Works Platform

Feature	Period	Impact	Comments and Mitigation included in design
Sheet piling	Construction	Expected to penetrate the Chalk and create a groundwater flow barrier in the superficial and Chalk aquifers. Groundwater levels and flow direction are only altered locally and temporarily as drainage features ensure that groundwater levels outside the construction area remain unchanged.	Temporary drainage to mitigate against the risk of flooding. Sheet piles are removed after construction.
Engineered fill	Construction	Engineered fill is shallow and permeable and is therefore not expected to significantly alter groundwater and surface water flow and interaction.	Culverts would be included where Temporary Works Platform crosses drainage channel

Feature	Period	Impact	Comments and Mitigation included in design
Construction dewatering	Construction	Any dewatering required for the Temporary Works Platform construction or sheet piling is expected to be minor due to the shallow depth of the Temporary Works Platform, and would therefore be temporary with only a local impact.	Abstraction license and discharge permits are standard mechanisms to avoid unacceptable impacts on receptors. No large scale and long-term dewatering is proposed.
Residual Engineered fill	Operation	Remaining engineered fill is shallow and permeable and is therefore not expected to significantly alter groundwater and surface water flow and interaction.	Drainage system is controlling local groundwater levels and would ensure that on and off site water levels remain within preconstruction levels.

5 Steady state numerical model construction

5.1 Introduction

5.1.1 The hydrogeological conceptual model described in Section 2 forms the basis of a numerical groundwater flow model developed with the code MODFLOW-USG and the graphical interface Groundwater Vistas (v7). This Section focuses on the description of the numerical model. Objective of the model was to simulate the expected change in groundwater levels following the construction of the proposed viaduct foundation piles. Considering that groundwater levels are very shallow throughout the year, only steady state conditions (i.e. representative average conditions) have been simulated.

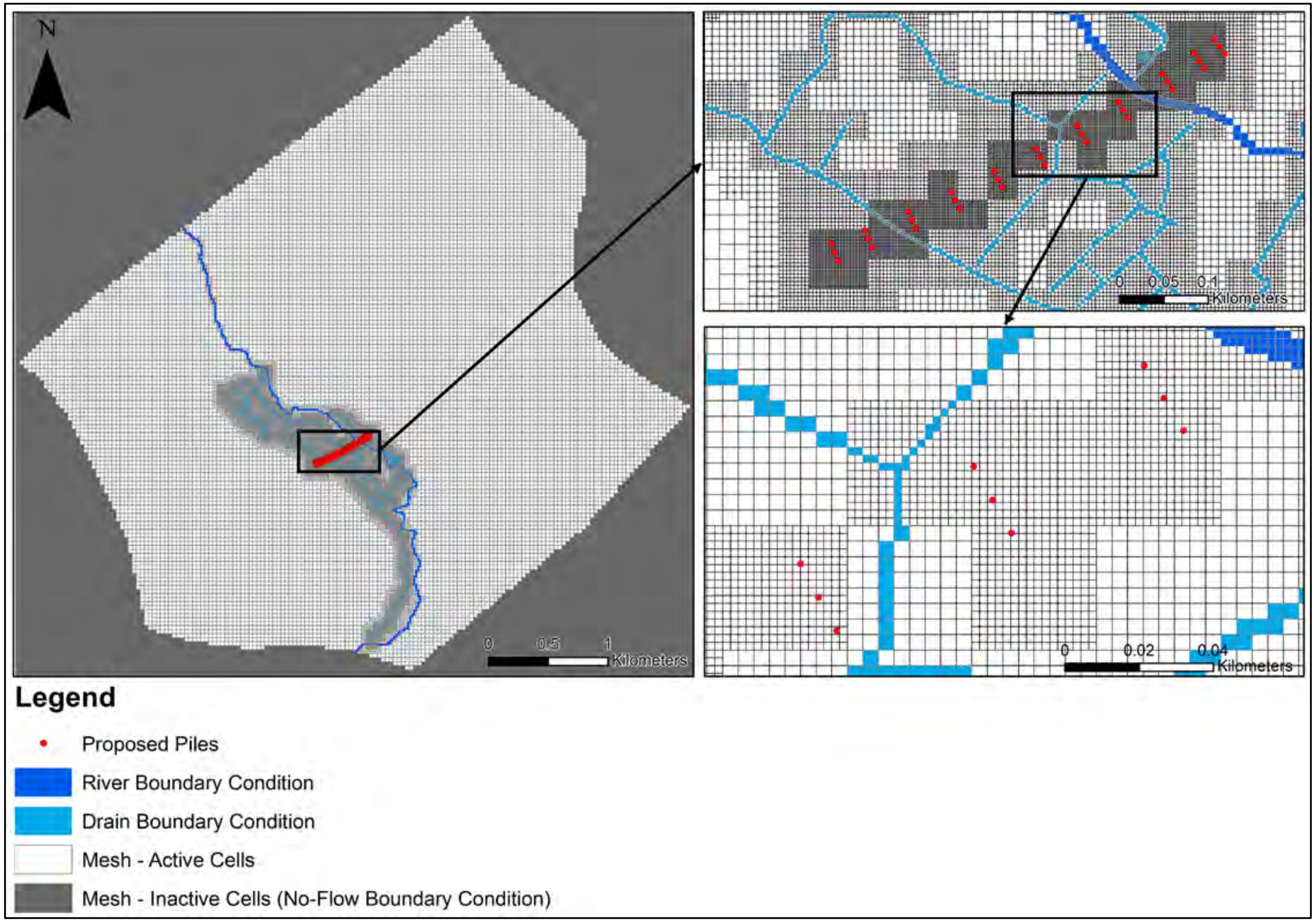
5.2 Model domain and mesh

5.2.1 The model domain and grid are presented in **Figure 5.1**. The model domain and boundaries are consistent with the wider Study Area described above (**Figure 2.1**). Within the model boundary are the active cells, whereas outside the boundary, cells in the numerical model are no-flow cells. The active area is approximately 4.5km in length by 4.5km wide.

5.2.2 A quadtree mesh has been used for the model, optimising the number of cells and therefore the running times, with greater refinement in the areas of interest and larger cells further away where data is scarce.

5.2.3 The cells size varies from 2.1 m x 2.1 m in the viaduct area, which is consistent with the proposed piles dimensions (Section 3), to 33.6 m x 33.6 m further away from the viaduct area.

Figure 5.1 Numerical model domain and mesh



5.3 Vertical discretisation

5.3.1 The model consists of three layers and the characteristics of each layer are summarised in **Table 5.1**.

Table 5-1 Vertical discretisation of the numerical model

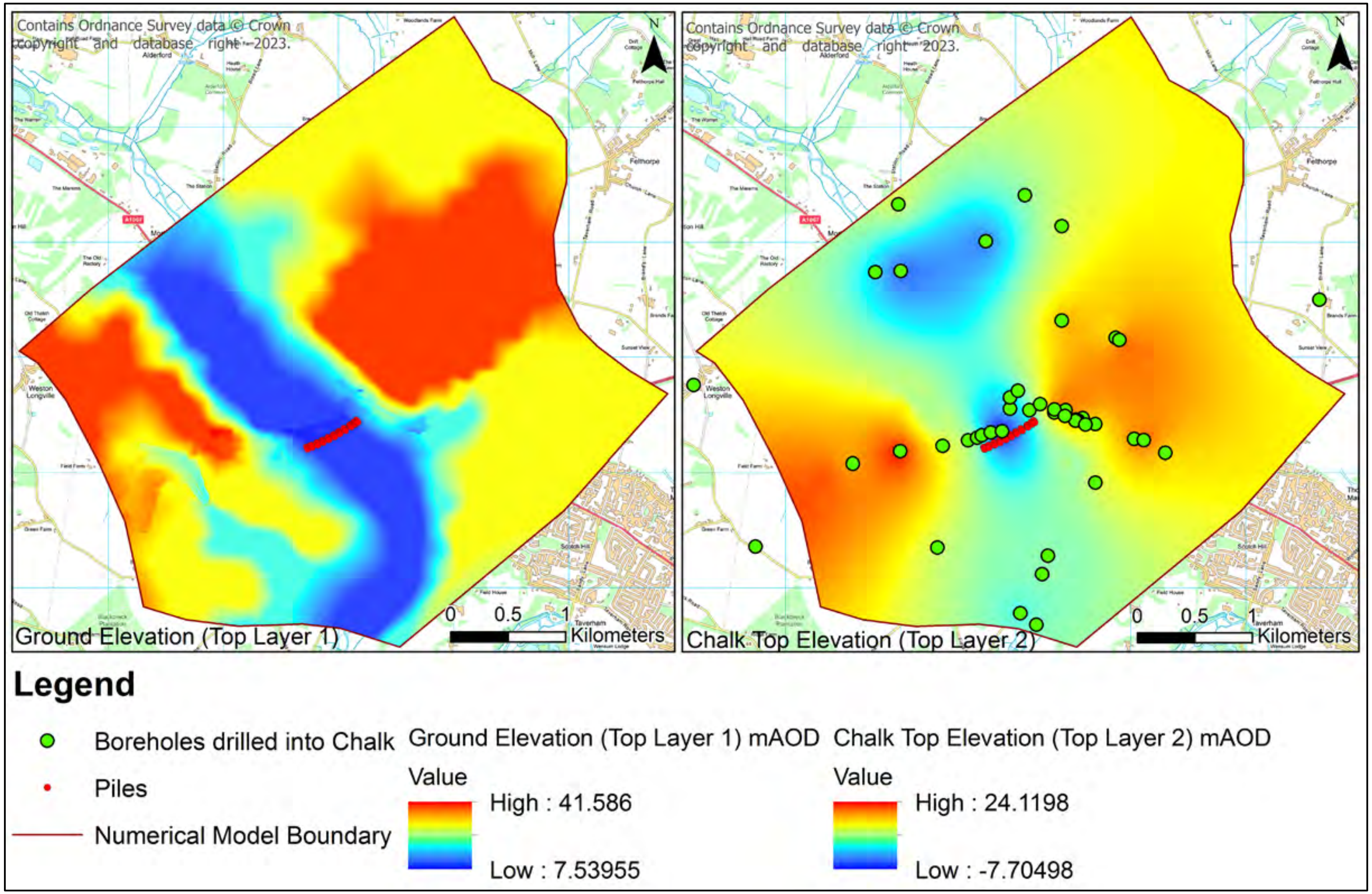
Layer	Aquifer	Hydrogeological Units / Formation	Thickness (m)
1	Shallow aquifer	Alluvium, River Terrace Deposits, Sheringham Cliffs Formation	Min: 1 Max: 35 Average: 9.7
2	Regional aquifer	Weathered Chalk	5
3	Regional aquifer	Fresh Chalk	45

5.3.2 For the top of layer 1 (representing the ground elevation), an elevation grid based on the OS map topographic contours and the detailed topography survey carried out by WSP has been built, as presented **Figure 5.2**. The top elevation of layer 1 varies between approximately 42mAOD to the southwest of the River Wensum and 8mAOD in the viaduct area, next to the river.

5.3.3 The top of layer 2 represents the contact between the superficial deposits and the underlying Chalk bedrock. An elevation grid has been created by interpolating the contact elevation between these two units observed in the borehole logs described in Section 2.4. Additionally, a few boreholes just outside of the Study Area have also been considered to better guide the surface. The grid has subsequently been manually adjusted to ensure that the top of the Chalk is always at least 1m below the top of layer 1. The grid elevation is presented in **Figure 5.2** and shows that the Chalk top elevation varies between approximately -8mAOD and 24mAOD.

5.3.4 Layers 2 and 3 have a constant thickness of 5m and 45m respectively.

Figure 5.2 Elevation of the top of layers 1 (ground elevation) and 2 (upper limit of the Chalk)



5.4 Boundary conditions

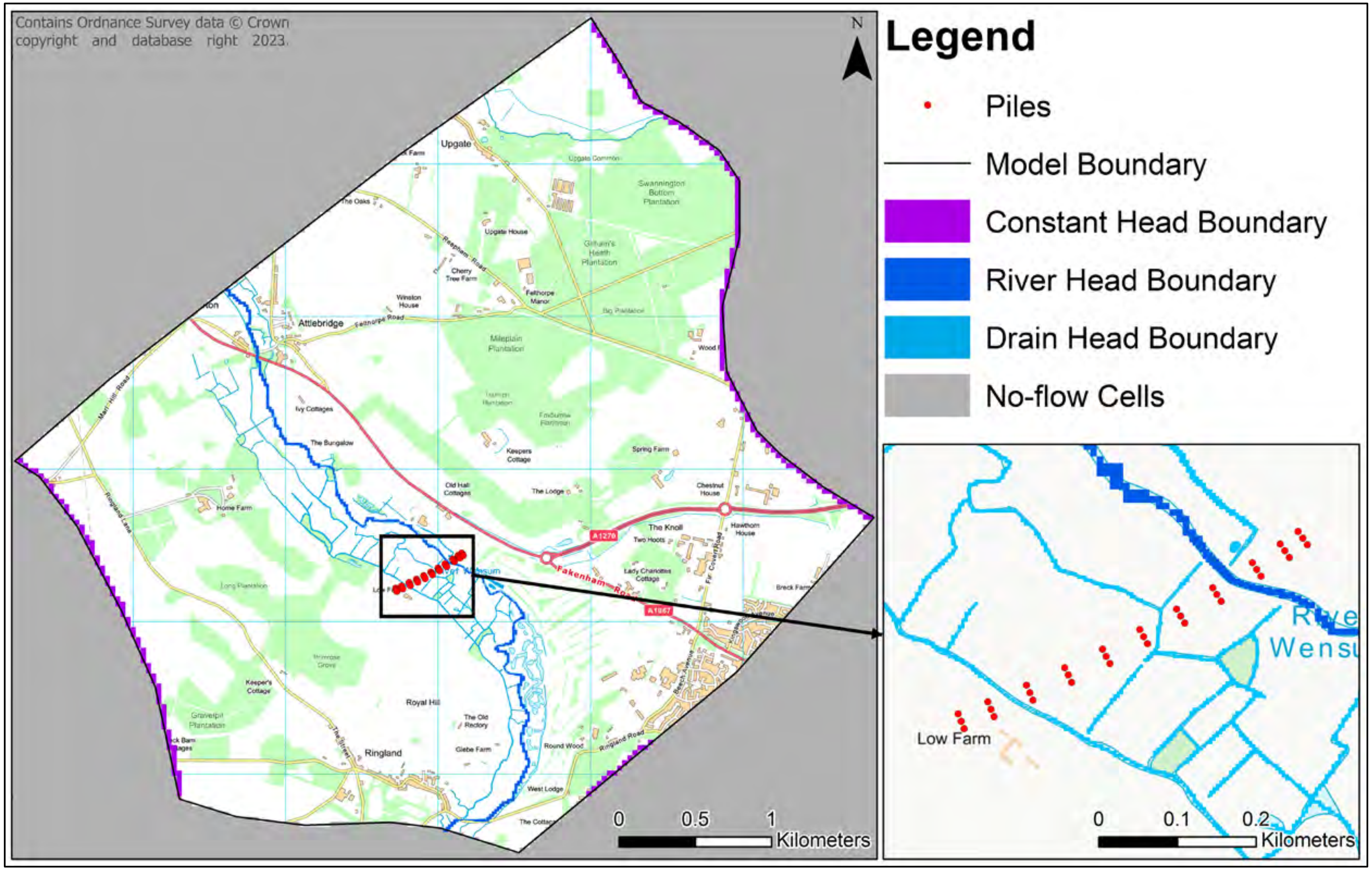
5.4.1 The boundary conditions, which are presented in **Figure 5.3**, are as follow:

- Constant head boundary condition to the east and west consistent with the groundwater level of 20mAOD obtained from the Hydrogeological Map of North East Anglia (**Ref 14** and **Figure 2.7**).
- Constant head boundary condition towards the south-east representing groundwater movement towards the Source Protection Zone (SPZ 1). Environment Agency groundwater monitoring borehole Beach Farm, located near the SPZ recorded a groundwater level of approx. 8mAOD on the 13th of December 2022 (**Ref 8**), which was used as a reference for the constant head boundary conditions. **Figure 2.7** shows the location of this constant head boundary towards the south-east set at 8mAOD.
- River boundary condition along the River Wensum. The stage of the river boundary condition in the cells has been defined based on the monitored values in the proposed viaduct area presented in Section 2.3 and the associated hydraulic gradient has been used to determine the river stage where the river enters the active area of the numerical model (9.15mAOD) and where it leaves it (7.75mAOD). Depending on the relationship between the groundwater elevation and the adjacent river stage, the river may lose water (river stage > groundwater level elevation, implying a flow from the river to the groundwater system) or gain water (river stage < groundwater level elevation, implying a flow from the groundwater system to the river). The width and length of the river in each cell is based on the cell dimensions, and a riverbed thickness of 0.5m and hydraulic conductivity of 100m/d have been assumed.
- Drain boundary condition to represent the drainage system in the floodplain area. The stage of the drains is defined based on monitored data shown in Section 2.3. The width and length of the drain in each

cell is based on the cell dimension, and a drain bed thickness of 1m has been assumed with a hydraulic conductivity of 100m/d. When the groundwater level is greater than the drain stage, then groundwater is released into the drain.

- The identified private abstraction boreholes have been represented in the model going through layers 2 and 3 (Chalk), representing a total pumping rate of approximately 617 m^3/d.
- No-flow cells surrounding the active area of the numerical model.

Figure 5.3 Model boundary conditions



5.5 Hydraulic parameters

5.5.1 The hydrogeological units defined in the conceptual model have been represented in the numerical model via hydraulic parameter zones as presented in **Figure 5.4**. The ranges of hydraulic conductivity values considered for each zone are summarised in **Table 5.2**. For simplicity, the Head Deposits and the Sheringham Cliffs Formation have been considered as one unit. The composition of the Head Deposits and the Sheringham Cliffs Formation are similar; therefore, they are characterised by the same hydraulic parameters. It should be noted that the model simulates only flow in the saturated zone, i.e. variable geology above groundwater table is not affecting the simulations.

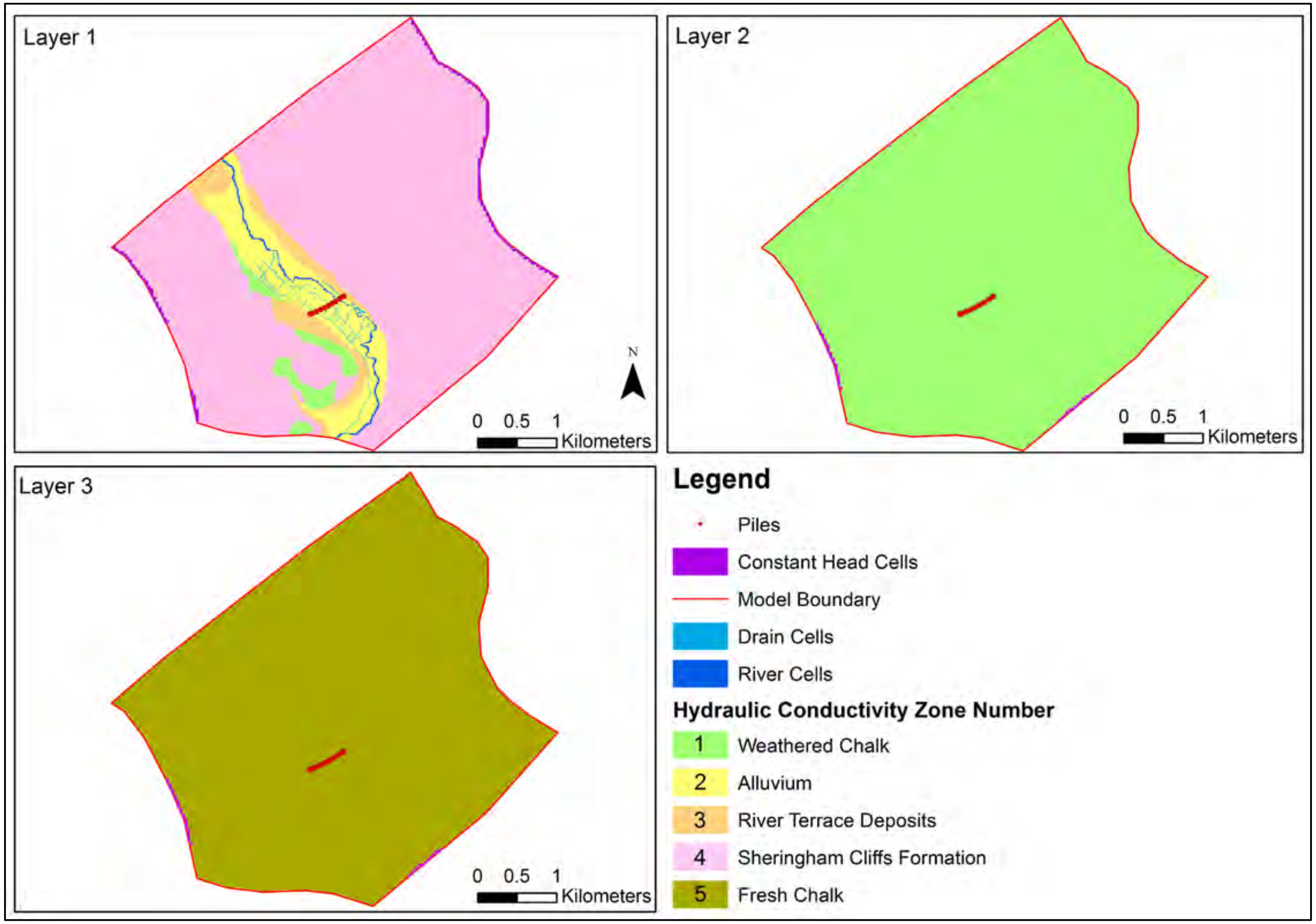
Table 5-2 Calibrated hydraulic conductivity (K) values for each hydrogeological unit

Zone N°	Layer	Aquifer	Hydrogeological Units / Formation	Min K_h (m/d)	Max K_h (m/d)	Calibrated K_h (m/d)
2	1	Shallow aquifer	Alluvium	0.1	50	3
3	1	Shallow aquifer	River Terrace Deposits	0.1	50	10
4	1	Shallow aquifer	Sheringham Cliffs Formation	0.1	80	0.1
1	1 & 2	Regional aquifer	Weathered Chalk	0.1	10	10
5	3	Regional aquifer	Un-weathered Chalk	1.0×10^{-3}	1	1

5.5.2 The hydraulic conductivity ranges considered for the numerical model (**Table 5.2**) are consistent with those presented in **Table 2.2** , with the exception that some of them have been slightly further restricted. In the case of the Chalk (weathered and un-weathered), most of the flow occurs through fractures and it is characterised by higher hydraulic conductivity values in fractured areas and low to very low values elsewhere. In the numerical model, this unit has been represented as an equivalent porous system and it has therefore been necessary to decrease the upper K_h value to represent more accurately the Chalk over the Study Area. In places, the hydraulic conductivity of the Alluvium and River Terrace Deposits can be higher or lower than the ranges proposed in **Table 5.2**, depending on the fine and coarse material content, but they have both been represented by one averaged hydraulic conductivity zone and do not account for the local heterogeneity of the units. The impacts of variable ground conditions on the modelling results has been addressed by sensitivity testing of the model results.

5.5.3 As mentioned in the Hydrogeological setting and conceptual model section (Section 2), an anisotropy ratio of 1:10 for K_v:K_h has been implemented for all hydraulic units in the numerical model.

Figure 5.4 Hydraulic conductivity zones



5.6 Recharge

5.6.1 As described in the Hydrogeological setting and conceptual model section of this report (Section 2.), recharge to groundwater originates from the direct infiltration of a proportion of the precipitation through the unsaturated zone. A single recharge zone has been considered over the whole model area and based on professional judgement, it has been assumed that 10% of the total precipitation monitored between January and December 2022 may recharge the aquifer, representing approximately 1.12×10^{-4} m/d of water entering the aquifer system. This approach is considered appropriate for the steady state simulation considering that the water level data used for model calibration were measured in December 2022.

5.7 Model Calibration targets

5.7.1 The numerical model targets correspond to the boreholes which were monitored on 13th December 2022 and the locations are presented in **Figure 2.9**. The vertical position of the targets in the numerical model has been defined based on the borehole screen position with respect to the elevation of the top and bottom of the numerical model layers at the borehole location. In the case that a screen stretches over more than one layer, the target has been implemented into the layer with the longest screen portion. **Table 5.3** summarises the model targets, their location, and their target values.

Table 5-3 Targets summary

Name	X	Y	Layer	Target value (mAOD)
BH210s	614081	315394	1	8.43
BH233	613205	315202	1	8.78
BH231	613306	315141	2	8.89
BH260	613308	315168	2	8.84
BH226	613718	315233	2	8.81
BH221	613831	315254	3	8.72
BH210d	614081	315394	3	8.79

5.8 Temporal discretisation

5.8.1 The numerical model consists of one stress period in steady state mode, meaning that it has been assumed that the groundwater system is at equilibrium, and no temporal variations have been considered. Although this approach gives a simplified representation of the reality, it has been considered appropriate for the study considering the limited number of monitored data over time (Section 2.7), as well as the objective of the study which is to assess the impact of the piles on the groundwater flow conditions long term. It should be noted that groundwater levels measured in December 2022 were close to surface, i.e. when considering groundwater flow the simulations represent a high groundwater level scenario.

6 Numerical model calibration and sensitivity analysis

6.1 Calibration process

6.1.1 The numerical model, such as presented in Section 5, was initially calibrated to historical 2020 data using PEST (Parameter Estimation). PEST is a widely used software package that efficiently tests a range of numerical model parameter values to obtain an optimum calibration, based on the information available.

6.1.2 The parameters considered for the calibration correspond to the hydraulic conductivity of the five zones in the model (**Figure 5.4**) and the recharge. The ranges used in PEST are consistent with those presented in Sections 5.5 and 5.6.

6.1.3 During the 2023 model revision the calibration of the numerical model was developed further using a manual calibration method to improve the fit to the 2022 monitoring data and enhanced conceptual understanding. Hydraulic properties assigned were compared against those used in the Wensum and Tud Area regional groundwater resource model (**Ref 26**) to ensure consistency.

6.2 Mass balance

6.2.1 The mass balance of the numerical model summarises all the inflows and outflows from the model and helps verify that the model is performing appropriately and in accordance with the conceptual model.

Table 6-1 Mass balance summary

Flow type	Inflow (m^3/d)	Outflow (m^3/d)
Well	0	546.85
Constant head	1534.30	216.11
River	4.60	2441.04
Drain	0	280.16
Recharge	1945.30	0
Total	3484.20	3484.17
Error (%)	0.00085	0

6.2.2 The recharge flows are in accordance with what has been presented in the Hydrogeological setting and conceptual model section of this report (Section 2). The total pumping rate in the model differs slightly to the total borehole abstraction rate in the conceptual model. This can be explained by the fact that the pumping boreholes are probably localised in highly fractured zones of the Chalk, which have not been represented in the numerical model. The average hydraulic conductivity of the Chalk in the numerical model could therefore be limiting the pumping rate. There is mostly groundwater inflow from the constant heads to the east and west and outflow into the river and drain boundary conditions, which is consistent with the overall understanding of the system. The percentage error is low, this therefore suggests that the numerical model is performing as intended.

6.3 Groundwater level results

6.3.1 The calibrated hydraulic conductivity values are presented in the last column to the right of **Table 5.2**, which allows a comparison with the conceptual ranges. The calibrated recharge rate is 1.12×10^{-4}m/d.

6.3.2 **Table 6.2** presents the numerical model statistics and **Figure 6.1** shows a graphic representation of the observed versus simulated levels for the most recent numerical model, calibrated to December 2022 groundwater level data. This allows identification of any boreholes which deviate from an ideal calibration (1:1 line). **Figure 6.2** and **Figure 6.3** show the distribution of the residual values within the numerical model.

Table 6-2 Numerical model statistics

Well Name	Layer	Observed level (mAOD) (1)	Simulated level (mAOD) (2)	Residual (m) (2-1)
BH210s	1	8.43	8.51	-0.08
BH233	1	8.78	10.49	-1.71
BH231	2	8.89	9.93	-1.04
BH260	2	8.84	9.87	-1.03
BH226	2	8.81	8.79	0.02
BH221	3	8.72	8.68	0.04
BH210d	3	8.79	8.71	0.08

Residual mean (m)	-0.53
Root Mean Square (RMS) Error (m)	0.60
Minimum Residual (m)	-1.71
Maximum Residual (m)	0.08
Scaled RMS (%)	1.31

Figure 6.1 Observed versus simulated groundwater levels

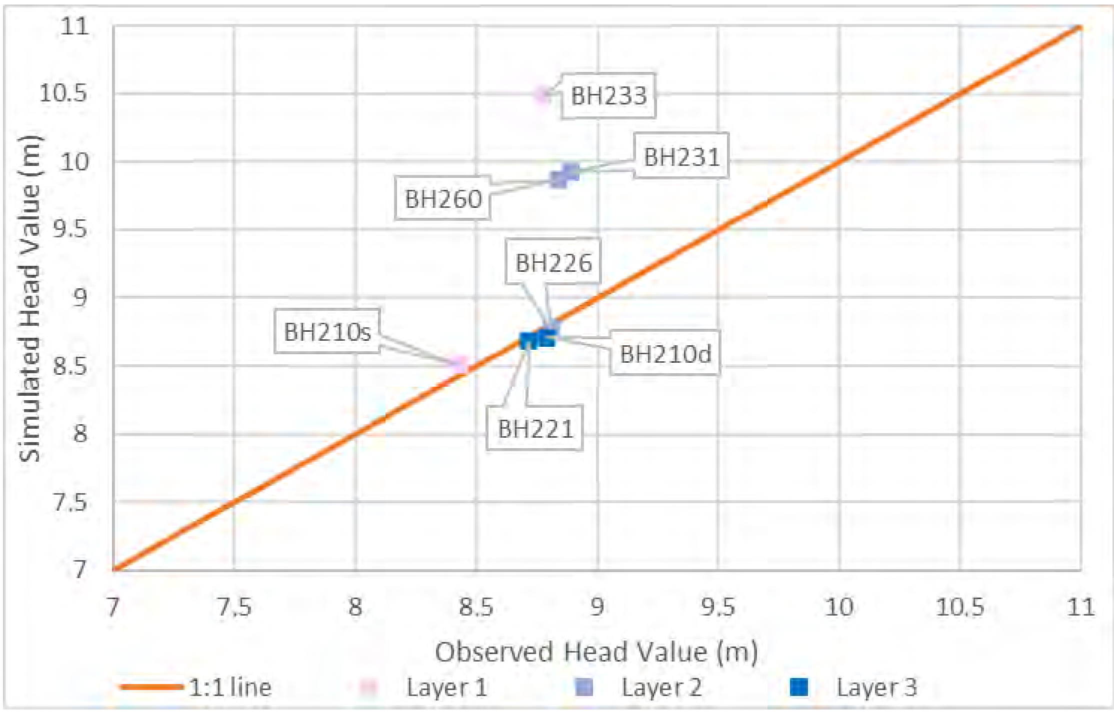


Figure 6.2 Residuals distribution

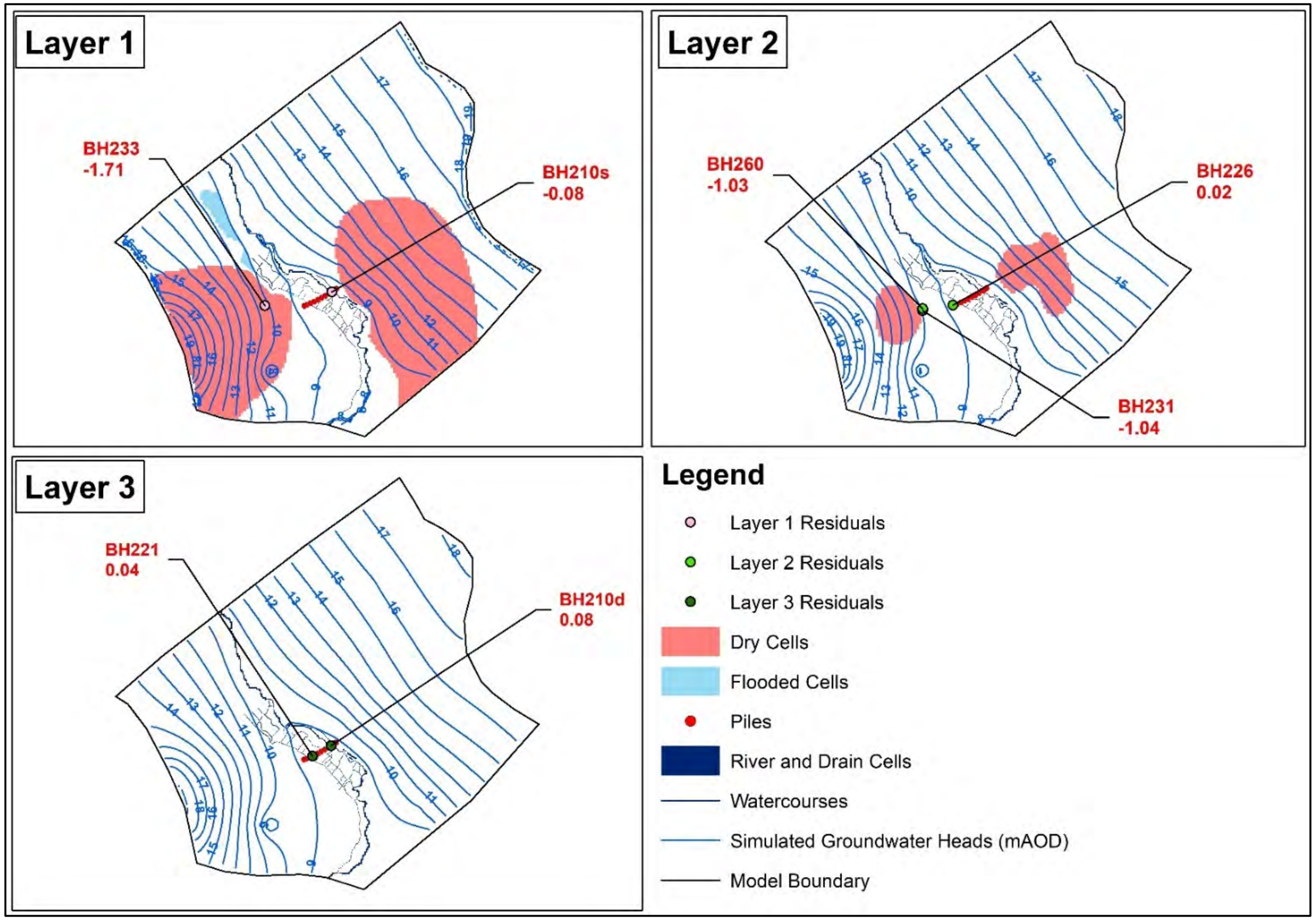
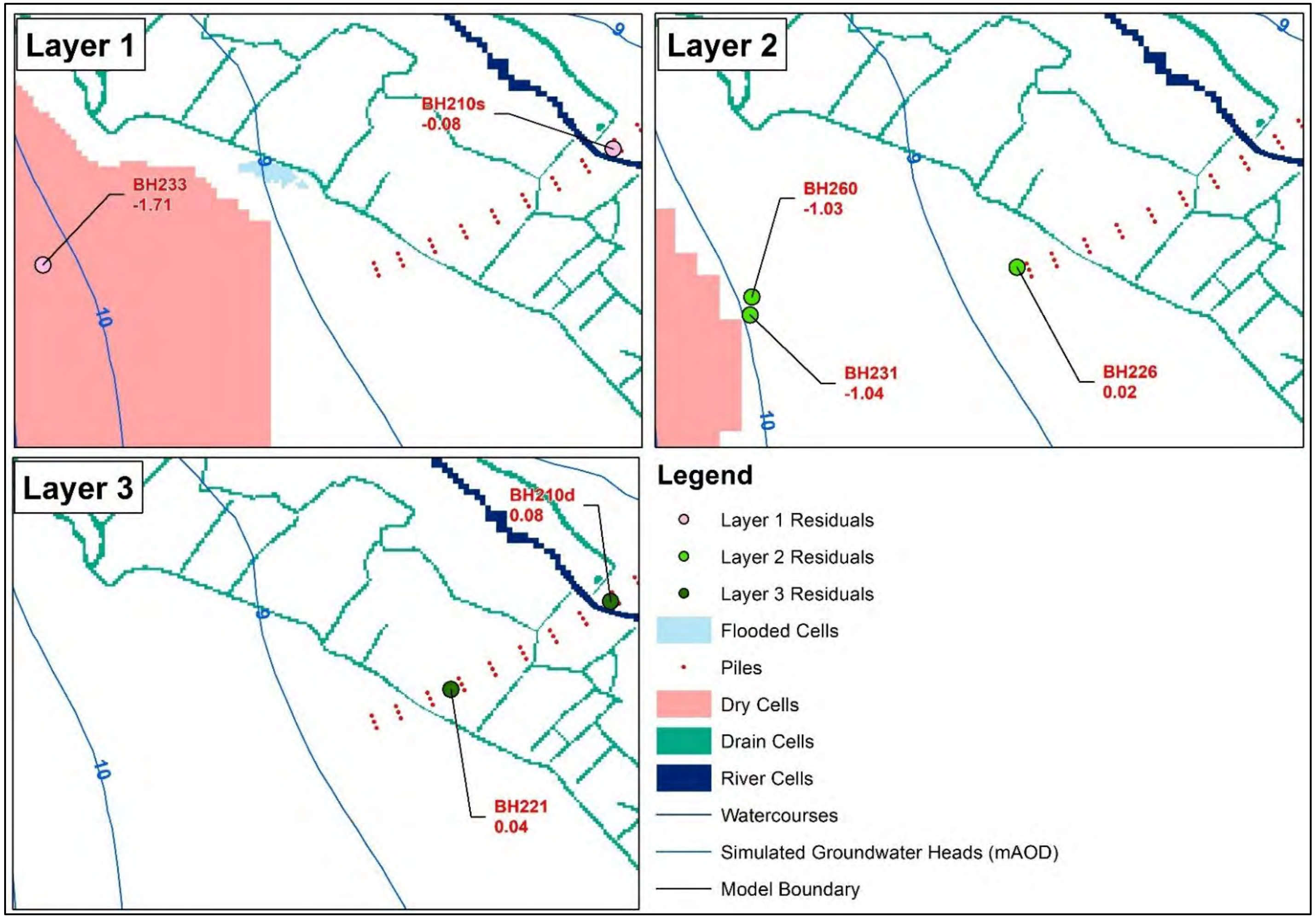


Figure 6.3 Residuals distribution



6.3.1 As presented in **Table 6.2**, **Figure 6.1**, **Figure 6.2** and **Figure 6.3**, the maximum difference in head between the observed and simulated levels is -1.71m in BH233 (layer 1). This difference may be caused by local heterogeneities in the area that have not been represented in the model. BH231 and BH260 in layer 2 also have residuals exceeding 1m, and are situated close to BH233. Since these boreholes are located approximately 0.5km away from the viaduct area, the calibration in this area has not been considered fundamental for the purpose of this study. In the viaduct area, the residuals are lower and of the order of a few centimetres (**Figure 6.2**), with the lowest residual being 0.02m in BH226. As presented in **Table 6.2**, the Normalised (or Scaled) Root Mean Square (NRMS) is of 1.31%, which is below the recommended 10%.

6.3.2 One of the limitations of the calibration is the heterogeneity of the different units within the superficial deposits which cannot be represented fully in the numerical model. Secondly, and as previously mentioned, groundwater flows predominantly through fractures in the Chalk, but it has been represented as an equivalent porous material in the numerical model.

6.3.3 **Figure 6.2** and **Figure 6.3** also present the simulated head contours associated with each model layer. The numerical model reproduces the conceptual model adequately, showing a general groundwater flow coming from the northeast and southwest and converging towards the river.

6.3.4 Overall, it is considered that the numerical model is well calibrated and adequately represents the observed hydrogeological behaviour of the Study Area. The model can therefore be used as a tool to assess the potential impact of the piles on the groundwater system.

6.4 Sensitivity analysis

6.4.1 Once the model was calibrated, two additional models with slightly different hydraulic conductivity (K values) and recharge values have been run to assess the impact of such changes on the quality of the calibration. **Table 6.3** summarises the sensitivity analysis runs, their characteristics and results.

Table 6-3 Sensitivity analysis runs

Model Name	**Calibrated model**	**Sensitivity 1**	**Sensitivity 2**
Model N°	**NRWCH2_3_4_NewAbs**	**NRWCH2_S1**	**NRWCH2_S2**
Description	Calibrated model with K and recharge values that are consistent with the conceptual understanding of the site.	Hydraulic conductivity values doubled.	Recharge values doubled.
K_h Alluvium (m/d)	3	6	3
K_h River Terrace Deposits (m/d)	10	20	10
K_h Sheringham Cliffs Formation (m/d)	0.1	0.2	0.1
K_h Weathered Chalk (m/d)	10	20	10
K_h Fresh Chalk (m/d)	1	2	1
Recharge (m/d)	$1.11x10^{-4}$	$1.11x10^{-4}$	$2.22x10^{-4}$
NRMS (%)	1.31	1.23	1.73

6.4.2 Although the Calibrated Model shows a higher NRMS in comparison with Sensitivity 1, the hydraulic conductivity and recharge values used in the calibrated model are considered to be more consistent with the conceptual understanding of the site. It should also be considered that higher permeability assumptions (Sensitivity 1) would generate less conservative model results with the increased ability of the groundwater to flow around the proposed piles.

6.4.3 Sensitivity 2 allows an assessment of the groundwater system behaviour with a higher recharge.

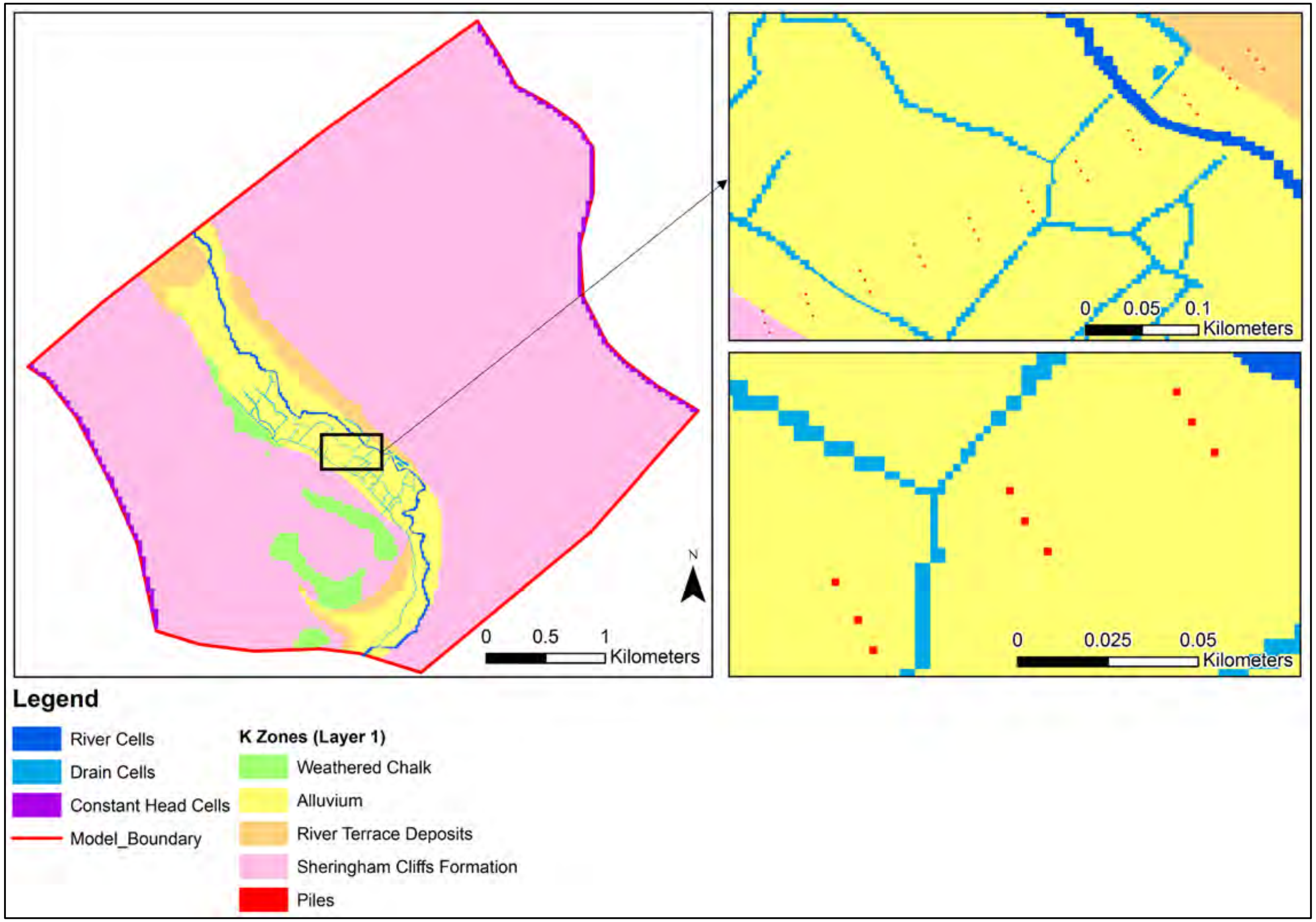
7 Predictive scenarios

7.1 Model settings

7.1.1 The calibrated model and the two sensitivity analysis models have been modified to include the piles and these modifications include:

- A low hydraulic conductivity zone (K_h=K_v=1.0x10^{-5} m/d) has been introduced at the location of the piles from layer 1 to 3, as presented in **Figure 7.1**. In the numerical model, the piles are 2.1m long by 2.1m wide (which is consistent with the piles design presented in Section 3) and more than 50m deep (which is deeper than the piles design, as a conservative assumption).
- Groundwater recharge at the location of the piles has been removed (i.e. no groundwater recharge in the model cells representing pile locations).

Figure 7.1 Piles location in the numerical model



7.1.2 The predictive models were run, and the groundwater heads exported and compared against equivalent models run without the piles.

7.1.3 The installation of the piles is expected to affect the groundwater flow and as a result has the potential to generate changes in groundwater levels. **Table 7.1** summarises the minimum and maximum groundwater level changes in the model, showing the difference in head between the models with the piles and the models without the piles (head from the model with piles minus head from the model without piles), for each layer. In **Table 7.1**, the minimum groundwater level difference (negative values) represents a decrease in level due to the installation of the piles, whereas the maximum groundwater level difference (positive values) represents an increase in level due to the installation of the piles.

Table 7-1 Predictive scenarios results summary

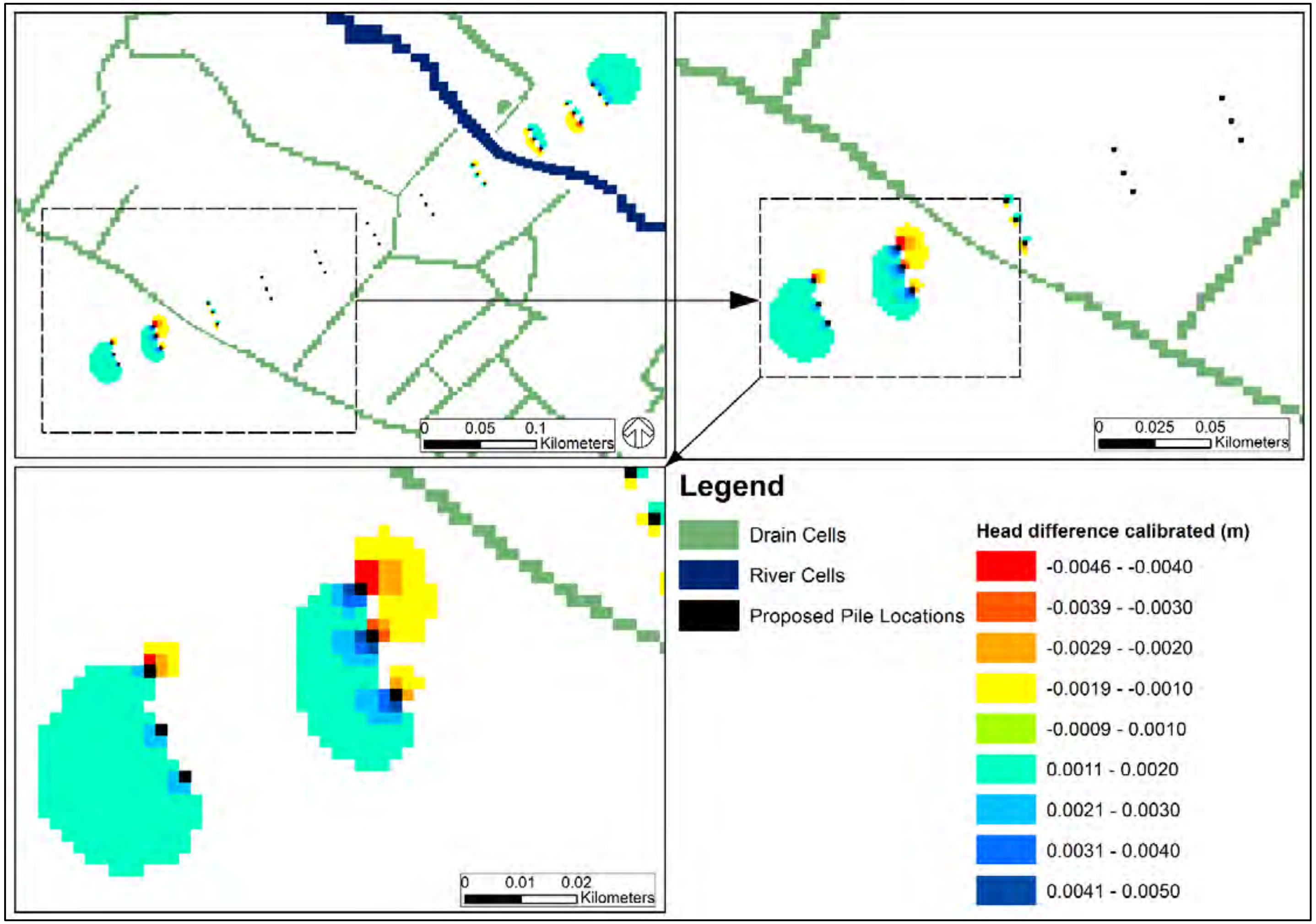
Model Name	**Calibrated model** **Calibrated model with piles**	**Sensitivity 1** **Sensitivity 1 with piles**	**Sensitivity 2** **Sensitivity 2 with piles**
Model N°	**NRWCH2_4_2NewAbs** (model without piles) **NRWCH2_3_4_NewAbs** (model with piles)	**NRWCH2_S1** (model without piles) **NRWCH2_S1_1** (model with piles)	**NRWCH2_S2** (model without piles) **NRWCH2_S2_1** (model with piles)
Description	Calibrated model with K and recharge values that are consistent with the conceptual understanding of the site.	Hydraulic conductivity values doubled	Recharge values doubled
Minimum head difference in layer 1 (Superficial deposits) (cm)	-0.46	-0.43	-0.66

Model Name	**Calibrated model** **Calibrated model with piles**	**Sensitivity 1** **Sensitivity 1 with piles**	**Sensitivity 2** **Sensitivity 2 with piles**
Model N°	**NRWCH2_4_2NewAbs** (model without piles) **NRWCH2_3_4_NewAbs** (model with piles)	**NRWCH2_S1** (model without piles) **NRWCH2_S1_1** (model with piles)	**NRWCH2_S2** (model without piles) **NRWCH2_S2_1** (model with piles)
Maximum head difference in layer 1 (Superficial deposits) (cm)	0.44	0.45	0.68
Minimum head difference in layer 2 (Weathered Chalk) (cm)	-0.31	-0.26	-0.43
Maximum head difference in layer 2 (Weathered Chalk) (cm)	0.35	0.31	0.51
Minimum head difference in layer 3 (Fresh Chalk) (cm)	-0.29	-0.23	-0.40

Model Name	**Calibrated model** **Calibrated model with piles**	**Sensitivity 1** **Sensitivity 1 with piles**	**Sensitivity 2** **Sensitivity 2 with piles**
Model N°	**NRWCH2_4_2NewAbs** (model without piles) **NRWCH2_3_4_NewAbs** (model with piles)	**NRWCH2_S1** (model without piles) **NRWCH2_S1_1** (model with piles)	**NRWCH2_S2** (model without piles) **NRWCH2_S2_1** (model with piles)
Maximum head difference in layer 3 (Fresh Chalk) (cm)	0.40	0.31	0.57

7.1.4 As presented in **Table 7.1**, the changes generated by the installation of the piles on the groundwater system are predicted to be negligible in the three layers of the model and does not exceed an absolute head difference value (i.e. considering both positive and negative values) of approximately 0.46cm. There is also no significant difference to the sensitivity analysis scenarios. **Figure 7.2** presents the distribution within the numerical model of the head difference in layer 1 associated with the Calibrated Model and Sensitivity 1 (only differences greater than 0.1cm are displayed). As presented in the figure, most of the predicted changes in groundwater head can be observed around the piles towards the northeast and southwest. This is likely to be due to the steeper groundwater gradient, and therefore increased groundwater flow, at the valley sides. The predicted change in groundwater levels due to the installation of the piles is minimal and very localised (**Figure 7.2**).

Figure 7.2 Predictive scenarios results



7.2 Model Limitations

7.2.1 The groundwater modelling work undertaken produces a reasonable representation of reality, even though the available data which underpins the model development presents some limitations. As is standard practice with groundwater modelling work, a series of sensitivity analyses varying hydraulic parameters and recharge have been performed. These are used to examine potential margins regarding possible groundwater levels variation and should be considered when making decisions on related scheme designs and / or impact assessments. The local factors which present a degree of uncertainty in the modelling work undertaken are summarised as follows:

- The Study Area consists of heterogeneous material (clay, silt, sand, gravel, and Chalk). However, each hydrogeological unit has been represented by a single set of hydraulic parameters, which does not consider the local heterogeneity of the material or the presence of fractures, and instead offers an average representation of the unit.
- The hydraulic conductivity of the site materials has been poorly characterised as no robustly derived hydraulic parameters are available. Correspondingly, particle size distribution data and literature values have been used to parameterise hydraulic properties. Particle size distribution data were obtained at specific locations along the scheme and provide point specific data which have been applied to wider areas covered by the numerical model. The hydraulic conductivity values used for the Chalk are based on literature review, information from the regional groundwater model and professional judgement.
- No information regarding the recharge to the groundwater system in the Study Area is available, and a percentage of the precipitation rate has been estimated based on professional judgement and calibration results.

- The monitored data is scarce over time and space. Concurrent data sets of groundwater and surface water levels associated with the 13th December 2022 and 15th October 2020 monitoring were available, which does not allow for an assessment of the variation of the levels over time. The monitored points do not cover the whole modelled area and the majority are localised around the proposed viaduct, which restricts verification of the numerical model further away from the main area of interest. Both uncertainties have been addressed by the modelling approach (sensitivity testing) and the fact that the groundwater levels observed in December 2022 were relatively high winter levels (close to surface) in the area of concern.

7.2.2 The limitations listed above should be considered when using the model results and, although the results indicate a negligible impact on the groundwater levels following the installation of the piles, the values obtained from the numerical model should not be considered as definitive numbers and should be used only as a guide as to what may be expected in terms of a magnitude of change.

7.2.3 The selected modelling approach (including sensitivity testing) has taken the data gaps and limitations into account generating robust and clear modelling result.

8 De-icing salt spreading study

8.1 Introduction

8.1.1 The calibrated numerical groundwater flow model was adapted to investigate the potential impact that winter de-icing of the River Wensum Viaduct may have on the local groundwater environment. De-icing involves the spreading of de-icing product on the road to prevent freezing. Based on information provided by the Applicant, in Norfolk ‘Thawrox Plus’ is used, a rock salt with additive. The rock salt is approximately 94% pure Sodium Chloride, dissolving in water and leading to the release of chloride (and sodium) to the environment. The bridge barrier minimizes the risk of salt directly being released to the River Wensum SAC and floodplain, but the road drainage is expected to capture the applied salt loading causing elevated salinity (mainly in form of elevated chloride) of the drainage discharge. Road drainage from the future River Wensum Viaduct is to be channelled into three infiltration basins (Basin 1, Basin 2, and Basin A1067). Basin 1 is not directly designed for infiltration but overflows into the existing adjacent Northern Distributor Road basin 1A. For the purpose of modelling Basin 1 was used directly for road drainage discharge to ground to keep the assessment specific to the River Wensum Viaduct impact.

8.1.2 To assess the impact on water quality that a release of chloride from the infiltration ponds would have, infiltration to groundwater from the base of the basins was represented in the model and a contaminant transport model was developed. This was used to model the movement of chloride (representative of salinity increase) through the aquifer over time, based on the groundwater flow regime predicted by the calibrated numerical flow model. Contaminant transport model results can be used to inform mass balance calculations, allowing a change in surface water quality to be predicted, with the River Wensum SAC being of particular interest.

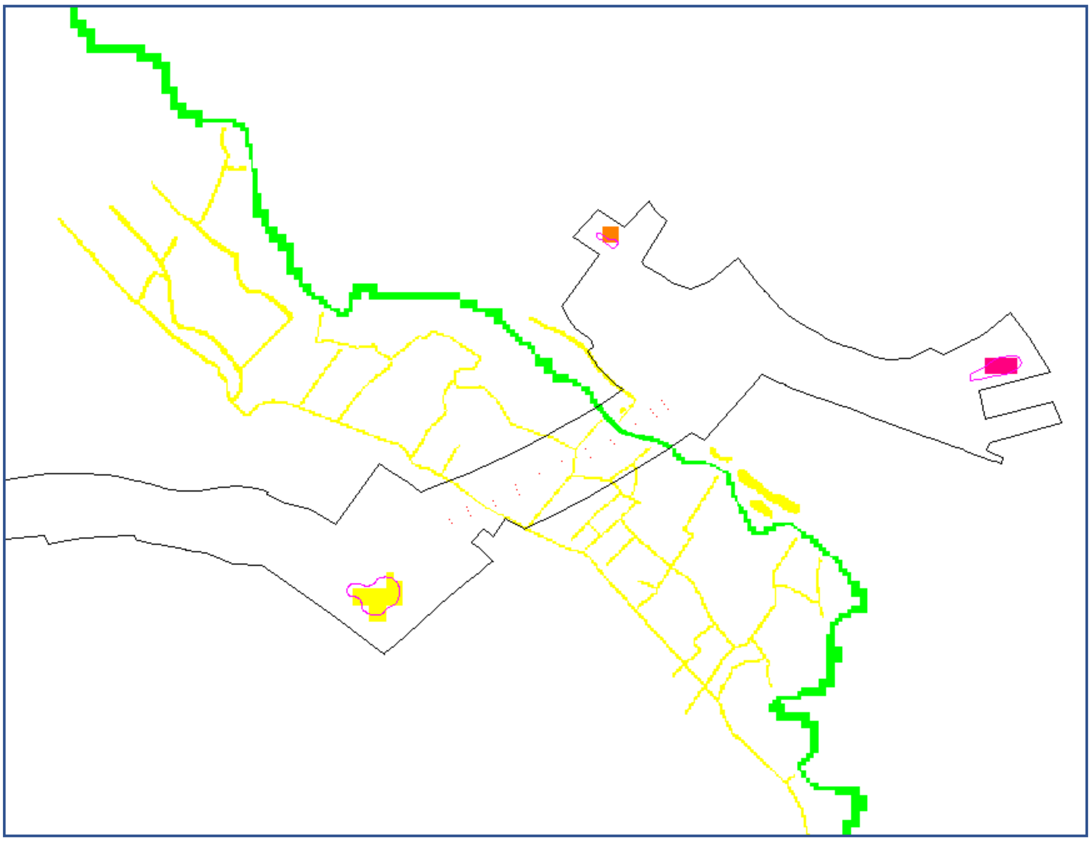
8.2 Transport model set up

8.2.1 The calibrated steady state flow model described in Section 5 was translated into a transient model for the purposes of the contaminant transport modelling. Since a transient calibration for the groundwater flow model was not practical due to a lack of available time variant groundwater monitoring data, where possible properties were kept constant throughout the predictive period in order to represent typical groundwater flow conditions.

8.2.2 The model was set up with monthly stress periods to run for a period of 100 years. 100 years was considered to be a reasonable maximum length of time to run the model because it is likely that aquifer conditions, salt spreading technology and climate may change in the future, meaning when running the model beyond 100 years outputs are more likely to become unrepresentative. Due to objectives to improve the quantitative status of the regional groundwater body, there is also increasing uncertainty on groundwater flow conditions with time, therefore it was not considered valid to run the model for any longer.

8.2.3 Model boundary conditions and hydraulic properties were consistent with the calibrated groundwater flow model described in Section 5, with the exception of recharge. The recharge rate used in the calibrated model represented conditions in 2022 in order to calibrate to groundwater levels recorded in 2022. In the predictive model the recharge rate was changed to a longer term average rate, calculated from the full rainfall record available for the Salle rain gauge described in Section 2.2. This covers the period 2011 to 2023 and is considered to give a recharge rate more representative of the average rate than data from a single year. Additional recharge zones were added to the model to represent Basins 1, 2 and A1067, which would capture road runoff from their individual road drainage catchment areas. Steady infiltration of the captured volumes was assumed with discharge to ground being limited by the infiltration rates at each basin (assumed to be the design infiltration rate), with rainfall data providing an infiltration limit for each basin catchment. The location of the basins and their representation in the model is shown on Figure 8.1. Each recharge zone was assigned a recharge rate and chloride concentration based on salt loading calculations. A background concentration of zero was assumed for the rest of the aquifer. It is expected that the aquifer already contains low chloride concentrations, but setting the concentration at zero enables the increase in concentration caused by the scheme to be assessed. No salinity issues in the groundwater and surface water were identified during the Environmental Impact Assessment process of the Proposed Scheme.

Figure 8.1 Infiltration basin locations and representation in the groundwater model



8.2.4 The porosity, specific storage and specific yield values used in the transport model are presented in **Table 8.1**. Since a transient calibration had not been possible, storage values used in the model are based on representative values from the Northern East Anglia Chalk Groundwater Investigation report for the Wensum and Tud Catchments (**Ref 26**), which presents the storage values used to represent local geological units in the calibrated regional groundwater flow model. Literature values for different types of geology indicated by Domenico and Mifflin (1965) (**Ref 5**), Heath (1983) (**Ref 13**), Morris and Johnson (1967) (**Ref 23**) were used to assign porosity in the model, and to verify storage.

Table 8-1 Specific storage, specific yield and porosity values used in the transport model

Zone N°	Hydrogeological Units / Formation	Specific Storage	Specific Yield	Porosity
2	Alluvium	0.0139	0.050	0.29
3	River Terrace Deposits	0.0139	0.100	0.29
4	Sheringham Cliffs Formation	0.0001655	0.150	0.29
1	Weathered Chalk	0.0003	0.015	0.20
5	Un-weathered Chalk	0.000033	0.015	0.18

8.2.5 The transport model was run with only advection and dispersion active. Adsorption and decay were not considered relevant for the current study. Longitudinal dispersivity was set as 25, transverse dispersivity was 2.5 and vertical dispersivity was 0.25, where methodology behind these values is outlined in Appendix D in Carey et al. (2006) (**Ref 12**) remedial report undertaken for the Environment Agency.

8.3 Salt mass loading calculations

8.3.1 Norfolk County Council gritting runs cover a total of approximately 2,200 miles (3,500 km) on different priority class roads including commuter and major bus routes and as far as is possible one route into all villages. The River Wensum Viaduct would be classed a high priority route. Data was provided by the Highways Services department at Norfolk County Council detailing the number of occasions high priority routes were gritted during the last five winter seasons. A nationally established treatment matrix for weather conditions exists which includes details of the required spread rate of the de-icing product in different scenarios, these being 7.5g/m^2, 10g/m^2 and 15g/m^2 (Norfolk County Council). Based on the data provided, the average number of gritting occasions during the winter season over the past five years was 66. Assuming a worst case spread rate of 15g/m^2 this was calculated to be equivalent to a total of 990g/m^2 of salt each winter period.

8.3.2 In order to calculate the modelled chloride concentration in water infiltrating to groundwater from the designed infiltration ponds initial estimates of salt loading assumed that a conservative maximum of 1000g of salt would be spread per m^2 of road each winter period. Of the 1000g of salt spread, calculations took account of the atomic weight of chloride and sodium to calculate a chloride load, used thereafter to represent salinity. It was assumed for the purposes of the modelling that salt is spread over 5 months of the year (November to March inclusive) in line with the Council records.

8.3.3 Design infiltration rates for the infiltration basins were found to exceed rainfall totals for the catchment if it is assumed that infiltration occurs at the same daily rate throughout the year. As such, for the purposes of the modelling, the infiltration rate for each basin was set to the average rainfall volume for the basin catchment area, distributed over the area of the basin itself. The volume of chloride predicted to accumulate from de-icing each month was then used to calculate an average concentration for the infiltration occurring during the pre-defined five winter months. In reality, chloride concentration in the infiltration pond would fluctuate depending on the frequency of de-icing, however for the purposes of the current modelling study an average rate for the winter period was sufficient to predict the long-term movement of the resulting plume. Infiltration rates and concentrations applied to the model are presented in **Table 8.2**.

Table 8-2 Calculated infiltration rates and chloride concentrations

Basin	Road surface area (m^2)	Salt loading per winter period (g/m^2)	Monthly infiltration (m^3/month)	Chloride load for basin per month during winter period (kg/month)	Infiltration in modelled basin per m^2 area (m/d)	Chloride concentration during winter period (kg/m^3)
1	36003	1000	1934	4370	0.02836	2.26
2	99629	1000	5350	12092	0.03304	2.26
A1067	19700	1000	1058	2391	0.03103	2.26

8.4 Model results and sensitivity analysis

8.4.1 Chloride concentrations predicted by the model after 100 years of de-icing are presented in **Figure 8.2**. The modelling predicts that the chloride plume would move laterally towards the drains and the river as well as vertically downwards into the Chalk. Over a period of 100 years the plumes originating from the infiltration basins have reached the River Wensum and the system is nearing a steady state. The chloride load entering the River Wensum and nearby surface water drains after 100 years is predicted to be approximately 89kg/d and 161kg/d respectively. There is also significant spread of chloride downwards into the Chalk aquifer.

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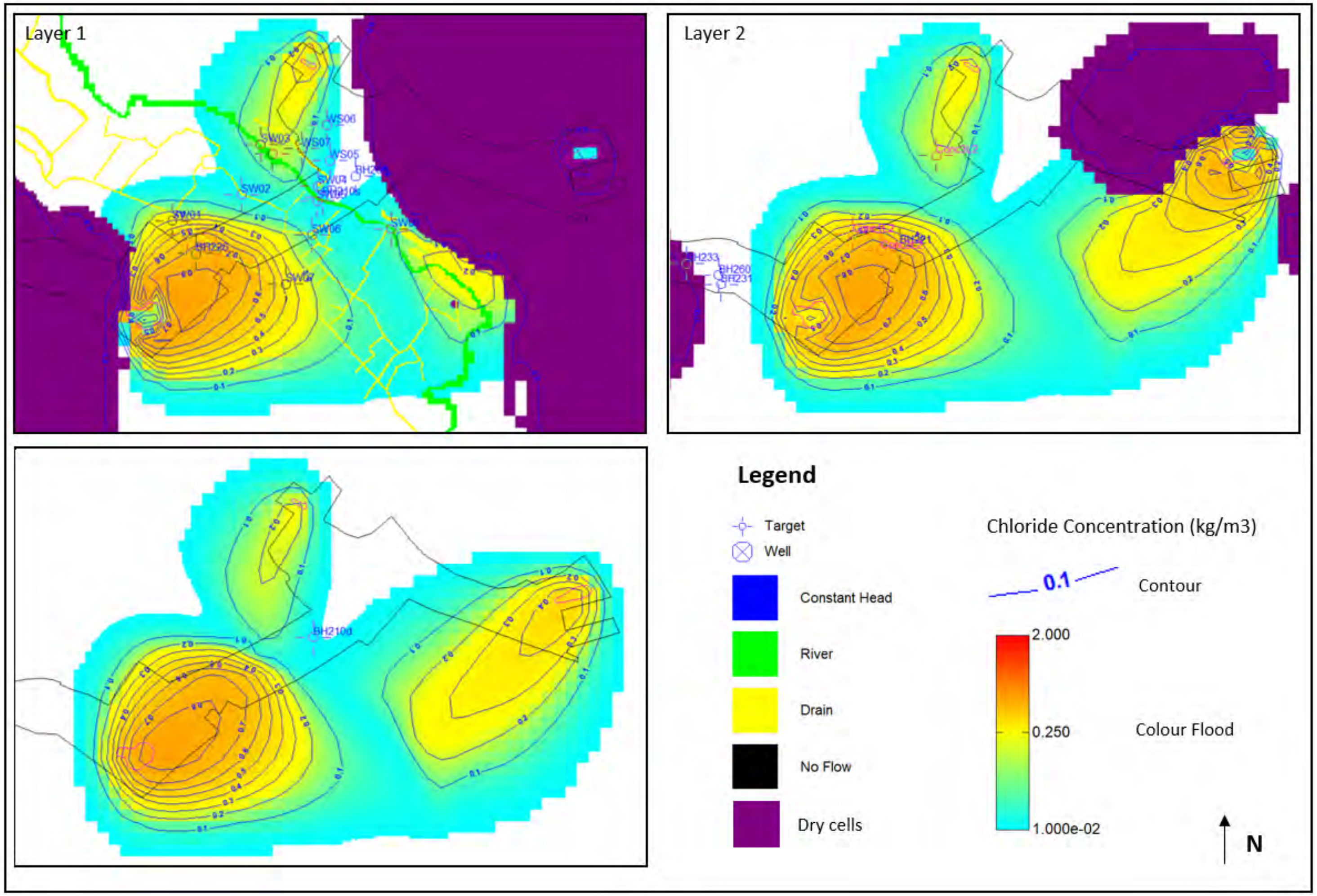
Figure 8.2 Modelled chloride concentrations after 100 years



8.4.2 Background concentrations of chloride in the River Wensum were recorded on a monthly basis between 2010 to 2013, approximately 4km southeast of the Proposed Scheme (**Ref 7**). Concentrations recorded over this period ranged from 33.7mg/l to 55 mg/l (**Ref 7**). Environment Agency flow gauge stations at Costessey Mill, close to the water quality monitoring point, recorded flow rates for the river over the same period (**Ref 9 and 10**). Considering chloride concentrations and river flow rates allows the background chloride load in the river to be calculated. Calculations were done for low flow summer months and winter months over the three-year period of overlapping data. The background chloride load in the river was found to vary from around 7,000kg/d during periods of low flow, up to a maximum of almost 36,000kg/d in March 2013.

8.4.3 After 100 years of operation the predicted additional chloride load entering the River Wensum as a result of the modelled salt spreading scenario is low compared to the chloride load in the River Wensum as suggested by the monitoring data. This implies the impact of the Proposed Scheme on chloride and salinity levels in the River Wensum is not significant.

8.4.4 Chloride concentrations in excess of around 250mg/l are known to give rise to a detectable taste in drinking water (World Health Organisation, 1996). Although chloride is not thought to be a significant risk to human health, 250mg/l is widely set as a recommended maximum concentration for drinking water. The Environmental Quality Standard for chloride is also 250mg/l. Water is considered brackish when chloride concentrations are between 500mg/l and 5,000mg/l and saline above this. Sea water generally has a chloride concentration of around 19,400mg/l. (**Ref 15**).

8.4.5 Concentrations in the predicted chloride plume between the basins and the river exceed the 250mg/l level, up to a maximum of around 800mg/l, implying the groundwater underneath the basins could potentially become slightly brackish. As a result, further models were run to assess the impact of the infiltration basins on the local groundwater quality and the Chalk aquifer as a groundwater resource.

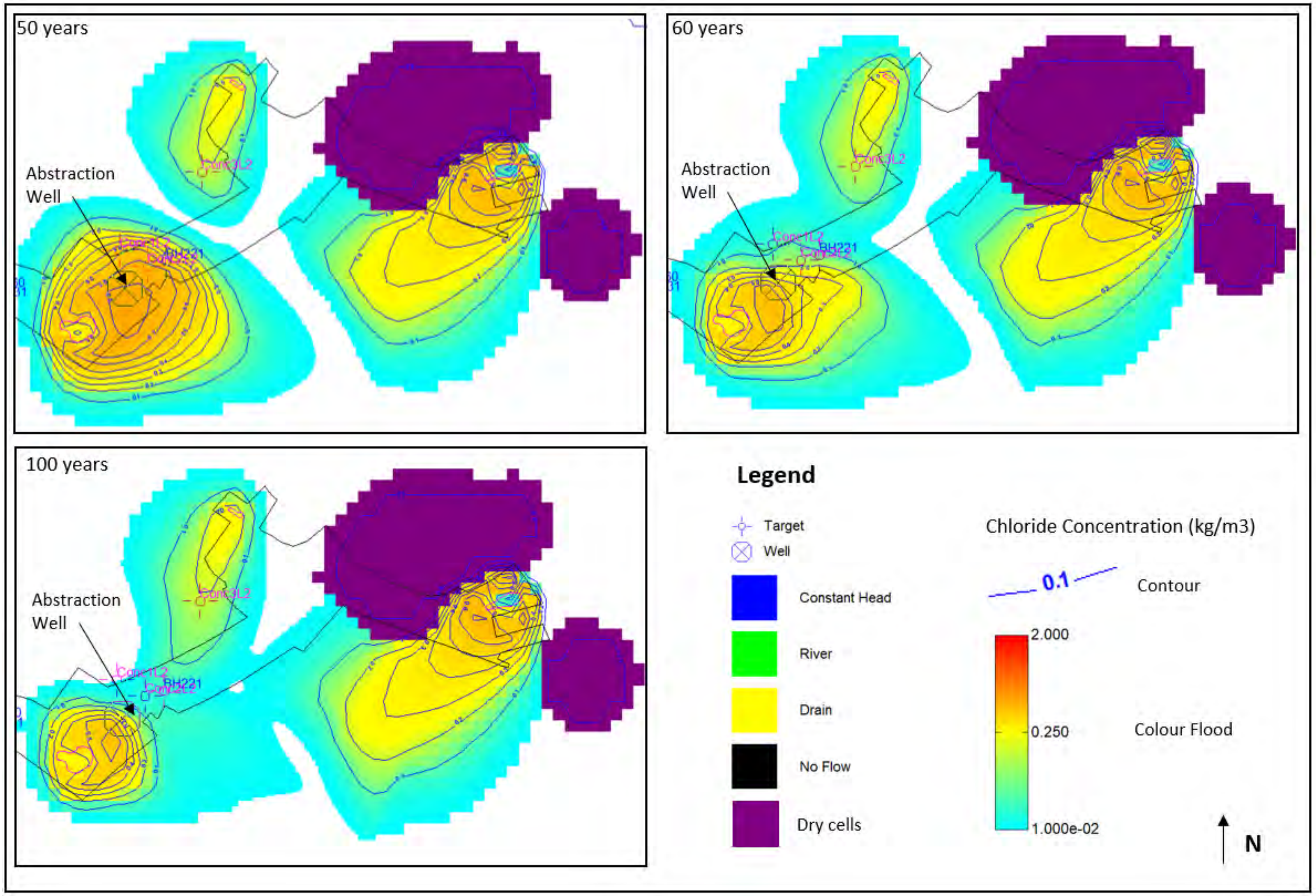
8.5 Groundwater abstraction

8.5.1 Chloride concentrations in the Chalk aquifer predicted by the modelling exceed the recommended level of 250mg/l and suggest that the aquifer may become slightly brackish underneath the infiltration basins (particularly Basin 2). In order to assess the impact this would have on the aquifer as a groundwater resource, an abstraction well boundary condition was added to the model mid-way between Basin 2 and the receiving surface water feature. The well was set up to be identical to nearby ABT4 (who's location is shown on **Figure 2.6**) and assigned the same abstraction rate of 546m^3/d. It is therefore assumed to represent a typical agricultural well. The well begins abstracting groundwater after the plume has been developing for 50 years, and abstracts groundwater for a further 50 years of the model run.

8.5.2 The results of the contaminant transport model run showed that, although in the vicinity of the infiltration basin chloride concentrations remained high, the contaminant concentration within the abstracted groundwater fell from 813mg/l at the start of abstraction to 317mg/l after 50 years of abstraction (excluding any background concentrations), not too far above the 250mg/l threshold and below the threshold for being considered as brackish. This is partly because fresh water is also drawn into the well from the surrounding area, diluting the accumulated concentrated groundwater next to the basin. Contaminant mass has also been removed through abstraction. The results of this model run suggest that despite the chloride plume, the Chalk aquifer is still likely to remain a useable resource being just above the preferred drinking water guidelines. As shown by **Figure 8.3**, the abstraction well also acts to prevent the plume migrating significantly beyond the location of the well and towards the river, however the plume from Basin A1067 is extended slightly as groundwater is pulled towards the well.

8.5.3 The simulated scenario also shows the sensitivity to flow changes, implying changes that cause increased groundwater flow would reduce the effect of local chloride concentration built up (including regular flooding events in the River Wensum floodplain). It should also be noted that the simulations are assuming a constant salt use each winter over the next 100 years, whereas in reality in can be expected that climate change, improved weather monitoring equipment and innovative de-icing products would gradually reduce the salt mass to be applied in the future.

Figure 8.3 Modelled chloride concentrations in layer 2 of the model for groundwater abstraction well scenario



8.6 Sensitivity analysis

8.6.1 During the transport modelling several different values for porosity and storage were tested. It was noted that the extent of the resulting plume was particularly sensitive to the storage properties assigned to the modelled Chalk, particularly specific storage. Increasing specific storage had a significant impact on the movement of the plume in the model, with lower storage values accelerating the movement of the plume. The resulting plume is likely to be similar in all cases, however a steady state is reached much sooner when storage is lowered. Earlier model runs used higher storage values which resulted in the plume not having anywhere near a steady state condition after 100 years.

8.7 Salt spreading study conclusions

8.7.1 The salt spreading modelling study suggests that, providing salt spreading stays around recent local average levels, the impact from the infiltration of chloride into the aquifer remains at local scale (limited to the highways basins and immediate downstream area only). A chloride plume was shown to develop, but concentrations within the plume remain at or below 800mg/l (in the centre of the plume). A modelled theoretical abstraction well within the Chalk downstream of Basin 2 which begins pumping after 50 years of plume development was initially found to abstract water with higher chloride concentrations (813mg/l), but concentrations fell rapidly during pumping and after 20 years were not too far above the recommended maximum level of 250mg/l (365mg/l after 20 years), suggesting that the Chalk aquifer remains a useable resource following a period of initial pumping. Taking into account the poor quantitative status of the groundwater body suggests a reduced likelihood of further abstraction licenses to be granted and a likely increasing dilution effect in the future. Regular flooding of the River Wensum’s flood plain should have an additional dilution effect on chloride levels, removing substantial chloride loadings from the groundwater, during such events.

8.7.2 The chloride load in the River Wensum is calculated to range from approximately 7000kg/d up to almost 36000kg/d during the period 2011 to 2013, based on Environment Agency monitoring data (**Ref 7** and **Ref 10**). After 100 years the predicted chloride load entering the River Wensum and connected drains is approximately 250kg/d. Averaging over the full year 262kg/d of chloride is added to the model from the three basins, suggesting that the system has almost reached a steady state. Therefore, it can be concluded that the additional chloride load entering the River Wensum as a result of the modelled salt spreading activities would be significantly less than the chloride load in the River Wensum as suggested by the monitoring data. Based on measured background chloride concentrations in the river of around 50mg/l, this equates to an increase in chloride concentration of just under 2mg/l during periods of low flow, which is within typical variations of chloride concentrations in the river. Therefore the expected impact is concluded to be not significant.

9 Conclusion

9.1.1 The development of the conceptual and numerical model associated with the area of the proposed River Wensum Viaduct enabled the estimation of the impact of the implementation of the proposed bridge foundation on the groundwater flow system.

9.2 Hydrogeological Conceptual Site Model

9.2.1 The conceptual model development entailed the review and compilation of a wide range of information such as: geological and hydrogeological maps, borehole logs, particle size distribution data, regional groundwater model information, meteorological data, topography, groundwater monitoring data and surveyed surface waters etc. Following the analysis of the geological information and despite the geological heterogeneity of the Study Area, five major hydrogeological units have been defined: Alluvium, River Terrace Deposits, Sheringham Cliff Formation, Weathered Chalk and Fresh Chalk.

The hydraulic parameters associated to the five hydrogeological units were then defined based on particle size distribution data and literature values. The groundwater system is mainly recharged by rainfall derived infiltration. The resultant groundwater flow is then expected to occur mostly horizontally in the superficial deposits and through fractures in the Chalk, from the west and east, towards the River Wensum and the drainage system within the floodplain, where the groundwater discharges. The groundwater levels in the River Wensum valley were observed to be close to the ground surface and the shallow groundwater, deep groundwater and the surface waters are hydraulically well connected there.

9.3 Temporary Works Platform

9.3.1 The Temporary Works Platform would be required to enable the construction of the viaduct over the River Wensum, where this extends across the floodplain of the River Wensum. It is expected that a permeable material, which does not impede groundwater flow would be used below groundwater to construct the Temporary Works Platform. The platform design is aimed to avoid surface water pathways as these have been found to be fundamental for the local groundwater level control. Where avoidance of such a feature was not possible, the existing surface water drainage channel (Water Course 5) is expected to be culverted to maintain hydraulic connection. Additional culverts are included in the design for flood protection purposes which are not discussed as part of this document (Appendix 2: Flood Risk Assessment (Document reference 3.12.02)). Sections of deep sheet piling would be required during construction, but sheet piles are designed to be removed at the end of the construction stage.

9.3.2 During construction, the engineered fill associated with the Temporary Works Platform is not expected to impact surface water and groundwater flows, due to the permeable nature of the material used in the saturated zone. Impacts to groundwater and surface water in this phase are expected to be localised, minor and temporary. Additional drainage is included in the design to mitigate against any groundwater rise caused by the sheet pile walls associated with the Temporary Works Platform, and all sheet pile walls would be removed after construction.

9.3.3 During operation, the remaining areas of engineered fill below ground surface are thought to be unlikely to have a significant impact on groundwater levels and flow in the flood plain. The remaining fill is shallow compared to the thickness of the sand and gravel superficial aquifer and its granular properties ensure good hydraulic connectivity laterally and vertically. Any impacts on groundwater and surface water because of the Temporary Works Platform are therefore expected to be localised and minor, and it was therefore not felt necessary to represent the Temporary Works Platform when constructing the numerical groundwater model.

9.4 Numerical Groundwater Model

9.4.1 The conceptual model was then used as a basis to create a numerical groundwater flow model (MODFLOW-USG with Groundwater Vistas), which consists of three layers, with cell sizes varying from 2.1m x 2.1m in the proposed viaduct area up to 33.6m x 33.6m further away from the main area of interest, where little information is available. The surface elevation between the Chalk and the overlying superficial deposits had been defined based on borehole log information. The boundary conditions applied to the model correspond to the River Wensum (river boundary condition), the drainage system associated to the floodplain area (drain boundary condition) to the centre of the model and constant head boundaries to the east and west of the model based on the hydrogeological map of the area and SPZ2 zone location. The model was run under steady state conditions.

9.4.2 The reference viaduct design consists of twelve rows of piles with three piles in each row. Each pile is characterised by a diameter of 2.1m and a depth of 50m.

9.4.3 The numerical model was initially calibrated to October 2020 groundwater and surface water monitoring data using PEST as an aid. The hydraulic conductivity associated with the five hydrogeological units and the recharge are the parameters that were modified to calibrate the model. The numerical model calibration has then been manually updated using the more recent December 2022 groundwater and surface water monitoring data. Overall, the resulting model was considered to be well calibrated, with a good match between simulated and observed data in the viaduct area, representing well the conceptual understanding of the local groundwater flow regime. A sensitivity analysis has also been carried out to assess changes in hydraulic conductivity and recharge on the results.

9.5 Numerical Model Findings

9.5.1 The calibrated model has been used as a tool to estimate the impact of the proposed viaduct piles on the groundwater system. The piles were implemented into the numerical model as low hydraulic conductivity zones. The results show that, under steady state conditions, the installation of the piles associated with the proposed viaduct has a negligible impact on the wider groundwater system. The greatest increase and decrease in groundwater levels due to the installation of the piles are expected to occur in the superficial deposits and are predicted to be in the order of a few millimetres (<0.005m based on the model results) directly adjacent to the piles. The model results are considered robust taking into account sensitivity testing and the fact that observed and calibrated groundwater levels close to the surface already represent a conservative scenario. This also suggests that even if the final detailed design of the bridge foundations deviates slightly from the assessed reference design groundwater flow impacts are considered unlikely. The high permeability of the superficial deposits is sufficient to deviate groundwater flow around the proposed piles without forcing water pressures to build up.

9.5.2 The calibrated model was used to develop a contaminant transport model to predict the potential impacts that salt spreading on the future River Wensum Viaduct may have on the nearby River Wensum and groundwater quality. The results of the modelling predict localised increases in chloride (salinity) concentrations in groundwater underneath and adjacent to the road drainage infiltration basins but no significant impact on the River Wensum SAC. Carefully management of the quantities and types of products used to de-ice the future bridge would further reduce the risks.

10 References

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