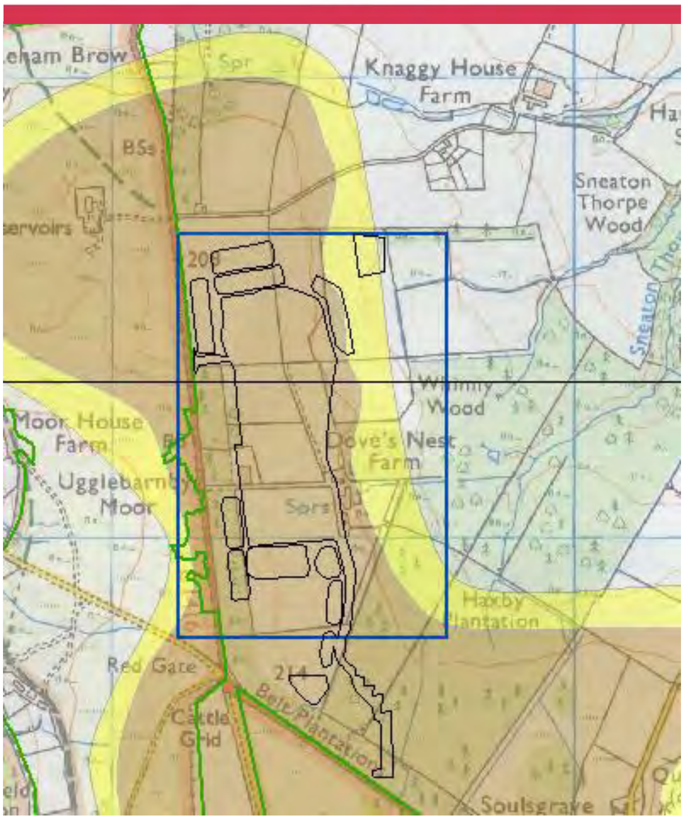
APPENDIX 4

ESI LTD, 2017 - YORK POTASH: GROUNDWATER MODEL UPDATE AND SIMULATION OF THE PHASE THREE PREPARATORY WORKS, REPORT NO. 61415R6



York Potash: Groundwater Model Update and Simulation of Phase 3 Works

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Report reference: 61415R6 Rev1, March 2017
Report status: Final

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York Potash: Groundwater Model Update and Simulation of Phase 3 Works

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61415R6 Rev1. Final

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Revision record:

Issue	Report ref	Comment	Author	Checker	Reviewer	Issue date	Issued to
1	61415R6 D1	Draft report submitted for external review.	CDW	BCH	BCH	8/3/2017	Richard Izatt-Lowry
2	61415R6	Final Report	CDW	BCH	BCH	14/3/2017	Richard Izatt-Lowry
3	61415R6 Rev1	Final Report with updated results for amended design	CDW	BCH	BCH	22/3/2017	Richard Izatt-Lowry

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1 INTRODUCTION

1.1 Background

In September 2014, the York Potash Planning Application was submitted which incorporated the Hydrogeological Baseline Report (FWS, 2014b), Hydrogeological Risk Assessment (FWS, 2014C) and groundwater modelling appendix (ESI, 2014). Following receipt of planning consent for the mine in 2015, baseline groundwater level and spring flow monitoring continued to March 2016.

Development of the mine site is to be undertaken in phases. ESI (2016) assessed the impact of the Phase 2 Works on spring flows and groundwater levels. This modelling report has been undertaken to evaluate the impact on groundwater levels and spring flows of the Phase 3 Works, as shown in Dove's Nest Farm Construction Phase 3 Masterplan (Arup Drawing no. YP-P10-DNF-CX-050) (FWS, 2017).

1.2 Scope and Objectives

ESI Limited (ESI) has been engaged by FWS Consultants Limited (FWS) to simulate the effects of the proposed Phase 3 Works using the existing groundwater flow model. The scope of work undertaken for this modelling work includes:

- Generating a new predictive transient groundwater flow model to account for the Phase 3 Works construction elements shown in Arup drawing No. YP-P10-DNF-CX-050 that are to be undertaken between June and October 2017;
- Processing the groundwater model results to determine predicted groundwater level and spring flow changes around the Site, with a focus around the Spring Flush area of the Ugglebarnby Moor Special Area of Conservation (SAC); and
- Production of a standalone groundwater modelling report to cover the model construction and the Phase 3 modelling results.

1.3 Data Sources

The original model was constructed using information sources that are outlined in ESI (2014b). Revisions to the model were made based during the previous Phase 2 Works modelling runs (ESI, 2016). This modelling has been undertaken using the sources of data listed below:

- York Potash Phase 2 Works Model Update (ESI, 2016);
- Dove's Nest Farm Construction Phase 3 Masterplan (Arup Drawing no. YP-P10-DNF-CX-050); and
- York Potash Multi-Layer Model Report (ESI, 2014b).

1.4 Report Outline

This report includes the following:

- A summary of the conceptual understanding of the Site and surrounds (Section 2);
- A description of the model construction is summarised in Section 3;
- A discussion of model calibration is presented in Section 4.
- Section 5 includes a description of the relevant Phase 3 Works construction elements, how these have been included in the model and the predictive runs undertaken;
- Figures and tables to show simulated changes in groundwater levels due to the proposed Phase 3 Works are presented in Section 6;

- Sensitivity analyses have been undertaken to test the robustness of the model results, and the results of these are presented in Section 7; and
- A summary of the conclusions and key results is provided in Section 7.

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2 CONCEPTUAL MODEL

This section briefly discusses the features of the conceptual model relevant to the groundwater model. This conceptual model has been formulated based on information presented in the most recent Hydrogeological Baseline Report (FWS, 2016a). The Hydrogeological Baseline Report is in turn based on previous reports (FWS, 2013; 2014b), but has been updated with recently collected groundwater level, spring flow data and Phase 4 Stage 2 fieldwork investigation results. The conceptual model summary outlined below is for context only and further detail can be found in the most recent hydrogeological risk assessment report (FWS, 2017).

2.1 Geology

Superficial deposits are present across the Site. These drift deposits are generally clays of varying composition but they can contain significant thicknesses (> 0.5 m) of sand. In the vicinity of the Site superficial deposits are typically between 1 and 4 m thick. Around Ugglebarnby and Sneaton Low Moor SACs they vary in thickness from around 1.5 to 4.7 m, with the lesser thicknesses seen around Sneaton Low Moor to the south of the Site.

Bedrock geology at the Site comprises a series of relatively thin alternating Jurassic sandstones and siltstones/mudstones of the Ravenscar Group. The Whitby Mudstone is a thick, low permeability unit which forms the effective base of the sequence in terms of the local groundwater system. A summary of the sequence is provided in Table 2.1.

Table 2.1 Summary of the geological units and thicknesses underlying the Site

Stratigraphic Unit	Thickness at the Site (m)	Description
Long Nab Member	1.5 to 1.75	Sandstone with mudstone at base
Moor Grit Formation	4 to 12.8	Two sandstone units with intermediate mudstone/siltstone
Scarborough Formation	9 to 13	Three units – upper mudstone/siltstone; middle sandstone/siltstone; lower basal mudstone/sandy limestone
Cloughton Formation	32 to 43	Mudstone unit over sandstone
Ellerbeck Formation	4 to 6	Sandstone with basal ironstone
Saltwick Formation	c. 50	Two mudstone/siltstone units with intermediate sandstone
Whitby Mudstone	77	Mudstone

These units are sub-horizontal, and dip at a low angle towards the east and north. When combined with topography, this results in the younger units outcropping to the south and older units outcropping as the land dips away to the north (towards the River Esk) and the stream valleys to the east and west. The Whitby Mudstone does not outcrop in the vicinity of the Site.

The solid geology units that outcrop beneath the Ugglebarnby and Sneaton Low Moor SACs are the Long Nab Member (Sneaton Low Moor only), Moor Grit, Scarborough, and Cloughton formations. These are the key formations with respect to indirect groundwater impacts on the SACs. The moisture contents in the soils at the SACs are predominantly dependent on groundwater within the superficial deposits upon which they sit rather than groundwater within the underlying solid geology aquifers (FWS, 2016a and b). Locally however, it is reported by FWS (FWS, 2016a and b) that in the northern part of the spring flush area underlain by Moor Grit strata, groundwater from these aquifers contributes to soil moisture within this area of this SAC.

The assessment of indirect impacts of groundwater level changes in the solid geology aquifers on groundwater levels within the superficial deposits is beyond the scope of this modelling exercise and is not discussed within this report.

2.2 Hydrology and Hydrogeology

2.2.1 Springs and surface water

A number of discrete but generally very small springs have been identified in the vicinity of the Site. Figure 2.1 shows the location of these springs. With the exception of SP02, SP03 and NHF (all sourced from the Cloughton Formation), these springs are not thought to flow continuously throughout the year (FWS, 2016a). Monitoring of spring flow at the springs further supports this assertion.

The key groundwater discharge of relevance to this study is Moorside Farm Spring (MF2) and the associated spring flush area of the SAC. A proportion of the flow from the spring at MF2 provides the spring water that feeds a domestic storage tank, whilst the remaining (and larger) proportion forms the water source to the spring flush area within Ugglebarnby Moor SAC (FWS, 2016a). Due to the nature of the groundwater discharge, no flow rates can be monitored at the groundwater discharge point (MF2). However, flow rates have been measured for the storage tank discharge (MF1) and it is evident that spring MF2 is unlikely to provide a continuous flow of groundwater to the storage tank at MF1. As MF1 is a storage tank for drinking water used by two properties, a zero flow from MF1 does not directly represent a zero flow of groundwater from spring MF2 (FWS, 2014b).

Based on their location and elevation and recent hydrochemical analysis (FWS, 2016a), the springs appear to drain the superficial deposits, Moor Grit, Scarborough Formation and Cloughton Formation (see Figure 2.1). Hydrochemical analysis of the spring waters suggests that Moorside Farm Spring (MF2) and Moorland Spring (SP01) may derive a proportion of their water from the superficial deposits. It is possible that these springs are independent to some degree from the underlying bedrock geology groundwater systems (FWS, 2016a). Further details of the springs and the formations from which they are believed to derive are given in FWS (2016a).

From the monitoring data available, flows in the springs are generally very small and highly variable and they are frequently dry over the summer. Exceptions to this are SP02 and SP03 which drain the Cloughton Formation and have been observed to flow continuously during the monitoring period. Measured flow rates (for the period January 2013 to March 2016) are summarised in Table 2.2.

Remaining groundwater discharges have been identified as follows:

- Dove’s Nest Farm Spring (DNS1) – baseflow to Sneaton Thorpe Beck;
- Soulsgrave Farm Spring (SF2) – baseflow to Soulsgrave Slack, and associated storage tank (SF1);
- Ugglebarnby Moor Spring (SP01) – groundwater discharge in Ugglebarnby Moor SAC;
- Northern Springs (SP02, SP03 and SP04); and
- Newton House Farm (NHF) – licensed groundwater abstraction 2/27/29/149.

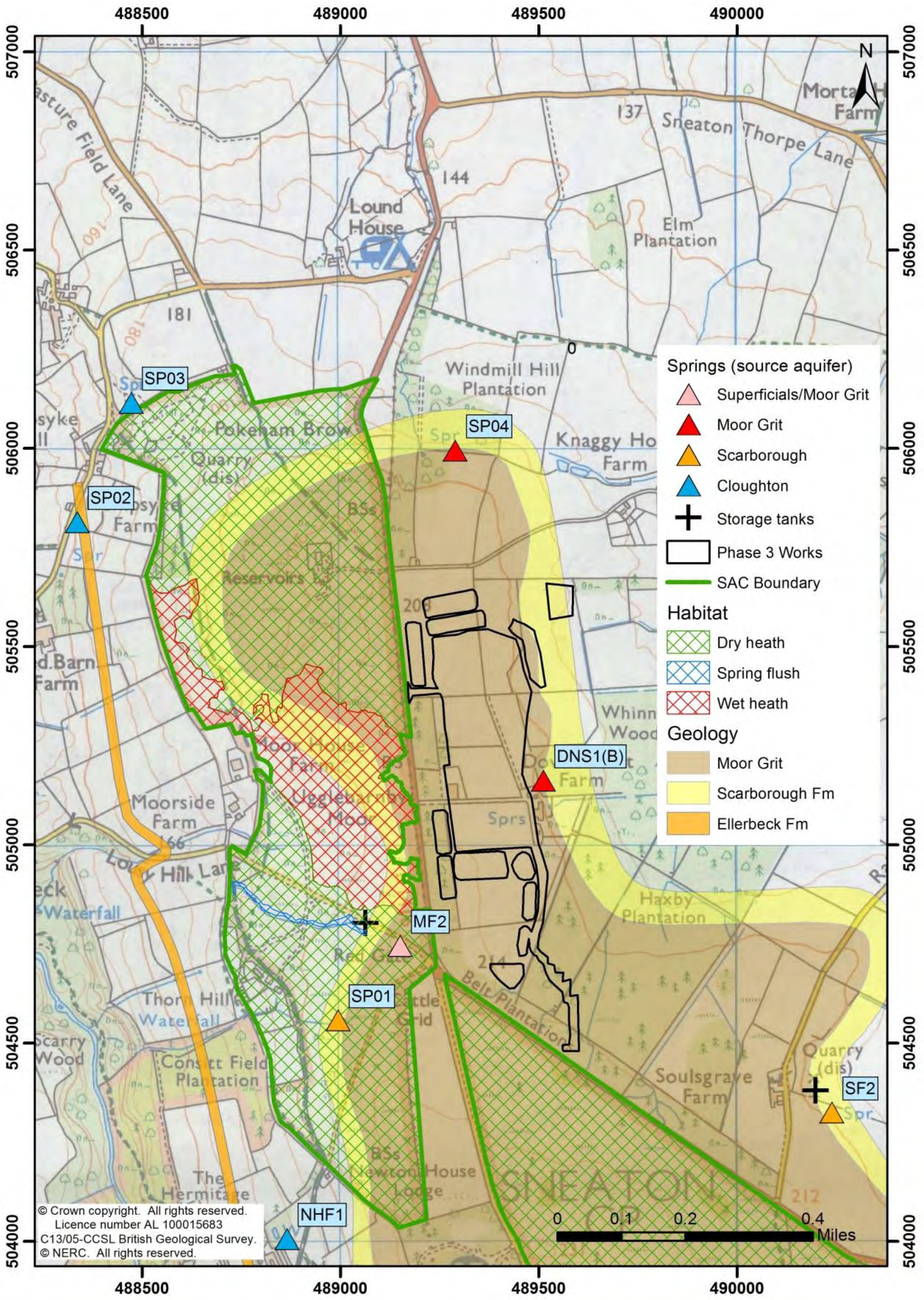

Figure 2.1 Location of known springs and source aquifer

Table 2.2 Measured flow rates for springs in vicinity of Dove's Nest site

Spring ID	Easting	Northing	Name	Source aquifer	Measured flow (m^3/d)
SP01	488994	504558	Moorland spring	Superficials/Moor Grit	0 – 68
SP02	488336	505814	Hempsyke spring	Cloughton	1 – 70
SP03	488473	506115	Quarry spring	Cloughton	10 – 2,321
SP04	489290	505995	Windmill Hill Plantation spring	Moor Grit	Not measured
NHF	488866	504006	Newton House Farm	Cloughton	Not measured
SF1	490198	504380	Soulsgrave Farm Tank	-	-
SF2	490239	504325	Soulsgrave Farm Spring	Scarborough	0 – 97
MF1	489063	504803	Moorside Farm Tank**	-	-
MF2	489151	504746	Moorside Farm Spring	Superficials/Moor Grit	0 – 22*
DNS1	489510	505070	Dove's Nest Farm	Moor Grit	0 – 432

*Flow at MF2 measured at MF1

**A small amount of flow is taken off from the tank for domestic supply to two properties. Assuming a maximum of 8 inhabitants this would not be expected to exceed ~1 to 1.5 m^3/day.

Although not confirmed in the field, it is also expected that more diffuse spring flow/seepage occurs around the outcrop boundaries of the higher permeability units. These springs and seepages represent one of the discharge components for the groundwater system in the area.

Run-off and spring flow are directed to the Little Beck to the west, the Wash Beck and Buskey Beck to the north or the Rigg Mill Beck and its various tributaries to the east. These ultimately feed into the River Esk which flows eastwards and is located to the north of the site.

2.2.2 Groundwater levels and flow

Groundwater level monitoring at the Site demonstrates a degree of hydraulic separation between the individual thin sandstone aquifer horizons. This is consistent with a low vertical hydraulic conductivity (K_v) for the aquitard layers (ESI, 2014a). There is a steep downward vertical hydraulic head gradient driven by recharge to the uppermost layers. Evidence for this is given by higher units having higher groundwater levels. For example between the Moor Grit and Scarborough aquifers there is a difference in groundwater levels of around 5 m; between Scarborough and Cloughton it is around 7 m; and between Cloughton and Saltwick it is around 40 m. Generally, groundwater levels in the underlying aquifer are below the base of the overlying aquifer. This means that there is unlikely to be any significant effect on heads in one layer from changes in head in a vertically adjacent layer. This was demonstrated during the pumping tests (ESI, 2014a).

There is a smaller degree in variation of groundwater levels within individual layers[1]. The highest observed groundwater levels occur in the south and a groundwater high appears to run from south to north in the Moor Grit and Scarborough formations. This groundwater high runs closer to the western outcrop boundary of the aquifers than the east and consequently flow over much of the aquifer extent (including the Site) has an easterly component. This is presumably due to the springs on the eastern outcrop being lower than in the west, due to the slight north easterly dip.

In the Cloughton and Saltwick formations there are fewer monitoring points to confirm the pattern of groundwater flow. However, the data that are available are consistent with a similar flow pattern in these units.

The drivers for these groundwater flow patterns include:

- Recharge that occurs across the outcropping aquifer units,
- Vertical fluxes between units (either via leakage through the underlying aquitards or via downwards flow through the more weathered zones of these layers at the edge of outcrop); and
- The presence of springs, seeps and watercourses to the west, north, and east resulting from steeply dipping ground levels intersecting the groundwater surface in each of the aquifers.

2.2.3 Recharge Processes

Recharge is expected to occur through the superficial deposits and into the outcropping aquifer units and weathered feather edges of mudstone layers. It is likely that some spatial variation in recharge exists due to the variable nature and thickness of the superficial deposits. However, this cannot be confirmed on the basis of available information. Along with reduced superficial deposit thicknesses, higher groundwater levels in the vicinity of Sneaton Low Moor could be caused by the effects of uniform recharge over the widest part of the outcropping aquifer (i.e. further from discharge points) or a minor perched layer. Recharge rates applied to the groundwater model are discussed in more detail in Section 3.6.

Although vertical hydraulic conductivities of the intervening aquitard layers are estimated to be very low (ESI, 2014a), if allowed to drain under unit hydraulic gradient, it is possible to provide enough water via vertical flow to sustain groundwater levels in aquifer units below the outcropping unit. For example, under free-draining conditions, an aquitard with K_v of 10^{-9} m/s (consistent with the results of the pumping tests and the observed lithology of the aquitards) would allow vertical throughflow of around 30 mm/a irrespective of thickness. It is therefore considered likely that recharge occurs to the outcropping aquifers and that this then supports groundwater levels in the underlying formations through slow vertical leakage. Under these circumstances, whilst the various aquifer units are to some extent hydraulically disconnected, the rate of recharge still exerts an important control on groundwater heads in confined aquifers.

2.3 Proposed Development

This report only addresses the Phase 3 Works elements of the mine site development, as shown in the following Arup drawing:

- Dove’s Nest Farm Construction Phase 3 Masterplan (YP-P10-DNF-CX-050)

This drawing is shown in Appendix 2 of the FWS Hydrogeological Risk Assessment (HRA) Report (FWS, 2017). Further details of the Phase 3 Works construction can be found in Appendix 2 of the HRA report.

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[1] NB Some of the variation within individual layers may reflect vertical hydraulic gradients within the layer as much as horizontal variations

3 MODEL CONSTRUCTION

This section describes the construction and parameters adopted for the final calibrated steady state and transient models. The model was constructed using the United States Geological Survey (USGS) numerical finite difference groundwater model code MODFLOW-2005 (Harbaugh, 2005) within the Groundwater Vistas 6 (GV6) interface. A modified version of MODFLOW-2005, called MODFLOW-USG (Panday *et al.* 2013), has been used which allows for the use of unstructured grids such as nested grids.

Two baseline models have been constructed;

1. Steady state calibration model – calibrated to average groundwater levels and spring flows. Whilst no structural changes have been made to this model in the current phase of work, results have been compared to average level/flow based on the full data series from January 2013 to March 2016. Results are presented in Section 4.1.1.
2. Transient calibration model – model with monthly stress periods for a 33 month period (January 2013 to September 2015) calibrated to monitored groundwater levels and spring flows. Initial conditions for the transient model have been taken from the steady state model. Results are presented in Section 4.1.2.

In general the steady state model was a useful pre-cursor to the transient model, but the latter is considered to be more robust, particularly with respect to the representation of the intermittent spring flows. With the exception of recharge (Section 3.6), model construction is identical for both the steady state and transient models.

3.1 Approach to Modelling

The approach to modelling was discussed extensively with the relevant regulators and their technical experts during discussions about the original scoping model. On the basis of these discussions, it was concluded that, although accurate modelling of thin, layered aquifers and the associated small, intermittent springs is challenging, this was an important exercise to carry out in order to provide confidence in the decision making.

As with any modelling exercise, it important to recognise that there will be uncertainties associated with the following aspects:

- Interpretation of the data used in the model;
- Conceptual understanding of the key processes and translation of those conceptual processes into the numerical model; and
- Uncertainties associated with the developed model as developed such as numerical and/or calibration issues.

These uncertainties should not detract from recognising that a carefully developed groundwater flow model is likely to be the most effective tool for exploring the likely effect of various development scenarios on the local groundwater system.

The steepest variation in groundwater levels in the local system is in the vertical plane and it was considered essential that the new, layered groundwater model should replicate these as accurately as possible. The shallower hydraulic gradients within individual layers are less well constrained (e.g. by lateral extent of monitoring) and are more prone to small scale variability in response to local variations in aquifer properties (e.g. variations in thickness, sediment nature and fracturing) and vertical gradients within layers.

In the absence of detailed information about this spatial variation in properties, the initial approach adopted in the model was to maintain uniform properties within individual layers. This approach is consistent with that generally adopted for regional groundwater models developed by the Environment Agency. However, despite concerted attempts to calibrate using globally uniform parameter values, it was not possible to achieve a satisfactory quality of calibration and a decision was made to adopt spatial variation (see Sections 3.5.1).

Notwithstanding the decision regarding the use of spatial variation, it is understood within the groundwater modelling community that models are generally more reliable at predicting changes between model scenarios rather than in achieving fit to absolute values.

3.2 Model Grid

The model location and dimensions are shown in Figure 3.1. Model origin is at NGR 487700 503200 with dimensions 3.7 km (east-west) and 6.2 km (north-south).

Model grid cells are set to 20 x 20 m size across the model, and are refined to 2 x 2 m across the Site area using a rectangular nested grid and the functionality of MODFLOW-USG (see Figure 3.1). This localised refinement allows for more accurate representation of Phase 3 construction features (see Section 5.1).

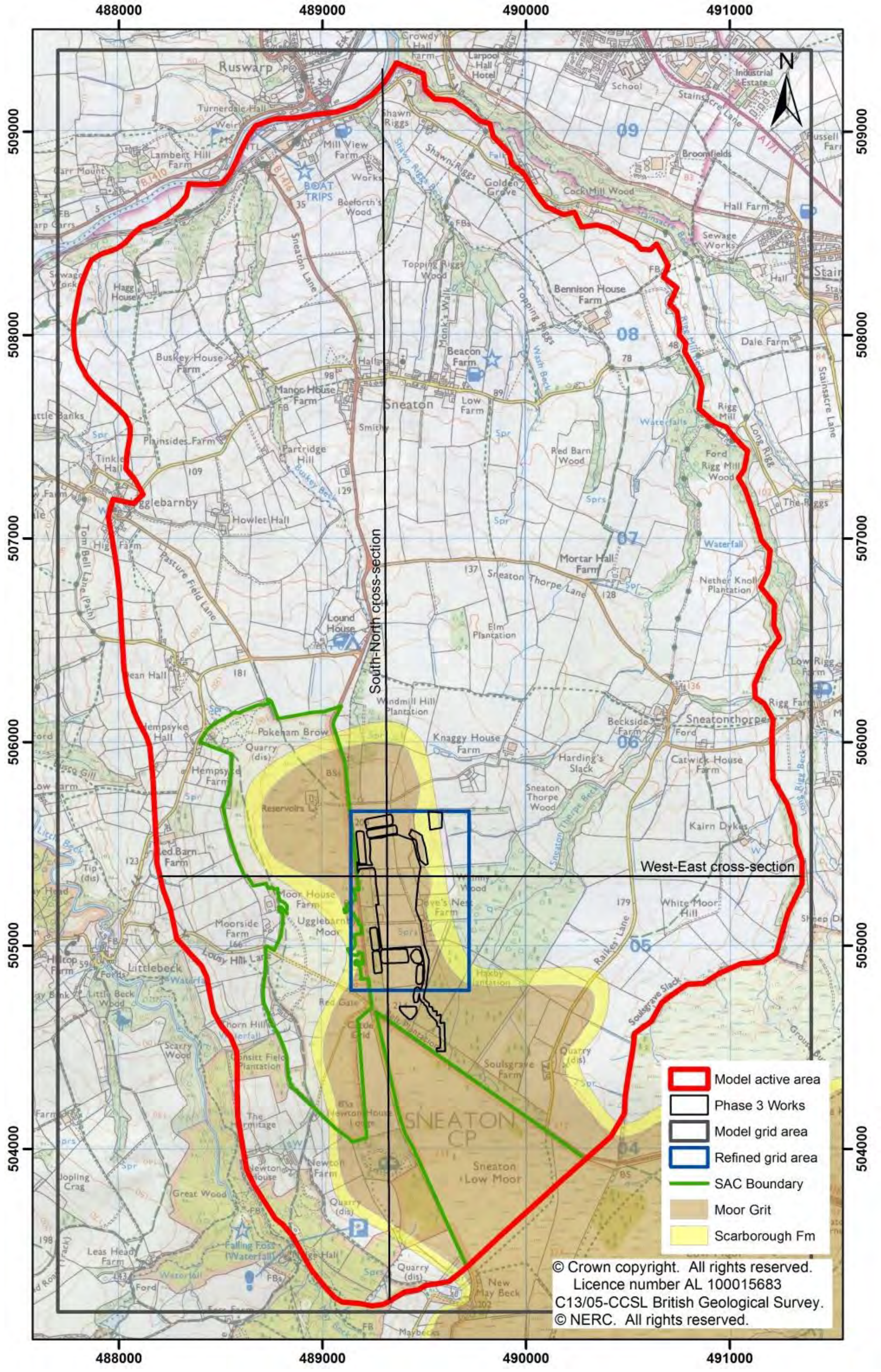

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Figure 3.1 Model extent

3.3 Model Layers

The model comprises seven layers representing four aquifer units and three intervening aquitard units (Table 3.1). The lateral extent of each layer corresponds to either the aquifer/aquitard extent or the active extent of the model and is discussed further in Section 3.4.

Superficial deposits at the Site have not been explicitly included in the model as a hydrogeological unit (i.e. calibrated hydraulic conductivity of the Moor Grit does not allow for the superficial units). However, the upper surface of layer one represents the ground surface meaning that the modelled Moor Grit layer does include the superficial deposits even those the effects of these have not been directly simulated. This should be considered when groundwater level changes in the vicinity of the SACs are presented. Rather, the superficial deposits are taken into account when calculating and calibrating recharge estimates. Only a small amount of additional storage is represented by the more porous superficial deposits in reality than is allowed for in the model. Therefore, this makes the model more conservative with respect to changes in groundwater levels.

As discussed in Section 2.1, moisture content in the soils at the SAC is predominantly dependent on groundwater within the superficial deposits rather than within the underlying bedrock aquifers. The assessment of indirect impacts of groundwater level changes in the solid geology aquifers on groundwater levels within the superficial deposits is beyond the scope of the modelling exercise. However, where the model is simulating groundwater discharge from the modelled layers within the SAC (e.g. along the line of outcrop of the Moor Grit and Scarborough Formation to the west of the Site), the model can be considered to represent part of the hydrological system on which the SAC is partly dependent. One such discharge area is the Spring Flush area, where the groundwater supported flora are understood to be located (Appendix 5 of FWS (2016b)).

Table 3.1 Model layers and typical elevation at Phase 3 construction area

Layer	Modelled Strata	Hydrogeological characteristics	Approximate Top elevation at Phase 3 construction area (m AOD)
1	Moor Grit	Aquifer	200 – 211
2	Mudstone (MS1)	Aquitard	193 = 204
3	Scarborough	Aquifer	189 - 201
4	Mudstone (MS2)	Aquitard	187 – 198
5	Cloughton	Aquifer	185 – 196
6	Ellerbeck Formation	Aquitard	141 – 163
7	Saltwick	Aquifer	118 – 146

Elevation of model layers was determined using a range of data sources as follows:

- Borehole logs – stratigraphic divisions based on available borehole logs across the Site area were provided by FWS.
- OS OpenData Terrain50[2] - topography data with a 50 m grid resolution.
- Outcrop geology based on BGS Solid and Drift Map for Whitby and Scalby (Sheet 35 and 44; BGS, 1998).

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[2] Contains Ordnance Survey data © Crown copyright and database right [2014]

- Pilot points – since no data were available between the Site area and the eastern model boundary, points with estimated elevation based on mean thickness were used along the eastern model boundary in the Cloughton, Ellerbeck and Saltwick Formations to constrain the interpolation from the Site eastwards. This ensured that an adequate thickness was maintained for these formations in the absence of data to indicate otherwise.

Elevations based on borehole data were used directly in the derivation of model layers as known elevation points. Borehole log data were also used to calculate mean thickness for each formation, and these thicknesses were used to supplement the dataset in formations where borehole data was limited. Topography data were used in combination with the BGS map of outcrop geology to extract surface elevation at outcrop for each aquifer unit. Spatial interpolation between known or estimated points was then used to create the model surfaces. Following interpolation, checks were made to ensure a minimum layer thickness of 0.1 m and corrections made where necessary.

Borehole logs from the Phase 4 Stage 2 fieldwork investigations (FWS 2016a) have been reviewed together with geological log data from previous investigations against the layer elevations in the model which correspond to geological unit boundaries. Residual differences between the model layer elevations and strata elevations from borehole logs have been calculated and these have been used to calculate the change in residual in unit thicknesses. It is layer thickness, not the absolute layer elevations that will have the greatest impact on the model results. The absolute mean thickness residual between model layers and the strata were encountered in borehole logs was typically less than 1 m for the top four layers. These residuals are spatially mostly non-uniform. There is some evidence that the Moor Grit Formation is thicker than that modelled to the south of the proposed shafts. However, any applied changes would be small (typically < 1 m).

A small change in layer thickness will not alter the model results significantly. Greater differences were identified in the deeper Cloughton and Ellerbeck formations. However, the Phase 3 Works will mostly affect groundwater levels in the Moor Grit and Scarborough formations and the main receptor is the SAC (at the surface). Amending these much deeper layers would have a negligible impact on the model results. Adjusting the model elevations in these areas could however improve the model calibration for these layers.

The lateral extent of mudstone units MS1 and MS2 was taken to be broadly similar to that of the Scarborough Formation. The Ellerbeck Formation outcrop was assumed to extend northwards beyond that mapped separating the Cloughton and Saltwick aquifer units.

Typical west-east and south-north cross-sections through the Site area are shown in Figure 3.2 (see Figure 3.1 for section lines). Layer elevations are more variable in the vicinity of the Site where data coverage is high (broadly within the box in Figure 3.1) whereas interpolation from the Site to model boundaries is typically more linear. This local-scale variability in layer elevations at the Site is an artefact of interpolation between nearby borehole logs and reflects inconsistencies, such as in borehole interpretation, and is an artificial effect of the model rather than the actual geology. These inconsistences have no consequence for the simulation of groundwater flow.

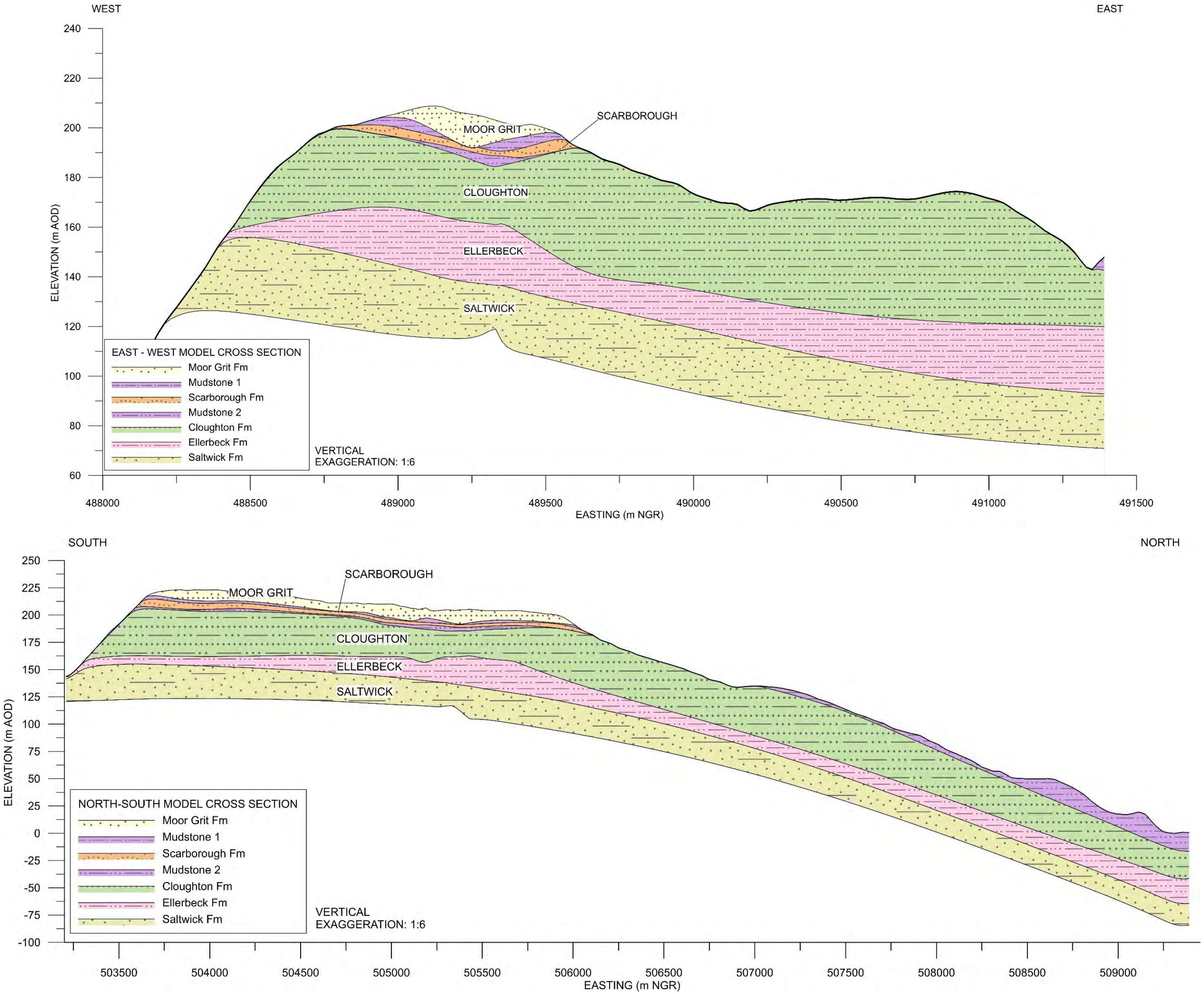

Figure 3.2 Cross-sections of model geometry (top is east—west section and bottom is north – south section). See Figure 3.1 for cross section locations

3.4 Model Boundaries

3.4.1 External boundaries

The active area of the model varies for each layer depending on the spatial extent of the aquifer/aquitard unit (see Figure 3.3). All model cells outside the active model area in each layer have been set to no flow. All lateral boundaries in aquitard units have also been set to no flow.

Due to the potential for inflow and/or outflows, the southern boundary of the model has been set as a MODFLOW General Head Boundary (GHB). This has been set approximately parallel with the groundwater flow direction in the Moor Grit and Scarborough Formation (based on contours presented in FWS, 2016a).

Groundwater contours from the Hydrogeological Baseline Report (FWS, 2016a) were used to specify the head at the southern boundary in the Moor Grit and Scarborough formations. Based on existing information on groundwater levels in the lower aquifer units, heads in the Cloughton and Saltwick were set at 5 m and 60 m respectively below those in the Scarborough Formation (based on the average difference in groundwater level at monitored locations). Hydraulic conductivity is also specified for GHBs, constraining inflow and/or outflow from the aquifer, and has been set consistent with the aquifer unit (see Section 3.5).

Remaining boundaries in the Moor Grit and Scarborough units were defined along the respective outcrop boundaries (see Figure 3.3) and are represented using MODFLOW Drain cells. Similarly, the western limits of the Cloughton Formation (defined by the Ellerbeck Formation) and the Saltwick Formation are represented using MODFLOW Drain cells.

MODFLOW Drain cells permit water to discharge from the aquifer when heads are above a specified stage level but do not allow water to enter the aquifer. At aquifer edges these therefore represent the presence of springs and seepages which are known to exist (although exact locations for all but a few are unknown). Known spring locations have also been represented explicitly and will be discussed further in Section 3.4.2.

For external model boundaries, Drain stage has been set at or slightly above the base of the relevant aquifer unit and hydraulic conductivity (K) was initially set so as not to be a limiting factor on discharge (i.e. was set the same as, or higher, than aquifer hydraulic conductivity). During the process of model calibration, it was necessary to modify Drain K to aid model calibration. In the Moor Grit aquifer, K was reduced along the western edge to maintain heads along this boundary. In both the Moor Grit and Scarborough, Drain K was increased to the east of the Site (coincident with the high aquifer K zone – see Section 3.5.1). The distribution of Drain K is shown in Figure 3.4 below.

Heads in the Cloughton and Saltwick units could not initially be maintained at observed levels due to high discharge from the western boundaries. Therefore, in order to achieve calibration Drain K was reduced in these layers. The northern boundary of both the Cloughton and Saltwick aquifer units has been set as MODFLOW Drain cells along the River Esk to represent possible discharge from the aquifer to the river. Drain stage is set 0.5 m below topography and hydraulic conductivity was reduced below that of the respective aquifer unit during model calibration to maintain heads in the aquifer.

The eastern boundary is set as no flow along Rigg Mill Beck, a surface watercourse over 1.5 km from the Site. This is considered to be sufficiently distant from the Site that any boundary effects are of limited significance to levels at the Site.

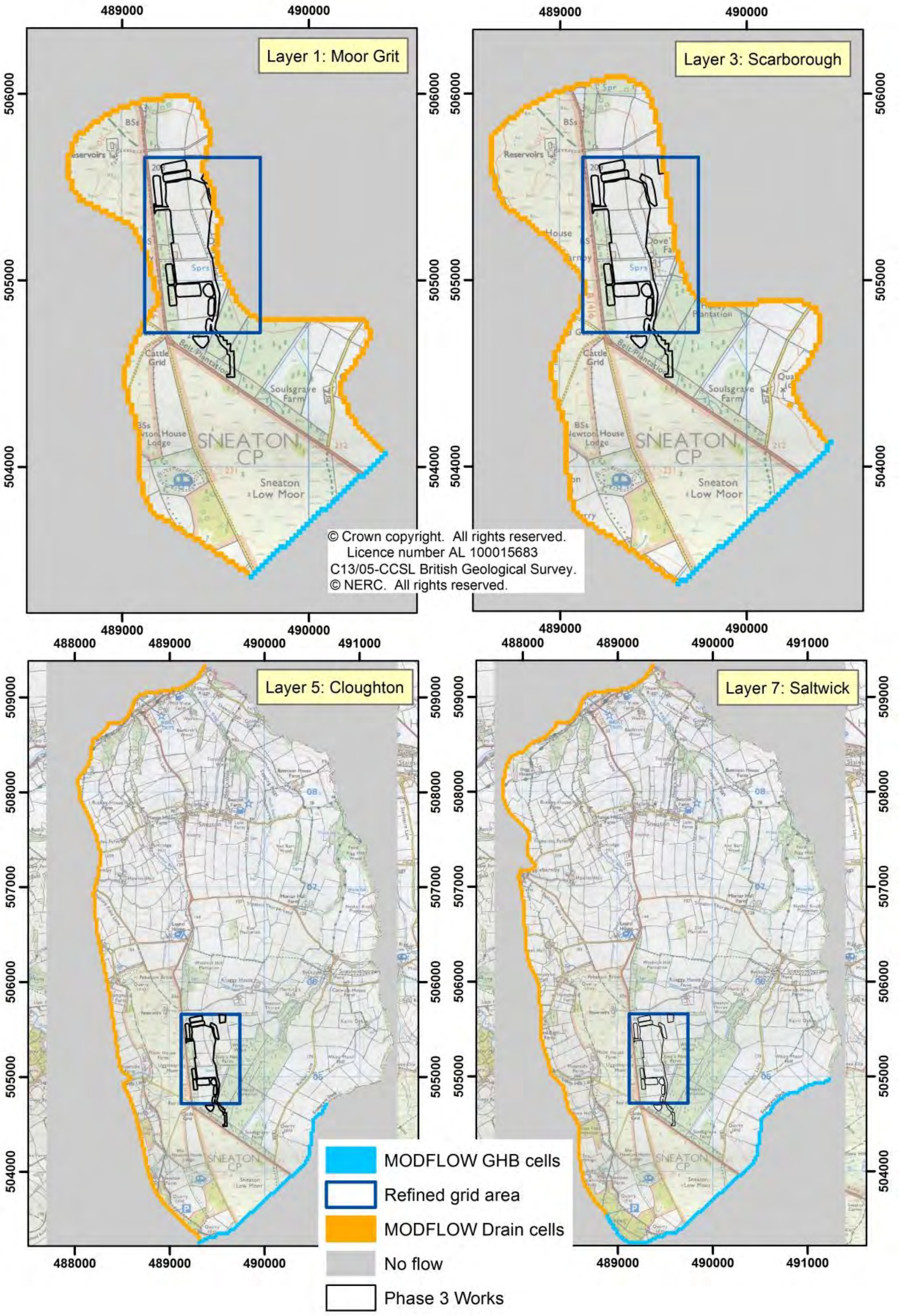

Figure 3.3 External model boundaries

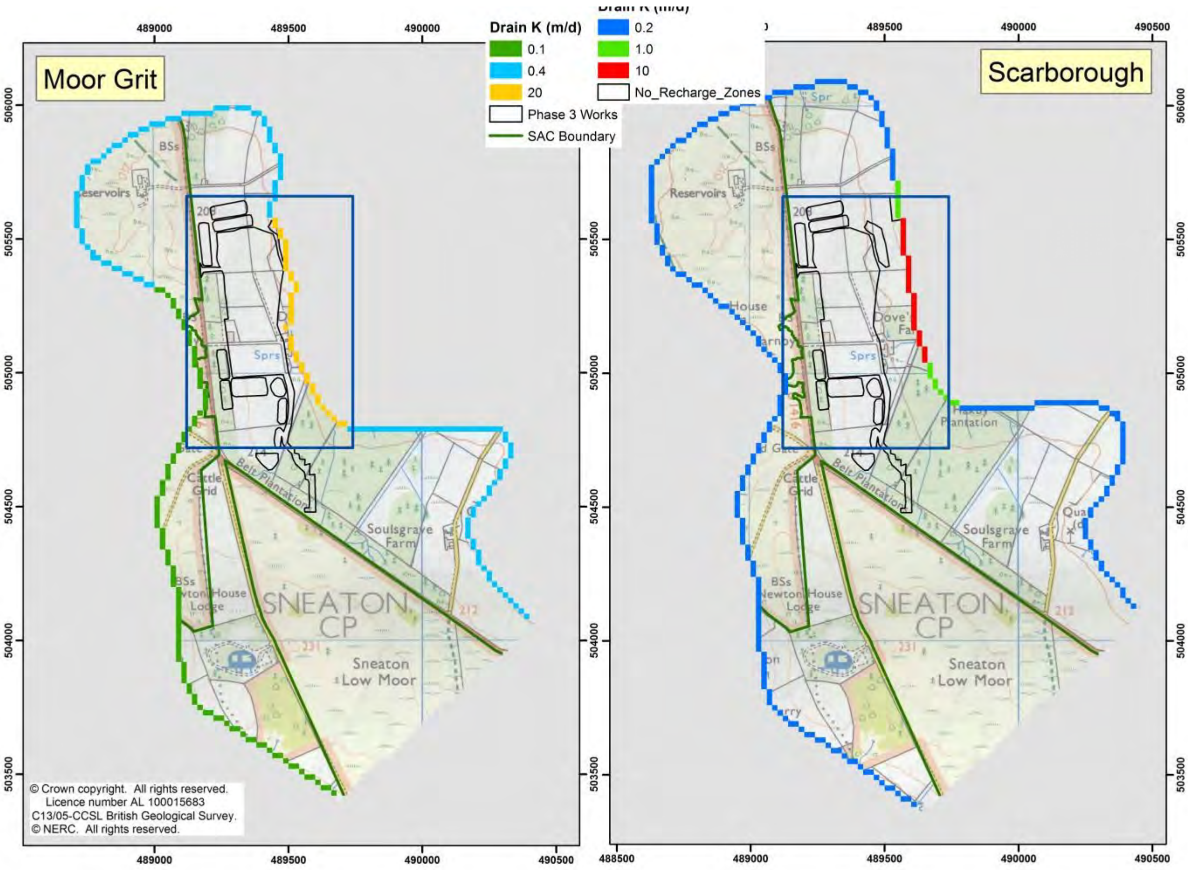

Figure 3.4 Modelled Drain K values in the Moor Grit and Scarborough Formations

3.4.2 Internal boundaries

Springs

Discrete springs which have been identified in the vicinity of the Site (see Figure 2.1) have also been modelled using MODFLOW Drain cells. Flow at the majority of these groundwater discharges is known to be intermittent (see Section 2.2.1).

The surveyed and modelled elevation of the springs is given in Table 3.2. All spring elevations were set and maintained at the surveyed elevation in the model with the exception of SF2, where modelled elevation was reduced to the base of the Scarborough Formation at this location (191.4 m AOD). This change in elevation was made in order to achieve reasonable spring flows. K applied to modelled springs is set 2 - 3 orders of magnitude higher than the other external boundary drain cells to force the majority of water to discharge at these known spring locations.

SP01 was simulated at the base of the Moor Grit Formation along the outcrop boundary in layer one of the model. The spring was simulated as being distributed along this model edge representing a series of seeps and springs rather than one discrete spring location. Due to this distributed representation in the model, hydraulic conductivity of this drain boundary has been set to equal 0.1 m/day,

Table 3.2 Details of springs included in the model

Spring ID	Name	Surveyed elevation (m AOD)	Modelled elevation (m AOD)	Source aquifer (FWS, 2016a)
SP01	Moorland spring	Various along edge of model at base of Moor Grit		Superficials/Moor Grit
SP02	Hempsyke spring	145.00	145.00	Cloughton
SP03	Quarry spring	162.42	162.42	Cloughton
SP04	Windmill Hill Plantation Spring	195.55	195.55	Moor Grit
NHF	Newton House Farm	174.32	174.32	Cloughton
SF2	Soulsgrave Farm Spring	196.78	191.40	Scarborough
MF2	Moorside Farm Spring	210.02	210.02	Superficials/Moor Grit
DNS1	Dove’s Nest Farm	199.00	199.00	Moor Grit

Drilling platform

Exploration drilling platforms for SM11 (South Shaft) and SM14 (North Shaft) were constructed in the northern area of the Site prior to drilling (November/December 2012). These consist of dolomite hardcore (of thickness from 0.3 to 0.9 m) and have an approximate base level of 201.7 m AOD. Given the high permeability of this material relative to the Moor Grit, these have been represented in the Moor Grit using MODFLOW Drain cells. These Drain cells allow water to drain out to a stage level of 201.7 m AOD. The Drain cells have been set with a high conductance in the green shaded area shown in Figure 3.5 below.

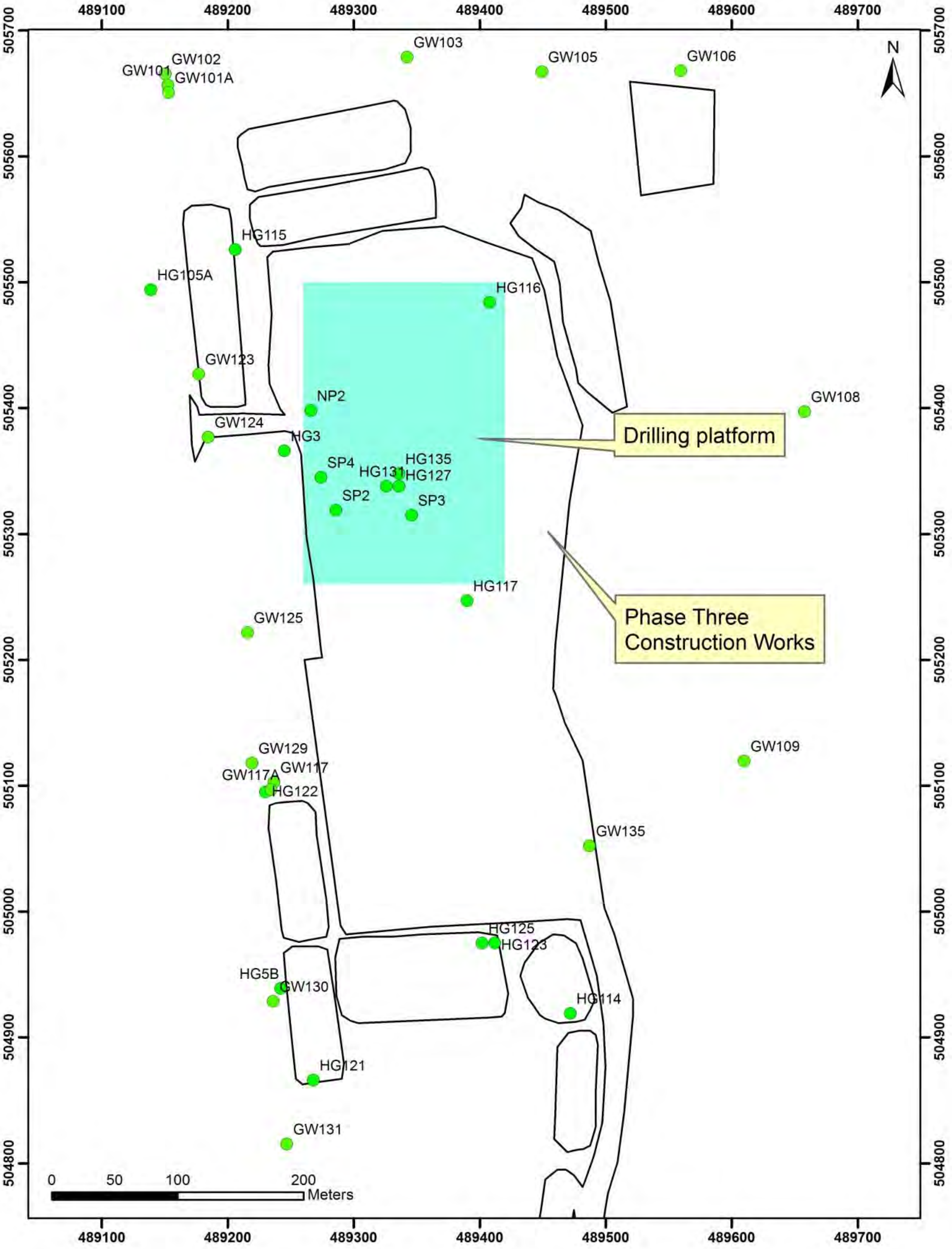

Figure 3.5 Location of MODFLOW Drain cells representing drilling platform

3.5 Hydraulic Parameters

3.5.1 Hydraulic conductivity

Aquifer hydraulic conductivity (K_h and K_v) values were based on the results of pumping tests (as reported in ESI, 2014a) and packer tests and variable head tests undertaken as part of the Phase 4 Stage 2 fieldwork investigations, as reported by (FWS, 2016a). These results are summarised in Table 3.3. Aquitard hydraulic conductivity values were determined to be at least two orders of magnitude lower than typical values of aquifer K_h (ESI, 2014a). Aquitard K_v was an important parameter for model calibration and will be discussed further in Section 4.

In the Cloughton and Saltwick formations, aquifer hydraulic conductivity has been set to a uniform, isotropic value (as shown in Table 3.3). In the Moor Grit and Scarborough formations, variable hydraulic conductivity zones were required to aid model calibration. Anisotropy has been incorporated into the Moor Grit Formation in the model, representing less flow in the west-east dimension than south-north.

Hydraulic conductivity zones for the Moor Grit and Scarborough formations are shown in Figure 3.6 and summarised in Table 3.3.

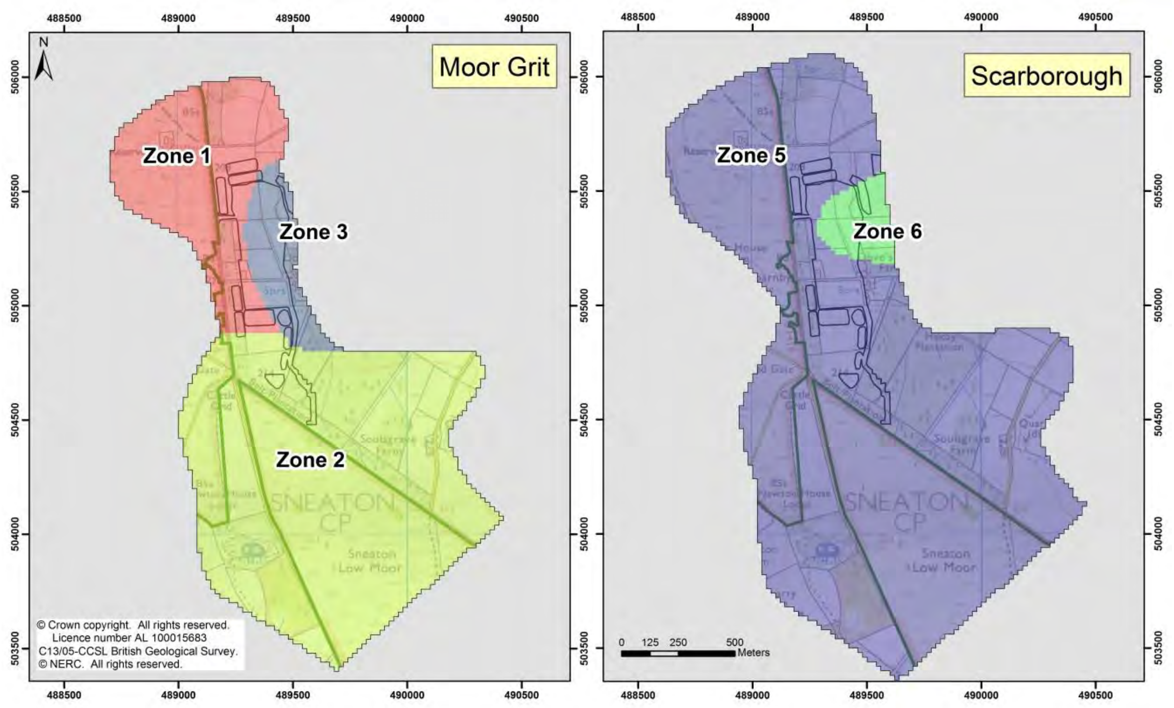

Figure 3.6 Modelled hydraulic conductivity zones in the Moor Grit and Scarborough Formations

The results of the pumping tests shown in Table 3.3 are discussed in more detail in the pumping test report (ESI, 2014a). Further details on the other hydraulic testing are available in the Hydrogeological Baseline Report (FWS, 2016a). These results suggest the possibility of anisotropy and spatial variation in K_h. In particular, the results from the Scarborough Formation show a range of several orders of magnitude which may be attributable to the local presence of fissures. It was therefore considered reasonable, after first attempting to achieve calibration using isotropic and spatially uniform parameter values, to explore spatial variation and anisotropy. More detail on the reasons for adopting the zones shown in Figure 3.6 above is provided in Section 4.1.1.

Table 3.3 Hydraulic conductivity – field measurements and modelled values

Layer	Zone	Strata	Hydrogeological characteristics	Estimated K_h range (m/s)			Modelled	
				Pumping tests*	**Packer tests****	**Variable head tests****	K_x (m/s)	K_y and K_z (m/s)
1	1	Moor Grit	Aquifer	1 x 10^{-7} – 3 x 10^{-6}	3.40 x 10^{-7} - 3.80 x 10^{-5}	3.2 x10^{-7} - 2.10 x 10^{-6} 4.32 x 10^{-7} - 2.99 x 10^{-5} (MG and SB)	2.3 x 10^{-6}	4.6 x 10^{-6}
	2						7.0 x 10^{-6}	7.0 x 10^{-6}
	3						5.8 x 10^{-5}	1.2 x 10^{-4}
2	4	Mudstone (MS1)	Aquitard	Unknown	1.20 x 10^{-6} to 5.20 x 10^{-6}	2.6 x 10^{-7} - 5.2 x 10^{-5} (aquifer and aquitard) 4.32 x 10^{-7} - 2.99 x 10^{-5} (MG and SB)	5.8 x 10^{-10}	5.8 x 10^{-10}
3	5	Scarborough	Aquifer	7 x 10^{-7} (unfissured)- 1 x 10^{-3} (fissured)	6.08 x 10^{-6} - 3.20 x 10^{-5}		2.3 x 10^{-6}	2.3 x 10^{-6}
	6						2.3 x 10^{-5}	2.3 x 10^{-5}
4	7	Mudstone (MS2)	Aquitard	Unknown	1.10 x 10^{-7} - 2.70 x 10^{-5}	1.11 x 10^{-9} to 6.97 x 10^{-7}	1.2 x 10^{-10}	1.2 x 10^{-10}
5	8	Cloughton	Aquifer	2 x 10^{-4} – 8 x 10^{-4}	2.33 x 10^{-5} - 3.25 x 10^{-5} (fractured siltstone) 6.45 x 10^{-5} - 1.21 x 10^{-4} (fractured sandstone)	1.09 x 10^{-7} (CL and SB aquitard) 1.70 x 10^{-6} - 5.68 x 10^{-5} (MG, SB, CL)	2.3 x 10^{-4}	2.3 x 10^{-4}
6	9	Ellerbeck Formation	Aquitard	Unknown	8.54 x 10^{-7} - 1.76 x 10^{-6}		9.3x 10^{-10}	9.3 x 10^{-10}
7	10	Saltwick	Aquifer	2 x 10^{-5} – 5 x 10^{-5}	3.20 x 10^{-5} - 5.75 x 10^{-5}	2.0 x 10^{-7} (aquifer and aquitard)	2.3 x 10^{-5}	2.3 x 10^{-5}

*Based on pumping tests (see ESI, 2014a) **FWS, 2016.

3.5.2 Specific storage

Unconfined specific yield was set to 0.05 (5%) and confined specific storage to 0.0015 (0.0005 in the Saltwick) in transient models. These values were determined by the fit to the amplitude of groundwater level variations.

3.6 Recharge

The Environment Agency's Water Framework Directive Recharge Calculator Version 2.63 (Environment Agency, 2007) has been used for assessing the transient variation in recharge at the Site. This tool is based on a water budget approach which estimates the direct (e.g. infiltration recharge) and indirect (e.g. run-off recharge) components of recharge. It includes estimations of effective rainfall, actual evapotranspiration and run-off (dependent on soil type, surface geology and land use) to determine actual recharge to an aquifer.

A recharge time series for the transient model has been calculated by inputting daily rainfall and potential evapotranspiration (PE) data into the recharge calculator. Several data sources have been used to reconstruct climate data time series:

- 1 January 2013 to 10 March 2014: daily rainfall and PE data (provided by the Met Office for MORECS Square 87).
- Due to time constraints and the availability of site data, data was not obtained from the Met Office for the update period. Therefore, from 11 March 2014 to 30 September 2015 (end of the model run period), daily rainfall and evapotranspiration data from a site weather station were used. Where the data was incomplete, the time series where infilled as follows:
    - Rainfall: data from the Whitby MET rain gauge. The data was weighted with a correlation between Whitby and site weather station to account for lower rainfall at Whitby than at the Site.
    - PE: long-term monthly average (1971-2000) of Met Office MORECS Square 87.

The resultant transient time series indicated an annual recharge of between 149 mm/a and 268 mm/a (based on clay soil type and 'rough grass/moor' land use) dependent on superficial deposit thickness and likelihood of bypass flow[3]. Given that MORECS Square 87 covers a large range of elevation, recharge at the Site was expected to be in the middle of this range.

Recharge in the steady state model has been set to 5.48×10^{-4} m/d (200 mm/a) during the process of model calibration and is considered to be a representative average value of recharge for the period to which the steady state model has been calibrated. In the transient model, the daily recharge sequence determined by the recharge calculator was summed on a monthly basis and factored to sum to an annual recharge of 200 mm/a (based on the steady state calibration) whilst maintaining the seasonal recharge variability. Recharge has been applied only to outcropping aquifer units and is zero where aquitard layers outcrop.

The transient recharge time series is shown in Figure 3.7 in comparison to monthly rainfall and PE (model input and Site weather station where different). There is no recharge simulated between April and October as PE is generally higher than rainfall during these months. As rainfall begins to exceed PE in the autumn, the soil moisture deficit is satisfied and recharge to groundwater can begin. Recharge is lower in the 2014/15 period than in 2013/14 – although rainfall was lower, this may partially relate to significant data gaps in the Site rainfall record for the period August to November 2014 and infilling with alternative data sources.

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[3] Determines Hydrology of Soil Type (HOST) class (see Boorman, D.B. and Hollis, J.M. Hydrology of Soil Types: A hydrologically-based classification of the soils of England and Wales).

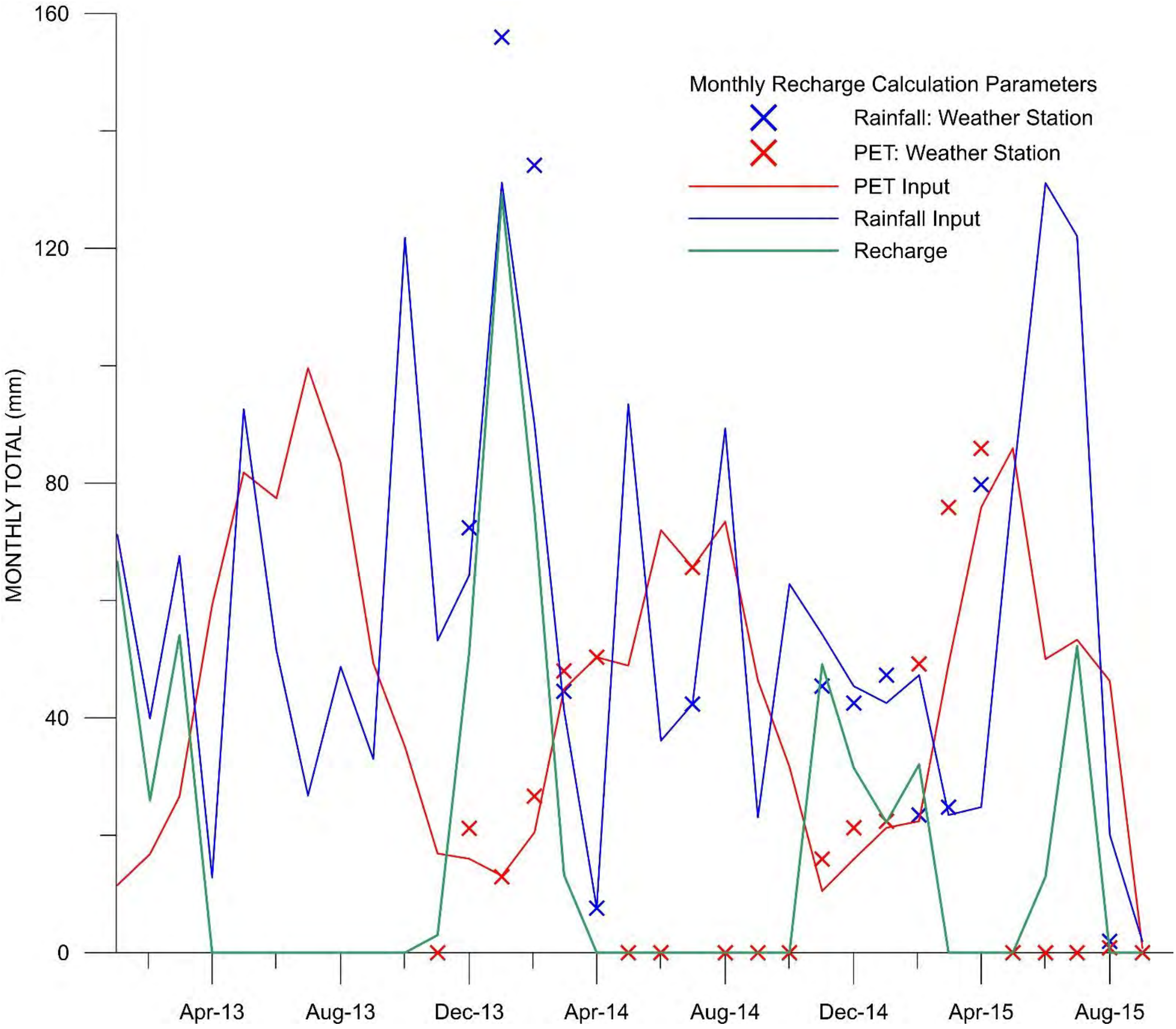


Figure 3.7 Monthly rainfall, PE and recharge used in the transient model run

4 MODEL CALIBRATION

Steady state and transient 'best estimate' calibration is discussed in the following sections. The steady state calibration focused on constraining the range of likely recharge and hydraulic conductivity and provided a 'best estimate' of typical heads to use as initial conditions for the transient run. Using a steady state model for calibration initially, rather than a transient model, significantly reduced the time required for model runs.

Transient calibration then focused on determining likely ranges of specific yield (unconfined) and specific storage (confined). Due to the intermittent nature of the small springs in the upper horizons, it is considered that the results of the transient model are more appropriate for reaching conclusions regarding the potential effect of the proposed development on the local groundwater system.

Both steady state and transient calibrations initially focussed on the period January 2013 to May 2014 (ESI, 2014b) and have since been extended to September 2015 for the transient model and March 2016 for the steady state model. Following review of the complete baseline data set to March 2016, which confirmed that these data were consistent with the existing model calibration, no recalibration was determined necessary as part of this model update. As such, the model results presented here include the full period January 2013 to September 2015.

Model calibration as part of this phase of modelling was focused on achieving a model that is fit for purpose for the following objective:

- Assessment of the effects of the proposed development on the Moorside Farm spring (MF2)/Spring Flush within Ugglebarnby Moor SAC.

As discussed in Section 3.1, the primary focus of the calibration was to simulate the steep vertical hydraulic gradients at the Site. Additionally, it was important to simulate the transient behaviour of the springs although, due to their intermittent nature, there were challenges with model cells drying that needed to be overcome to achieve this. It was accepted that accurate simulation of hydraulic gradients (and water levels) within individual layers would be hard to achieve. As discussed in Section 3.1, it is considered that the main strength of the model is in simulating the difference between two scenarios (i.e. change in flows or groundwater levels in response to construction activities) more reliably than the simulation of the absolute values.

4.1 Groundwater levels

Calibration to groundwater levels has focused on enabling the assessment of the effects of the proposed development on groundwater levels within Ugglebarnby Moor SAC.

4.1.1 Steady state calibration

Steady state groundwater level calibration targets have been set based on mean recorded groundwater levels during the period January 2013 to March 2016 at 72 observation boreholes. A complete dataset for this time period is not available for all observation boreholes, with monitoring at some locations within the Ugglebarnby Moor SAC only starting in January/February 2014. An additional 20 boreholes were drilled at the end of 2015 as part of the Phase 4 Stage 2 fieldwork investigations. Groundwater level data from these boreholes is only available from September 2015 to March 2016. This data has also been included, but average levels are only representative of those for this period.

Although average recorded levels provide a good indication of spatial variation in groundwater levels, the steady state model does not capture seasonal fluctuations. The transient model is therefore essential for assessing how potential impacts vary seasonally.

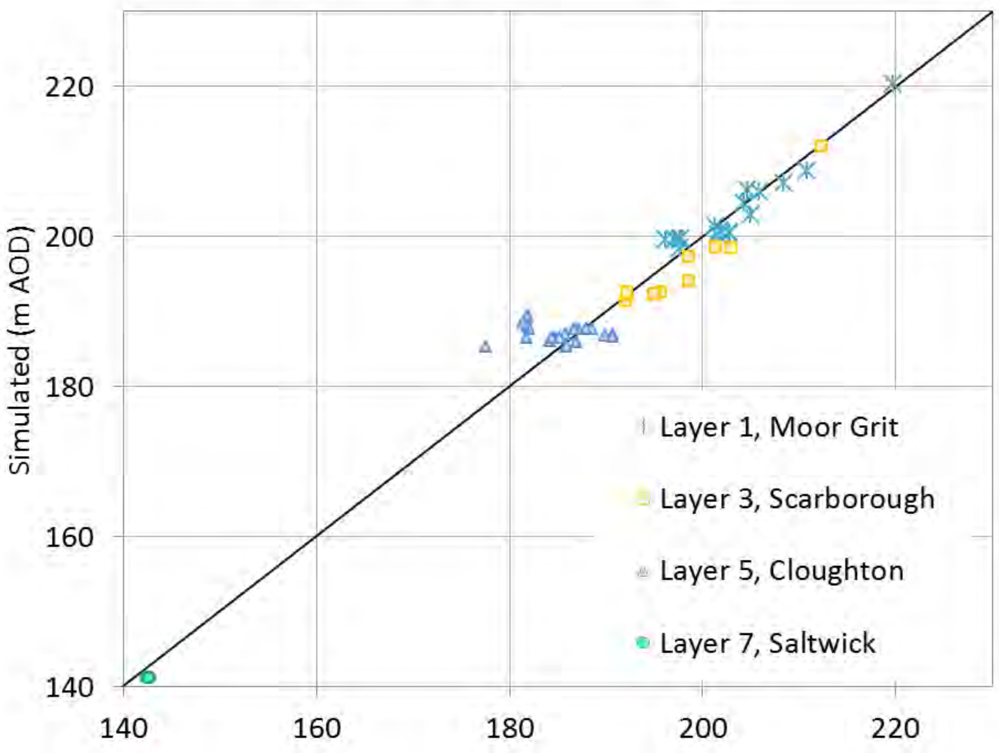
Plots of observed versus simulated heads for the steady state calibration are shown in Figure 4.1 and residuals for each model layer are presented spatially in Figure 4.2. A negative residual (labelled red in Figure 4.2) indicates that simulated heads are too high, whereas a positive residual (labelled blue in Figure 4.2) indicates that simulated heads are too low. Residual summary statistics are provided in Table 4.1 for the 72 boreholes used in the model as calibration targets. Boreholes drilled as part of the Phase 4 Stage 2 fieldwork investigations have also been included, even though observed data are only available since September 2015. The calibration statistics and plots indicate that model calibration is good particularly within the Moor Grit and Scarborough formations, where the main receptors are located.

Simulated groundwater contours for the Moor Grit and Scarborough formations are provided in Figure 4.3.

Table 4.1 Residual summary statistics for steady state model calibration

Statistic	All layers	Moor Grit	Scarborough	Cloughton	Saltwick
Number of observations	72	29	15	25	3
Range in mean of observations (m)	77.3	23.5	21.5	19.6	0.35
Absolute residual mean (m)	2.29	1.59	2.03	3.35	1.47
Scaled residual standard deviation (m)	0.96	0.84	0.98	0.023	0.048
Normalised sum of square residuals	73	30	19	29	350
Minimum residual (m)	-10.4	-3.43	-5.2	-10.4	1.32
Maximum residual (m)	8.0	2.34	4.46	8.0	1.65

51 initial OBHs used in the calibration process



20 additional Phase 4 Stage 2 OBHs (data from Sept 2015)

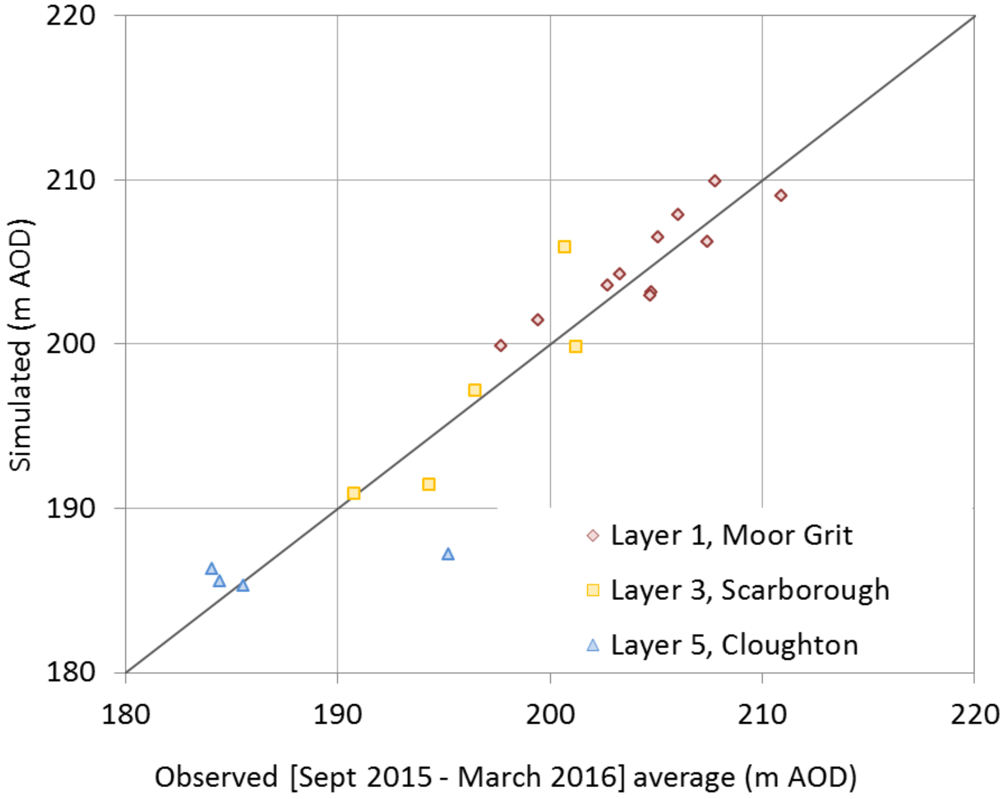


Figure 4.1 Steady state calibration – observed versus simulated groundwater levels

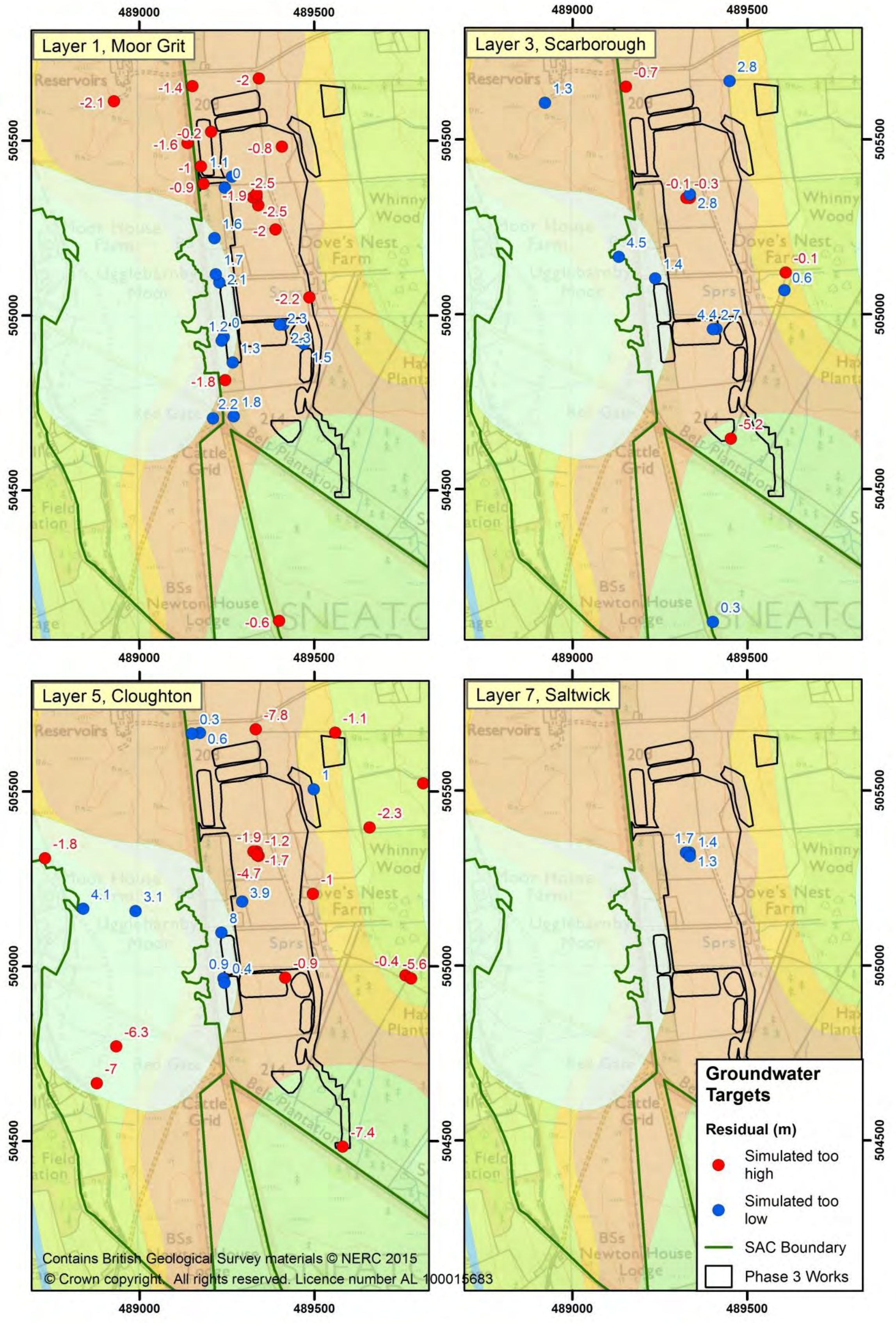


Figure 4.2 Steady state model – groundwater levels residuals for each model layer

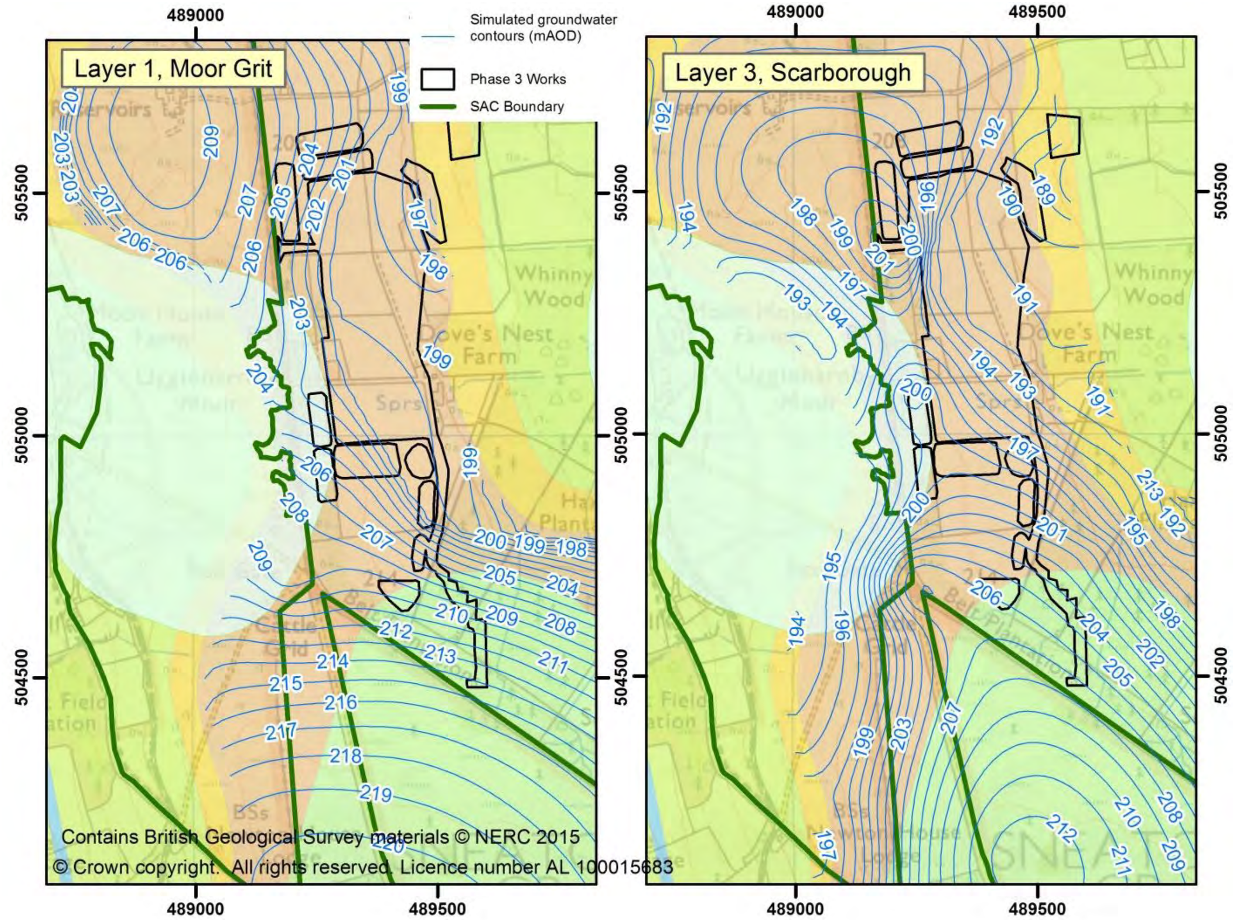


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Figure 4.3 Steady state model – Moor Grit and Scarborough groundwater contours

Residuals and groundwater contours for the Moor Grit and Scarborough formations show that a reasonable overall fit to observed heads and groundwater flow directions has been achieved. Where there is a relatively large change in the residual (and particularly where this changes from negative to positive) over a relatively short distance, this may be suggestive of local-scale processes which are not simulated in the model. Possible reasons for this are local perching due to lithological variation (including fractures), a heterogeneous hydraulic conductivity distribution, and vertical head gradients within the aquifer.

Despite concerted attempts, it was not possible to achieve adequate calibration using spatially uniform and isotropic parameters. In particular, the transition from relatively steep east-west gradients to the very flat gradient found along the eastern side of the model in the vicinity of the main shaft platform could only be simulated by inclusion of a high K zone in the eastern area (Zones 3 and 6 in Figure 3.6). The adoption of slightly lower K_x compared to K_y at the northern end of the Moor Grit aquifer (Zone 1) prevented the flattening of east-west gradients in this area that would have resulted from the higher K eastern zone. To the south in the Moor Grit and over most of the aquifer area in the Scarborough Formation (Zones 2 and 5), the isotropic K was unchanged from that used in the runs that produced the best calibration using isotropic and spatially uniform K values. Inclusion of variable hydraulic conductivity zones and anisotropy in the Moor Grit has allowed both the south-north and west-east gradients to be better replicated by the model.

Overall, representing the complex hydrogeological system using a multi-layered model has enabled the simulation of hydraulic separation between aquifer units and the vertical hydraulic gradients are well reproduced. Whilst some simulated heads are slightly too high and some too low within individual horizons, the calibrated steady state model successfully simulates the large range of heads between the various layers (i.e. the high degree of hydraulic separation). This model is therefore viewed as being a credible representation of the layered aquifer from this perspective. This vertical hydraulic separation is also replicated by the transient model (Section 4.1.2).

4.1.2 Transient calibration

Transient calibration to groundwater levels was carried out by comparing simulated heads with weekly manual dips undertaken at the Site for the period February 2013 to May 2014. This calibration was then checked against more recent data from May 2014 to 30 September 2015. There is a satisfactory fit to the more recent groundwater level data particularly in the Moor Grit and Scarborough formations. Therefore, only a check was performed on the existing calibration and it was considered unnecessary to recalibrate the model.

Observed (dots) and simulated (solid lines) hydrographs are shown in Figure 4.4 to Figure 4.10. The extended groundwater level times series beyond 30 September 2015 (the date to which the model was run until) are also plotted. Results from the transient runs are generally in keeping with the fluctuations in groundwater levels observed between October 2015 and March 2016.

Critical for transient modelling is the fit to the amplitude of groundwater level variations which are controlled by storage coefficients. Model calibration was therefore achieved through changes to specific yield (unconfined aquifers) or specific storage (confined aquifers). Observed and simulated groundwater level trends and the range of variation are well matched, particularly in the Moor Grit and Scarborough aquifers (e.g. HG3 at the Site and HG116 in the SAC). Within the Cloughton Formation, the model tends to simulate a flatter piezometric surface which also tends to be slightly higher compared to the observed levels. As with the Moor Grit and Scarborough aquifers this may reflect spatial variation in hydraulic properties. However, the focus of the model is in determining the impacts on receptors that are linked to the Moor Grit and Scarborough aquifers. The quality of calibration in the Cloughton Formation is considered adequate for this purpose.

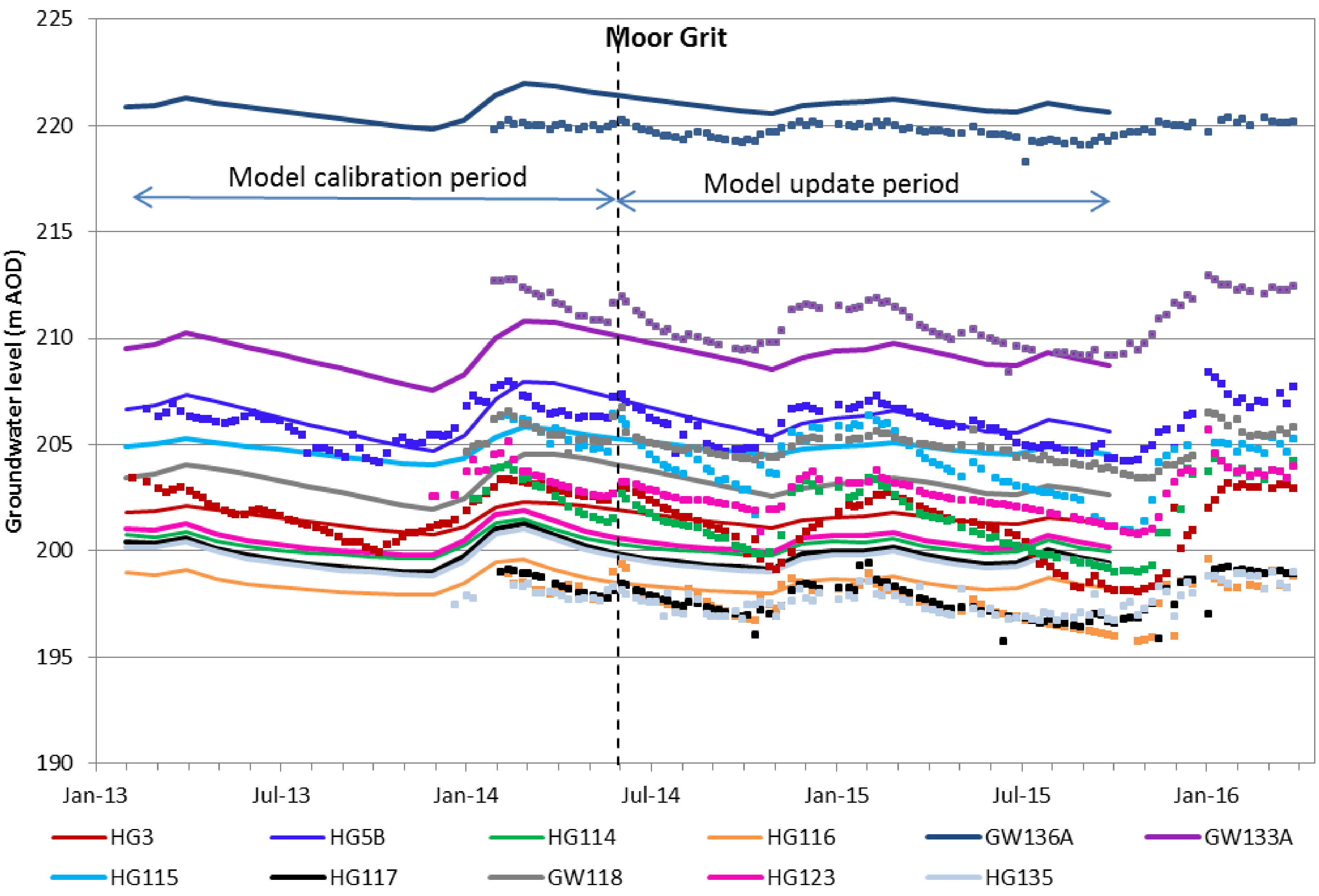

Figure 4.4 **Transient model – Comparison of observed (dotted) and simulated (lines) hydrographs, Moor Grit**

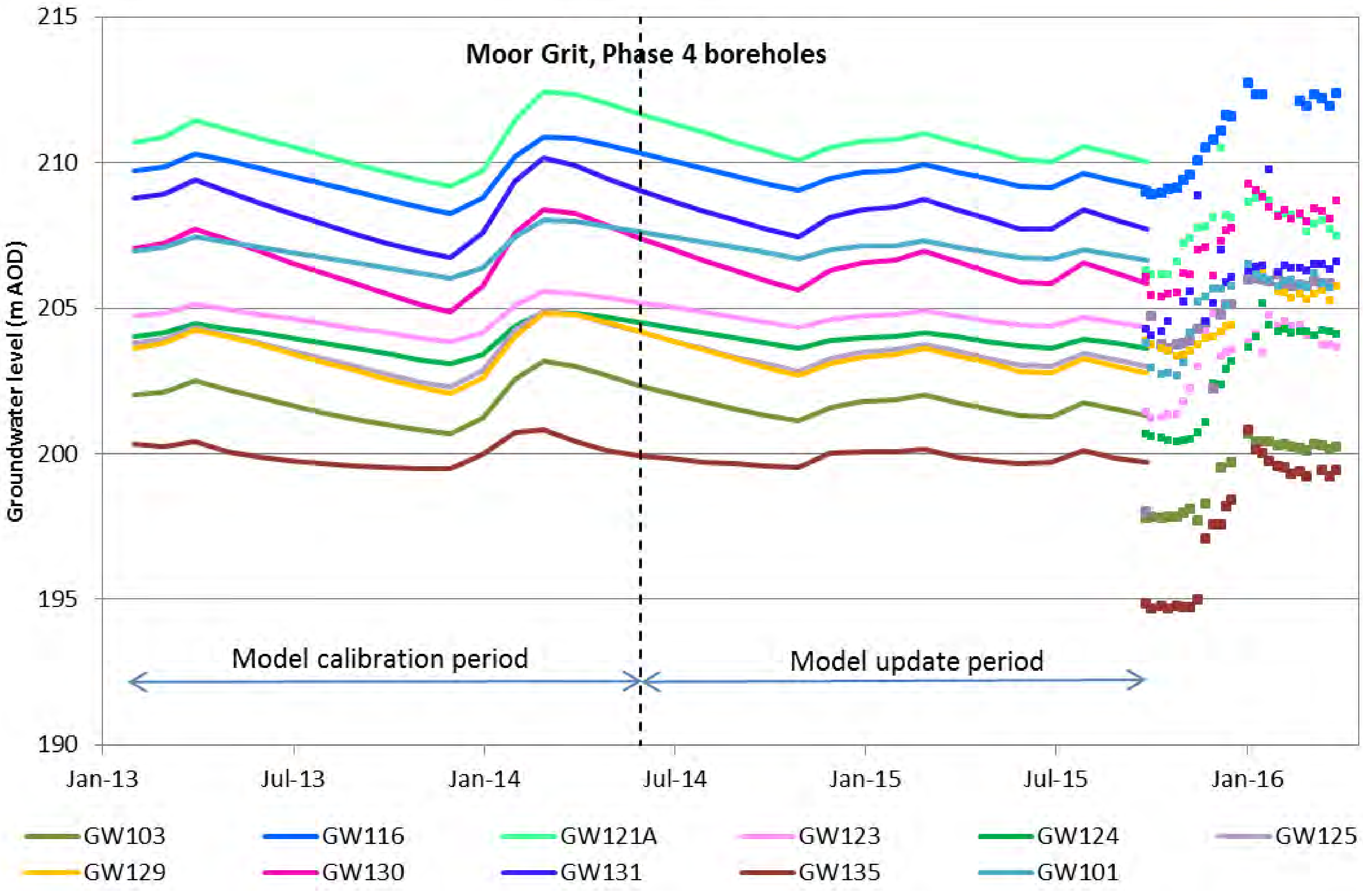

Figure 4.5 Transient model – Comparison of observed (dotted) and simulated (lines) hydrographs, Moor Grit (Phase 4 Stage 2 fieldwork investigation boreholes)

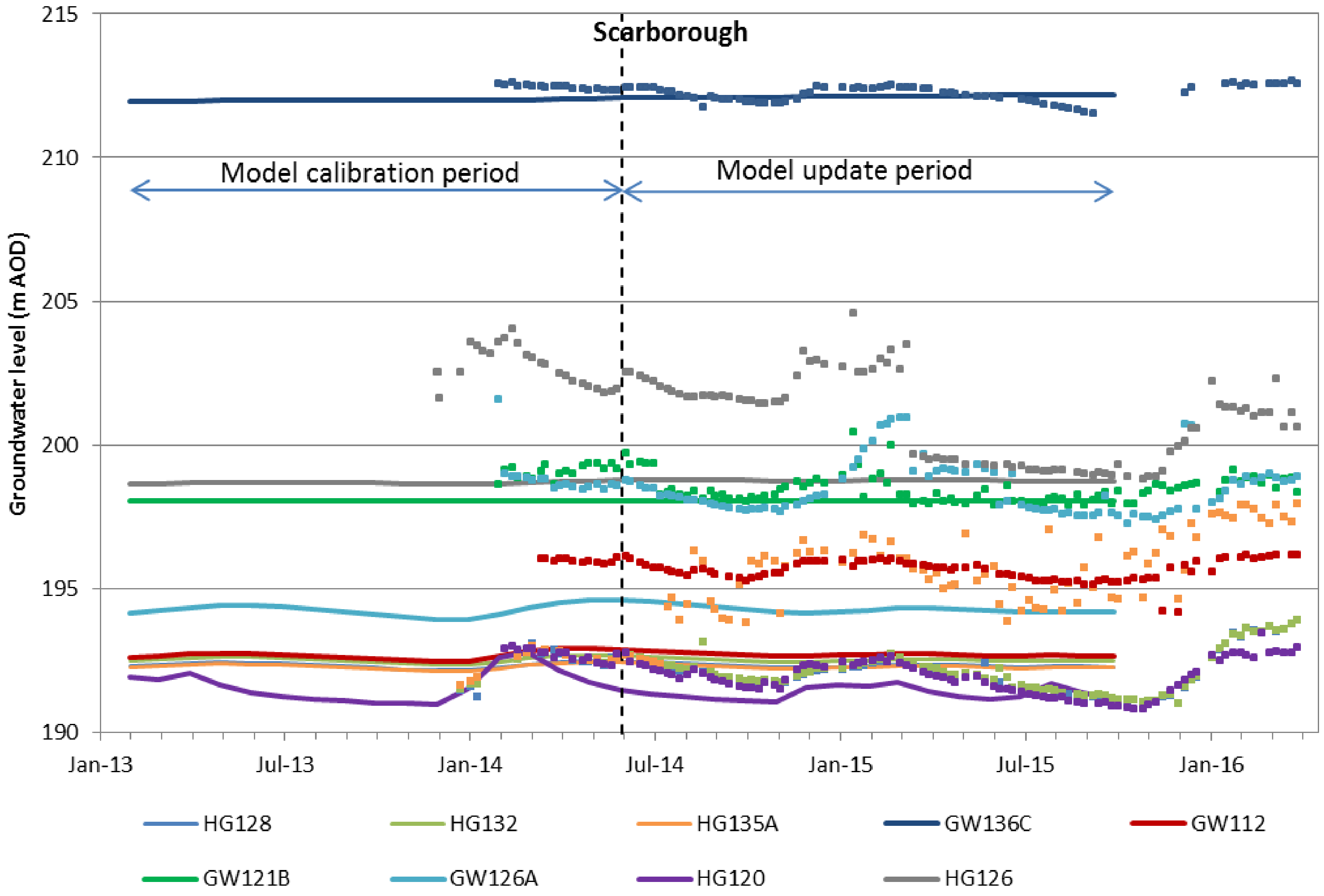

Figure 4.6 Transient model – Comparison of observed (dotted) and simulated (lines) hydrographs, Scarborough

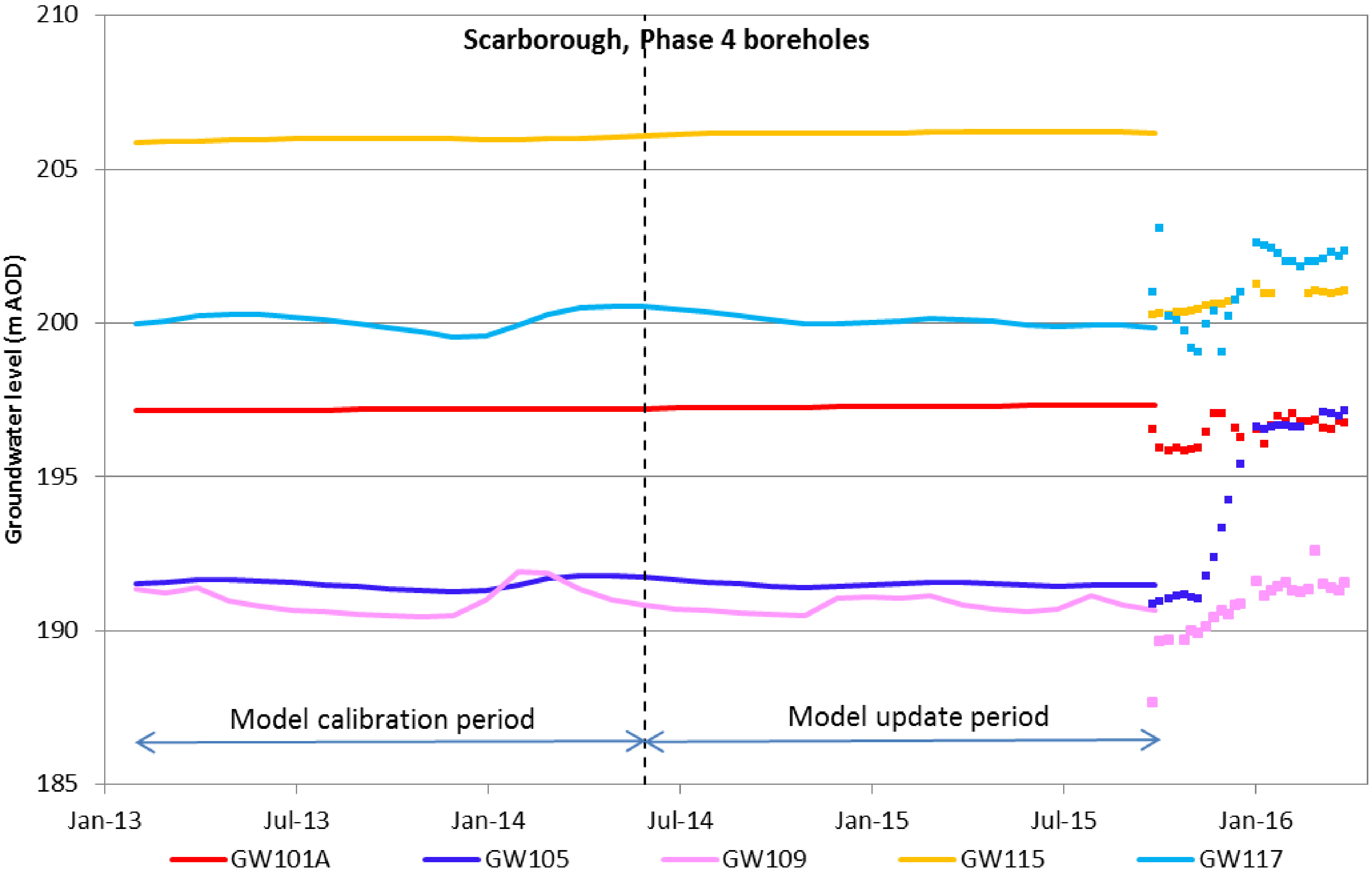

Figure 4.7 Transient model – Comparison of observed (dotted) and simulated (lines) hydrographs, Scarborough (Phase 4 Stage 2 fieldwork investigation boreholes)

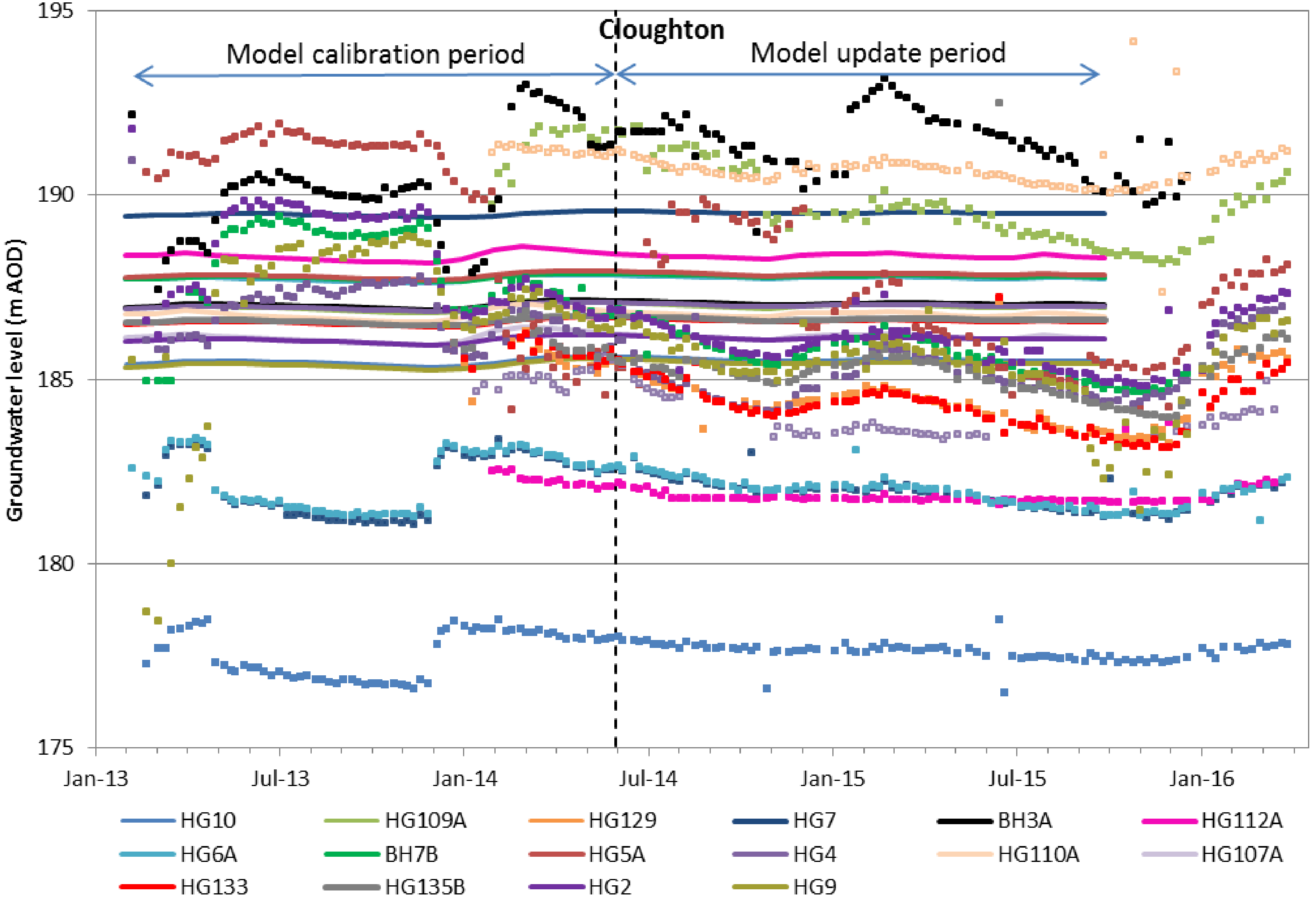

Figure 4.8 **Transient model – Comparison of observed (dotted) and simulated (lines)hydrographs, Cloughton**

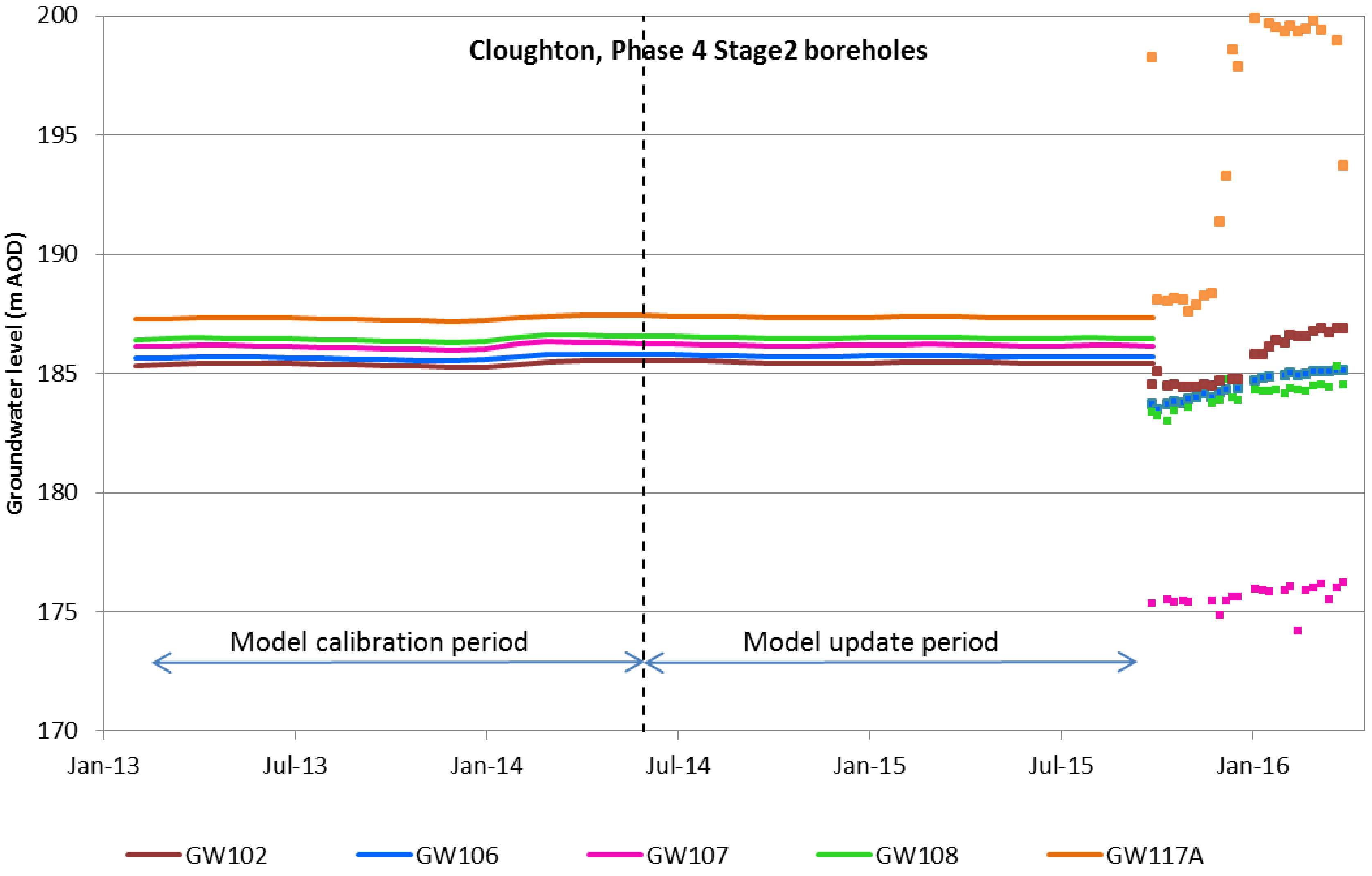

Figure 4.9 **Transient model – Comparison of (dotted) and simulated (lines) hydrographs, Cloughton (Phase 4 Stage 2 fieldwork investigation boreholes)**

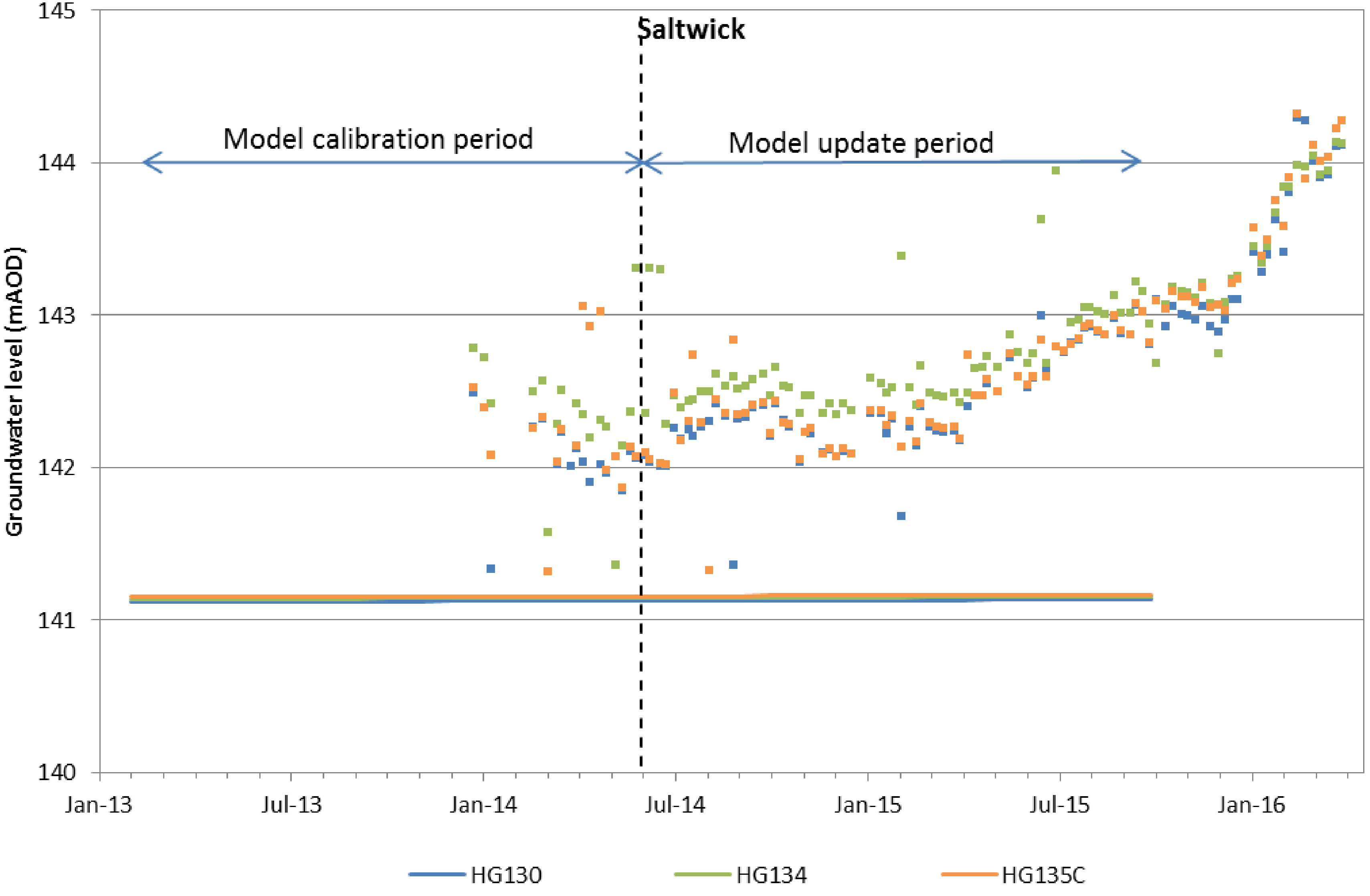

Figure 4.10 Transient model – Comparison of observed (dotted) and simulated (lines) hydrographs, Saltwick

4.2 Water Balance

Achieving hydraulic separation between aquifer layers in the model required a sensitive balance between recharge to outcropping aquifer formations and vertical flux between intervening aquitard layers. Despite the very low vertical hydraulic conductivity of aquitard layers, vertical flux between aquifer units dominates over horizontal flow (except in the Moor Grit). This is due to the large surface available over which vertical fluxes can occur. This does not suggest a high degree of connection between aquifer units.

For a given amount of recharge, vertical flux has to be sufficiently high to permit a sufficient amount of water to enter lower aquifer layers, but low enough to prevent drying of upper aquifer layers. This is illustrated by the water balance for the steady state model which is differentiated by model layer and presented in Table 4.2. Figure 4.11 shows this water balance for the steady state model in the format of a flow chart.

Approximately 44% of water flowing into the Moor Grit (via recharge) is released through the base and flows vertically to the underlying Scarborough Formation. This is either through the intervening aquitard layer, or by more diffuse downward seepage around the edge of the outcrop[4]. Of the remaining 56%, the majority is discharged via spring flow or diffuse seepage. Lateral outflows from the Moor Grit and Scarborough formations are in part constrained by calibration to observed spring flow (plus an allowance for diffuse seepage) and are discussed further in Section 4.3.

The lower aquifer layers are fed both by vertical flux from upper layers and GHB inflow. As with the Moor Grit, this is released via vertical flow into the lower layers or diffuse flow around the outcrop boundary.

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[4] The latter process is not formally represented in the model but, if occurring, would be captured during calibration by use of a slightly higher K_v in the underlying aquitard which, it is considered, would make the model generally conservative with respect to the assessment of effects of deeper dewatering activities on these shallow horizons.

Table 4.2 Steady state water balance by model layer

	Inflow (m^3/d)	Outflow (m^3/d)	Error (%)
Layer 1 (Moor Grit)			
Bottom	0.5	499	
GHB	61	145	
Drain	-	565	
Recharge	1,146	-	
Total	*1,208*	*1,208*	-5.6×10^{-3}
Layer 2 (MS1)			
Top	499	0.54	
Bottom	0.54	499	
Total	*499*	*499*	-6.8×10^{-6}
Layer 3 (Scarborough)			
Top	499	0.54	
Bottom	0.89	560	
GHB	22	1.2	
Drain	-	116	
Recharge	156		
Total	*677*	*677*	-1.1×10^{-4}
Layer 4 (MS2)			
Top	560	0.89	
Bottom	0.89	560	
Total	*561*	*561*	-6.2×10^{-7}
Layer 5 (Cloughton)			
Top	560	0.89	
Bottom	0	8,538	
GHB	5,886	1,118	
Drain	-	1,938	
Recharge	5,150		
Total	*11,595*	*11,595*	-1.1×10^{-4}
Layer 6 (Ellerbeck Formation)			
Top	8,538	0	
Bottom	1.8×10^{-4}	8,538	
Total	*8,538*	*8,538*	3.9×10^{-10}
Layer 7 (Saltwick)			
Top	8,538	1.8×10^{-4}	
GHB	200	941	
Drain	-	8,295	
Recharge	497	-	
Total	*9,236*	*9,236*	-3.7×10^{-6}

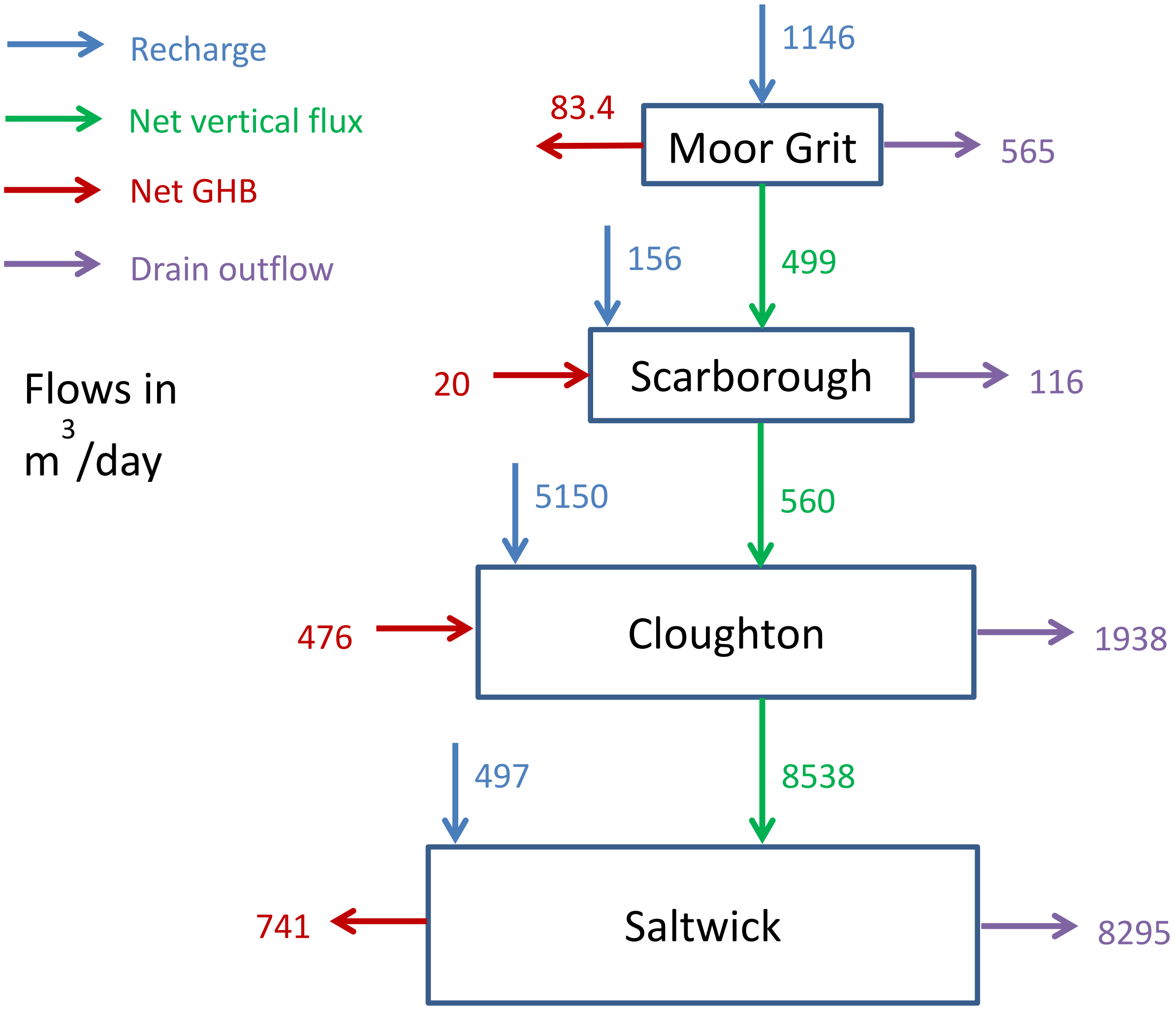


Figure 4.11 Flow chart of water balance by model layer

4.3 Spring flows

4.3.1 Steady state calibration

As discussed in Section 3.4.2, a number of springs were represented in the model using MODFLOW Drain cells. Spring flows simulated in the steady state model are summarised in Table 4.3. The full ranges of spring flows measured to date are given in Table 4.3 for comparison to the simulated flows.

In general, the steady state model simulates broadly the right amount of average flow at the various springs. However, because the springs are intermittent, it may be realistic to assume that some springs may be dry under steady state conditions. In this case the transient model provides a better approximation to flow (Section 4.3.2).

Flow at the Moorside Farm Spring (MF2) was simulated to be 0 m^3/day at steady state. Measured flows in the spring have varied from 0 – 22 m^3/day. Steady state represents long term average conditions; as Moorside Farm may only flow under higher water table conditions it is quite reasonable that no flow would be seen under average conditions. Flow at SP01 was simulated as the western edge of the Moor Grit in the model, as is discussed above.

Table 4.3 Steady state model – observed and simulated spring flow

Spring ID	Name	Source aquifer	Model layer	Measured flow (m^3/d)	Simulated flow (m^3/d)
SP01	Moorland spring	Superficial deposits/Moor Grit	3	0 – 68	12.1
SP02	Hempsyke spring	Cloughton	5	0 – 70	187
SP03	Quarry spring	Cloughton	5	10 – 2,321	106
SP04	Windmill Hill Plantation Spring	Moor Grit	1	Not measured	0
NHF	Newton House Farm	Cloughton	5	Not measured	79
SF2	Soulsgrave Farm Spring	Scarborough	3	0 – 97	2
MF2	Moorside Farm Spring	Superficials/Moor Grit	1	0 – 22*	0
DNS1	Dove’s Nest Farm	Moor Grit	1	0 – 432	1
	Moor Grit outcrop edge				497
	Scarborough outcrop edge				131
	Cloughton outcrop edge				712
	Saltwick outcrop edge				1,867
	Discharge to River Esk				7,281
	Drilling platform				4

*Flow at MF2 measured at MF1

4.3.2 Transient calibration

Simulated transient and observed spring flows at Moorside Farm are shown in Figure 4.12. On this plot, simulated flows (averaged over a one month model stress period) are compared to spot observed flows which are recorded at a given time instance. As a result a direct (or quantitative) comparison is not appropriate. It is known that the spring flows are flashy and respond rapidly to rainfall events (FWS, 2016a). Whether this flashy nature is captured in measured flows depends on the date gauging is carried out. Similarly, observed flows may have a run-off component which will not be captured by the model.

Despite this, a reasonable fit to spring flows at Moorside Farm Spring (MF2) is achieved and the transient model is considered to be suitable for assessing the effects of the proposed development on spring flow at MF2 (as set out in the model objectives).

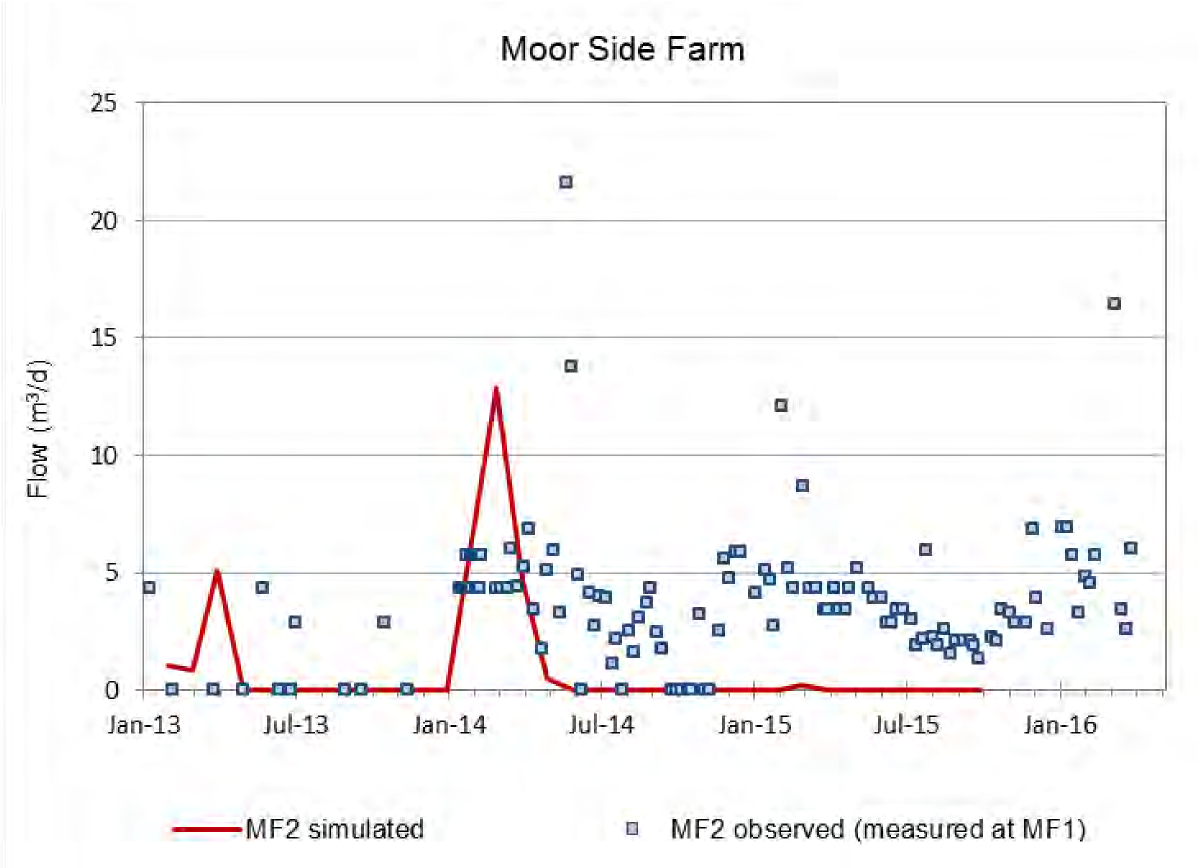


Figure 4.12 Transient model – simulated and observed spring flow at Moor Side Farm spring

4.4 Summary of Model Credibility and Appropriate Use

The multi-layered, transient model that has been developed from the extended baseline data (FWS 2016a) is considered to represent a significant improvement on the latter (ESI, 2013). In particular:

- The model simulates the steep vertical hydraulic gradients observed between the various thin aquifer layers on Site accurately; and
- The model simulates the seasonally intermittent flows in the key springs effectively.

Whilst the quality of fit between observed and simulated is variable across the model area, this is not considered to be a significant limitation on its use in predictive mode as models are generally accepted to represent the differences between two scenarios more reliably than the simulation of absolute heads and flows.

The update to the model undertaken specifically for predicting the effects of the Phase 2 Works and now Phase 3 Works confirms an adequate degree of model calibration to groundwater levels and spring flow and no recalibration was necessary.

The model is thus considered to be an appropriate tool for use in assessing the likely effect of the proposed Phase 3 Works on the local groundwater systems.

5 PREDICTIVE SCENARIOS

5.1 Modelled Phase 3 Works

The Phase 3 Works design is shown on the Dove's Nest Farm Construction Phase 3 Masterplan (Drawing no. YP-P10-DNF-CX-050) (FWS, 2017). Features of the design that are expected to impact on groundwater levels and spring flows have been simulated in the model. These elements are listed below and further details are presented in FWS (2017).

1. Extension to South Shaft Platform to a minimum of 202.6 m AOD, including a lined perimeter drain that will not drain groundwater.
2. Construction of a laydown and batching plant area.
3. Construction of a re-infiltration well platform and lagoon in the southern area.
4. Construction of new soil mounds around the shaft platform.
5. Construction of new lined attenuation ponds to the east.
6. Installation of dewatering wells around the Service, Production and MTS shafts with abstraction sufficient to reduce groundwater levels to 3 m below platform levels. Target groundwater levels are 200.5 m AOD at the Production Shaft, 200 m AOD at the Service Shaft and 197.5 m AOD at the MTS shaft.
7. Construction of a spring and groundwater drainage collection system in the north-east to a depth of 0.5 m below existing ground level.

Areas covered by features described in 1 to 5 above have been simulated in the groundwater flow model as no recharge zones. Over these areas, no recharge to groundwater is permitted. These zones are shown in Figure 5.1 and Figure 5.2 for the Moor Grit and Scarborough formations respectively. The no recharge zones incorporate and extend beyond those simulated by the Phase 2 Works modelling (ESI, 2016). In the model, recharge is only allowed to the upper most active layer. Therefore, the designated no recharge zones mostly only directly affect the Moor Grit Formation, but there are some direct effects on the Scarborough Formation and underlying formations to the east.

Thirty seven dewatering wells have been incorporated into the model as drain boundary conditions. These wells have been positioned around the Production Shaft, Service Shaft and MTS Shaft as is shown in Figure 5.1 Around the Production and Service shafts, a drain level of 196 m AOD has been set (within the Moor Grit Formation in Layer one). Around the MTS Shaft, the drain stage is set to be approximately at the base of the modelled Moor Grit Formation in this area (195 – 196 m AOD). These levels were chosen so that the required dewatering levels listed in point 6 (above) could be reached quickly.

The drain boundary cells cause groundwater levels to the lowered to the drain stage. This is analogous to pumping to the drain stage level. Drain conductance was set sufficiently high to ensure that there was no additional resistance to flow out of the model. This makes the hydraulic conductivity of the Moor Grit the limiting factor to outflow, as would be the case with dewatering in the field. The model calculates the rate of flow from the model through these drain cells, which is equivalent to the pumping rate required to achieve the levels calculated by the model.

Drain boundary cells were placed at a stage of 0.5 m below ground level to represent the groundwater drainage collection system (described in point 7). Due to the outcrop pattern, these cells are variably placed in the Scarborough and Cloughton formations where these outcrop at the surface.

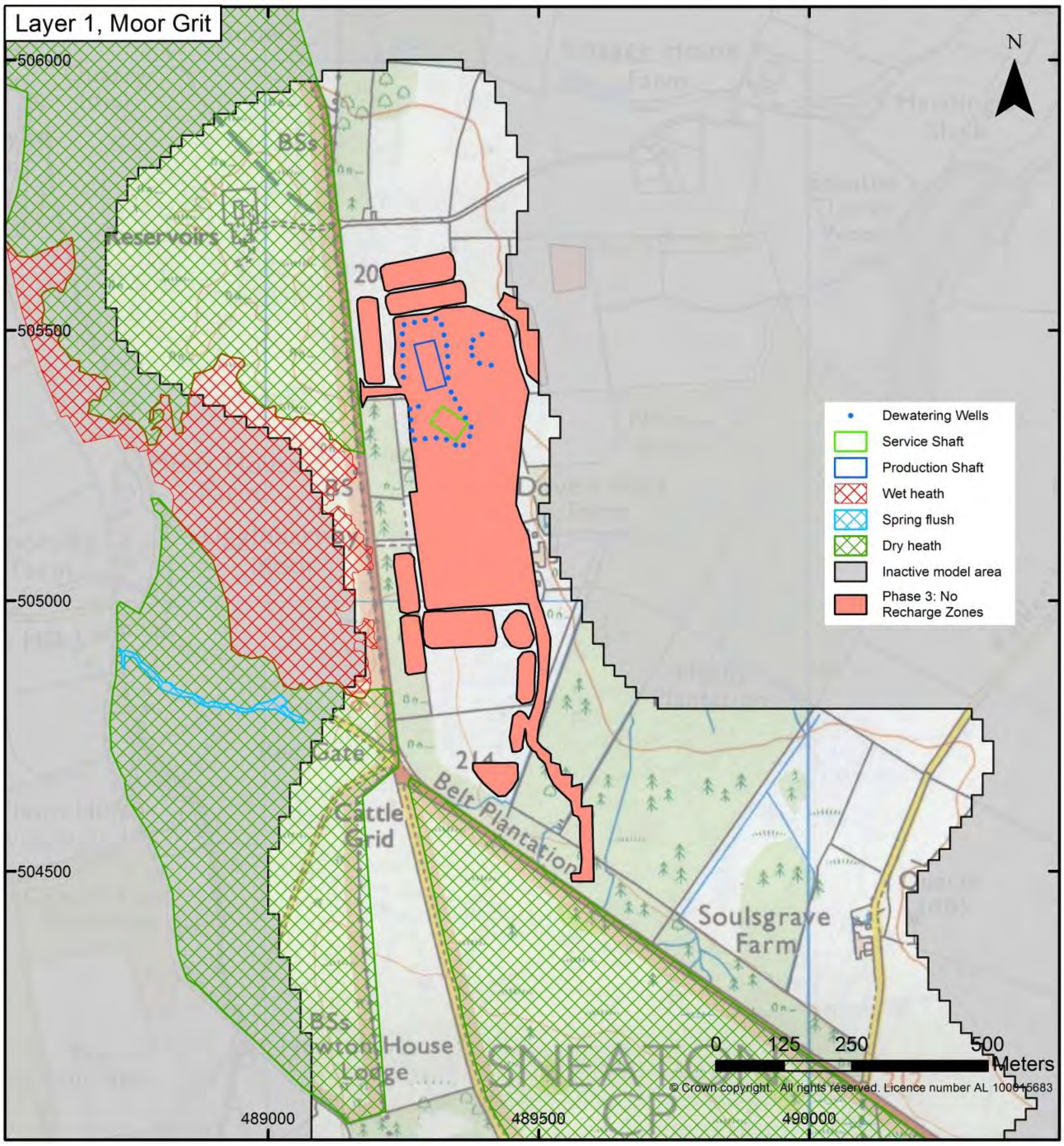


Figure 5.1 Phase 3 Works features represented in layer one (Moor Grit)

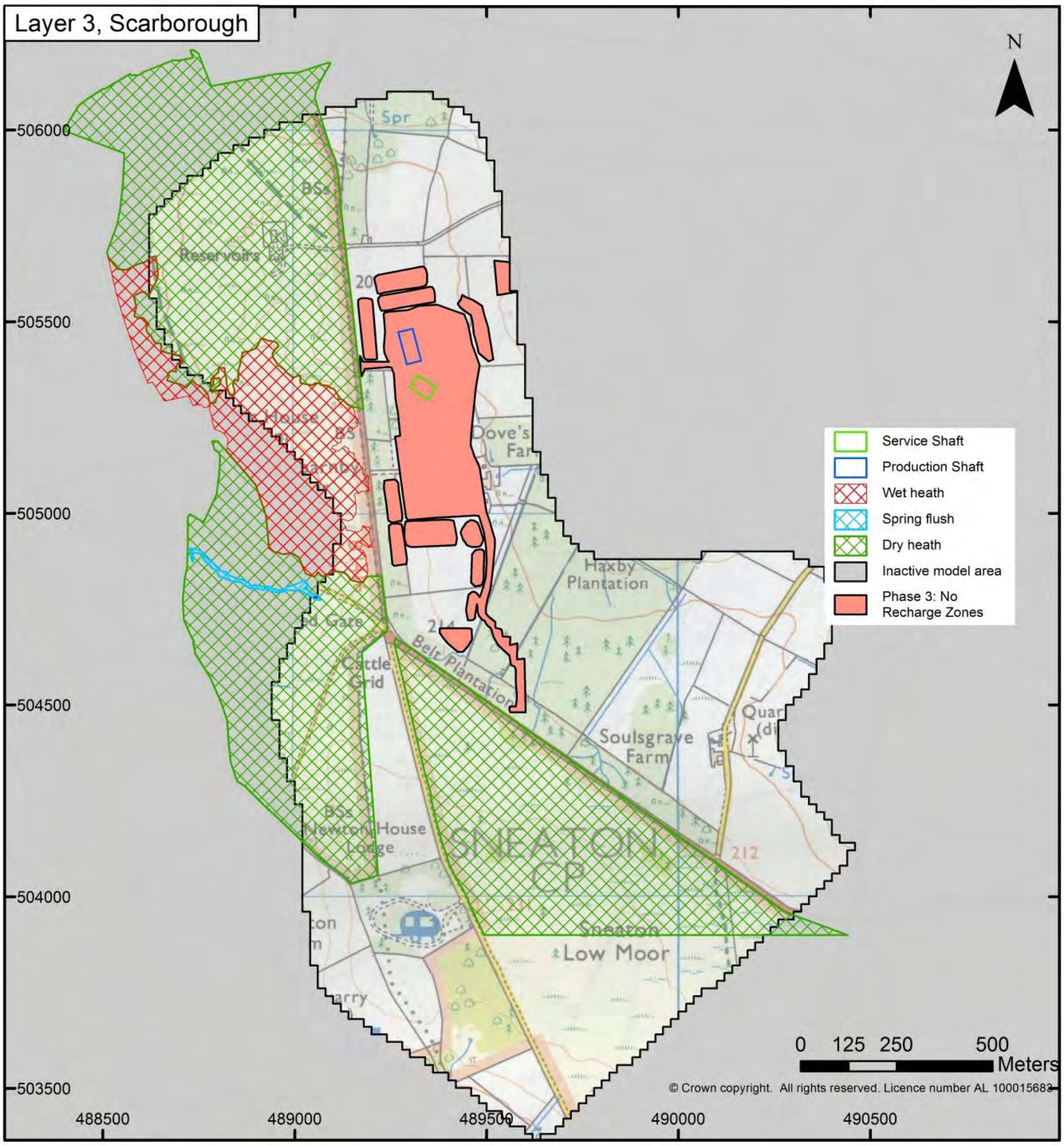


Figure 5.2 Phase 3 Works features represented in layer two (Scarborough).

5.2 Groundwater Model Runs

In order to simulate the effect of the Phase 3 Works on the MF2/Spring Flush area of Ugglebarnby Moor SAC, one conservative transient model run was undertaken. The details of this run are outlined below:

- Transient post-development run with calibrated steady state recharge over summer and autumn and a high recharge in winter. This summer and autumn recharge is much higher than would typically be expected. This run was undertaken to conservatively determine maximum change in groundwater levels within the first year (which tend to be greater with higher baseline groundwater levels brought about by higher recharge).

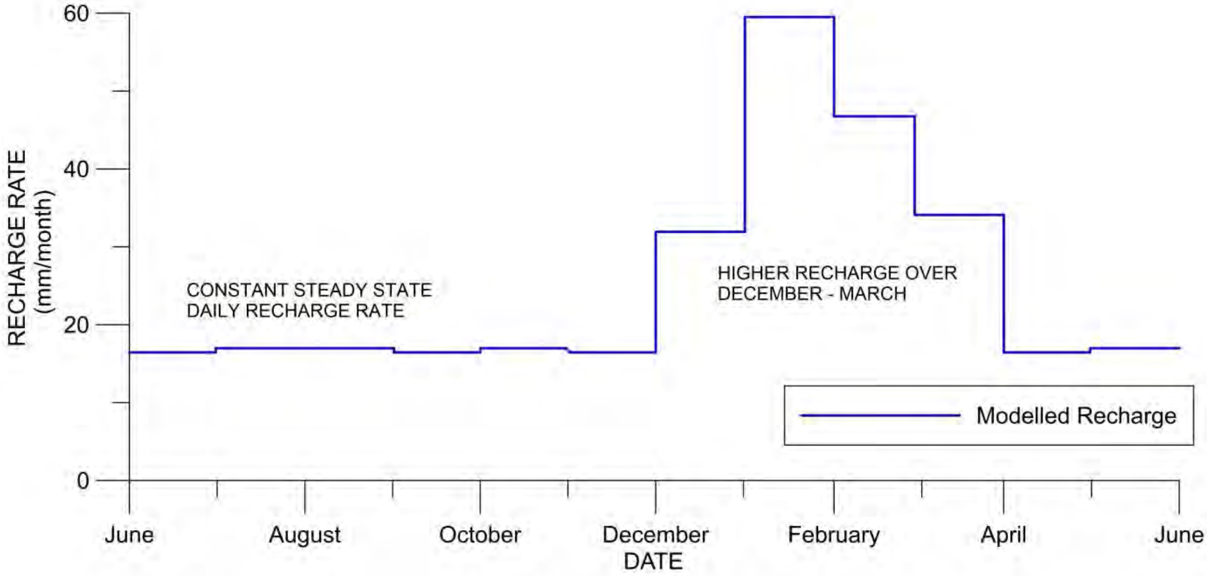


Figure 5.3 shows the recharge profile through time used in the transient model run. Recharge was maintained at the steady state daily rate of 0.55 mm/day from June to November, and thereafter increased to a maximum rate of 1.92 mm/day in January. This rate then decreases through to April when the steady state rate is resumed. These rates were multiplied by the number of days in each month to generate the total monthly recharge shown in Figure 5.3. This recharge profile corresponds to a total annual recharge of 306 mm which is approximately 50% more recharge than the calibrated annual recharge of 200 mm (based on rainfall and PET data).

Utilising such a high recharge is conservative in terms of changes in groundwater level and spring flows. This is because the base case high recharge scenario will predict higher groundwater levels, and therefore these levels have further to fall, particularly around the dewatering wells. This conservative model run has been chosen because the actual recharge is yet to occur and therefore unknown and, given this, a conservative approach was considered the most appropriate. In reality, recharge over the summer months (June to September) is likely to be close to zero, but the winter recharge could be similar to the profile used in the model. Due to the conservative nature of this model, results presented in Section 6 should be treated as upper bounds.

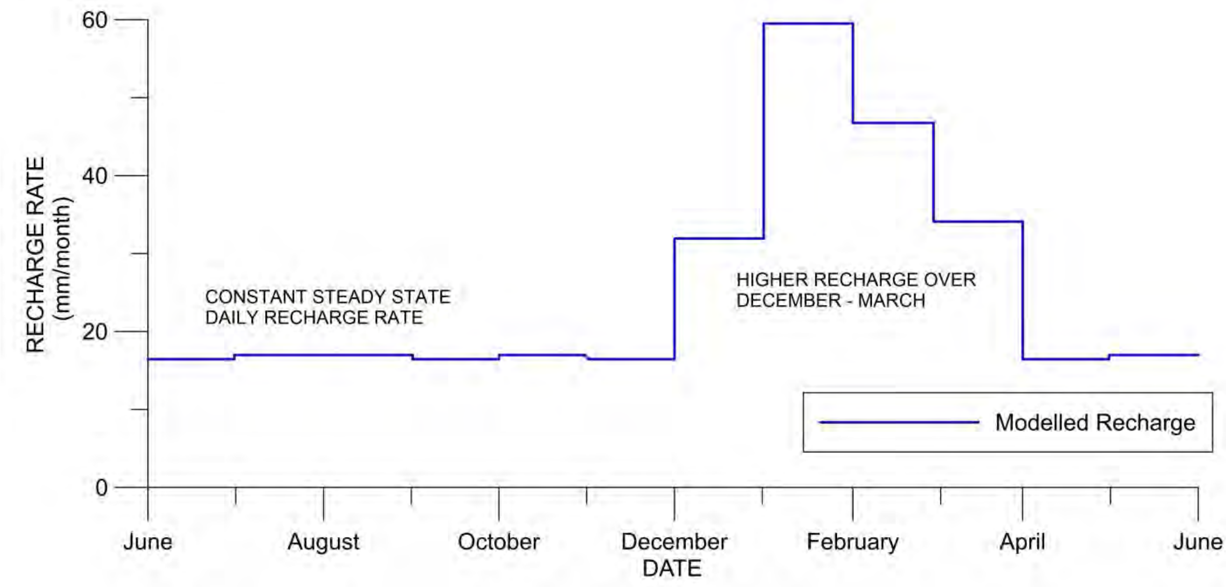


Figure 5.3 Graph of monthly recharge used for transient modelling

The base case steady state heads were taken as the initial conditions at the start of the model runs. For the post development model run, all of the Phase 3 Works were implemented instantaneously on 1st June 2017 (the start of the model run).

Steady state modelling represents long term average conditions. Predictive steady state runs have not been undertaken as part of this work. This is because the dewatering wells and many of the soil bunds (lasting 5 years) will be temporary construction features only and will therefore not influence long term average groundwater level conditions. Also, further construction work is planned following the one year period simulated for the Phase 3 Works as part of this modelling work. Subsequent construction works will modify the groundwater system further and the resultant changes to the groundwater flow system will be more representative of actual long term conditions. Steady state model results for the proposed Phase 3 Works will therefore not be representative of final development conditions, which are to be addressed by modelling of the subsequent construction phases.

6 RESULTS OF PREDICTIVE SCENARIOS

Differences between the base case and post-development models are presented in the following sections. These differences in groundwater levels allow the effects of the Phase 3 Works on groundwater levels and spring flows to be determined. These results can then be used to assess the effects of the proposed development on the Moorside Farm spring (MF2)/Spring Flush area within Ugglebarnby Moor SAC.

6.1 Assessment points

Changes in groundwater level as a result of the Phase 3 Works have been assessed under transient conditions at certain assessment points, chosen to be located near to the Moorside Farm Spring habitat of the SAC. Figure 6.1 and Figure 6.2 show the locations of the groundwater level assessment points within the Moor Grit and Scarborough formations respectively. Residuals at the target locations for the steady state calibration model (simulated levels too high or too low) are also displayed in the figures for ease of reference. Changes in spring flows have also been assessed at the springs shown in Figure 2.1. Table 6.1 provides details of the assessment locations used in the model.

Target locations with the prefix GW correspond to actual monitoring points installed by FWS (FWS 2016b) as opposed to theoretical assessment points. Changes in groundwater levels are of most interest for this study, and therefore the absolute levels and residuals of the assessment points are of lesser importance. It is not appropriate to view areas of higher and lower absolute residuals as being correlated with confidence in the results. The model calibration, as is indicated in Section 4.4, is considered good and the models are considered to be fit for the required purpose and suitable for predicting changes in groundwater levels in the Moor Grit and Scarborough formations.

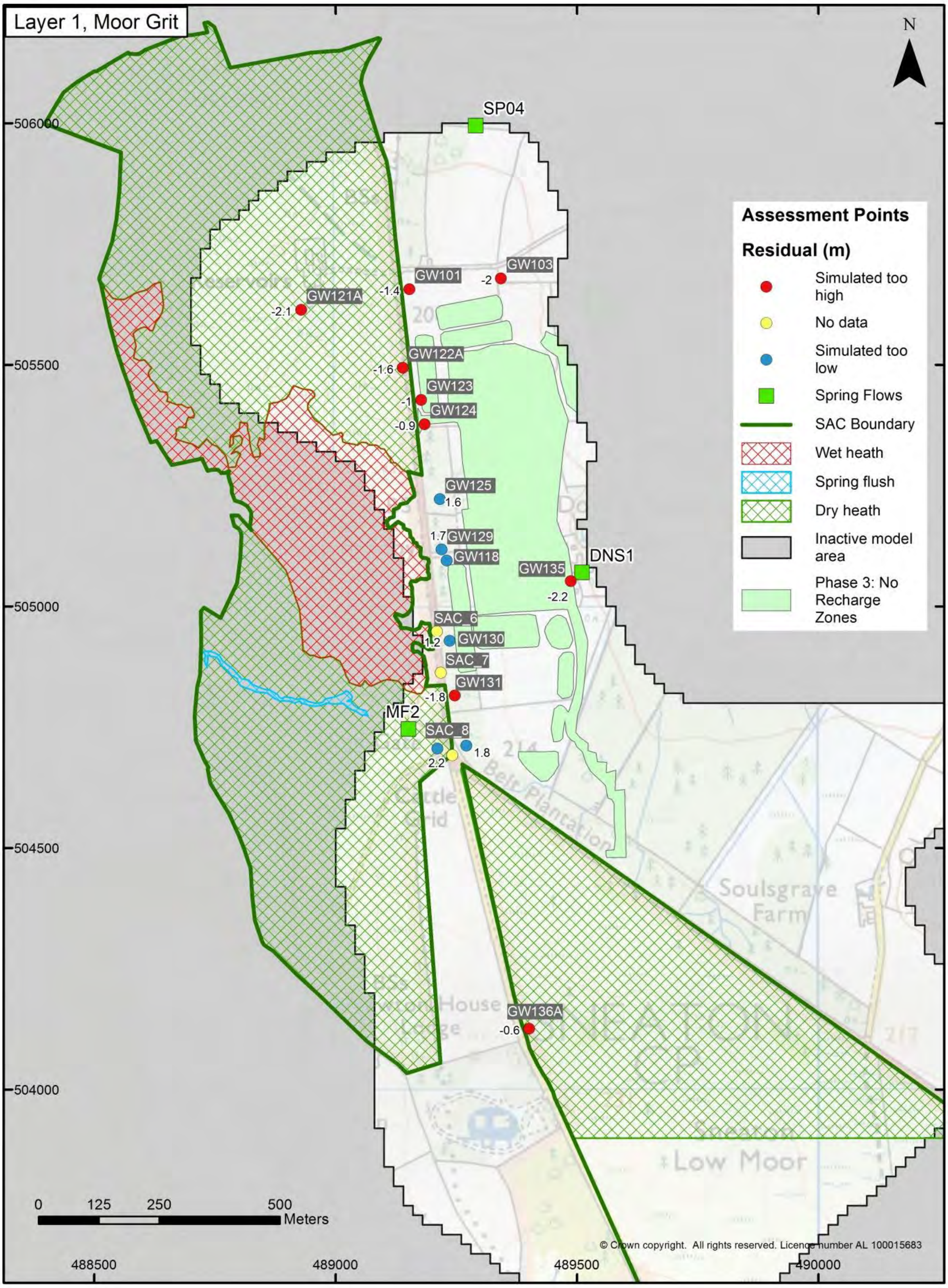


Figure 6.1 Location of groundwater level assessment points in Moor Grit Formation

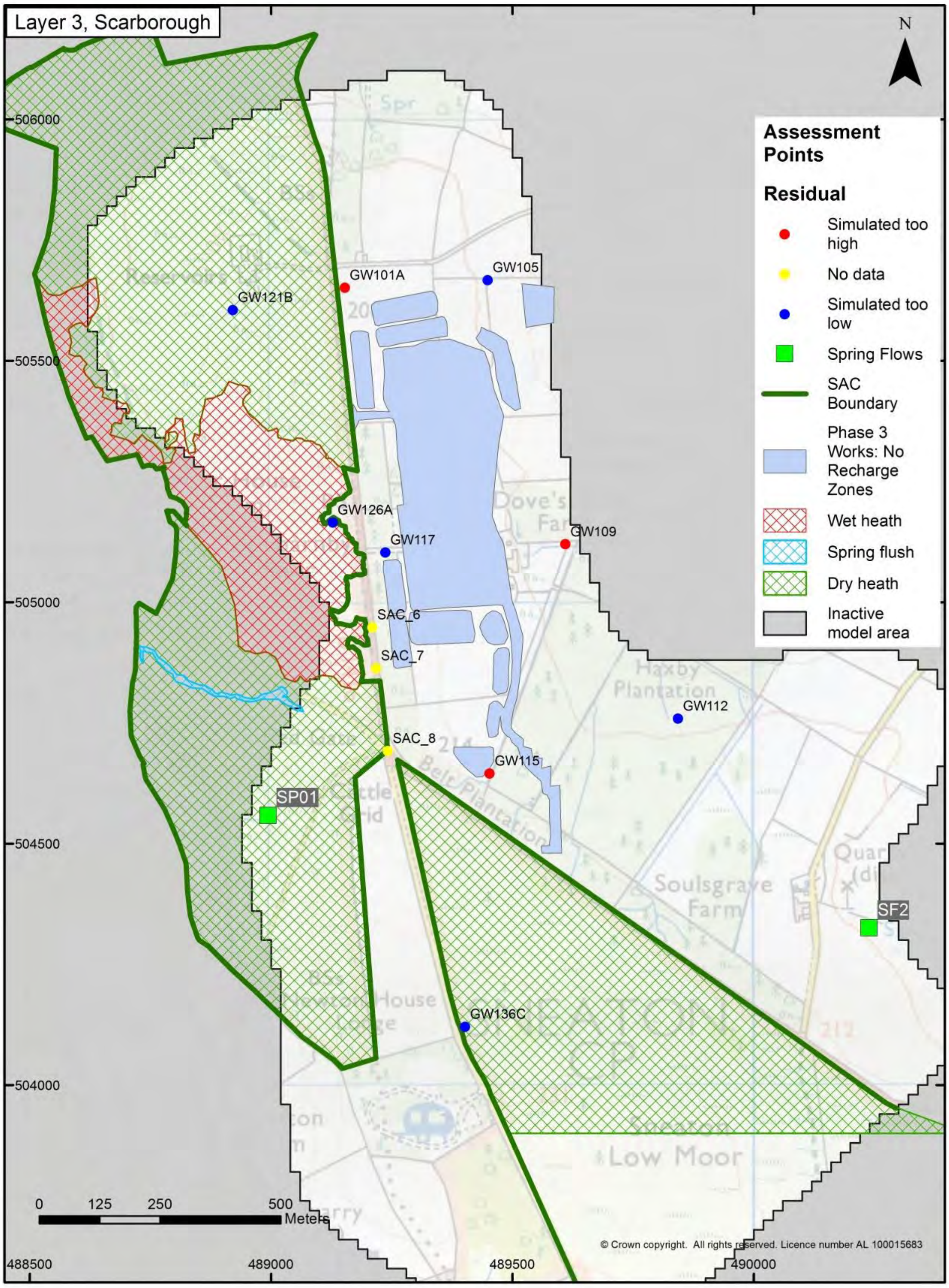


Figure 6.2 Location of groundwater level assessment points in Scarborough Formation.

Table 6.1 Predictive scenario assessment points

Name	Easting	Northing	Ground level (m AOD)	Response zone (m bgl) / unit
		Moor Grit Formation		
GW101	489153	505657	206.8	2 - 9.75 m
GW103	489343	505679	203.4	3 - 8.5 m
GW116	489271	504712	213.0	2.7 - 9.6 m
GW118	489230	505095	208.9	4.0 - 14.5 m
GW121A	488929	505614	211.7	3.4 - 6.6 m
GW122A	489139	505494	208.3	3.5 - 13.0 m
GW123	489177	505427	208.9	6 - 12.8 m
GW124	489184	505377	209.7	5 - 13.2 m
GW125	489216	505222	206.5	4.1 - 8.5 m
GW129	489219	505118	207.6	3.4 - 9 m
GW130	489236	504929	209.7	2 - 10.8 m
GW131	489247	504815	211.5	1.9 - 10.5 m
GW133A	489211	504706	213.0	2.0 - 10.0 m
GW135	489487	505052	202.3	3.4 - 8 m
GW136A	489401	504126	224.1	6.5 - 9.3 m
SAC_6	489210	504948	-	Moor Grit
SAC_7	489218	504863	-	Moor Grit
SAC_8	489242	504692	-	Moor Grit
MF2	489150	504745	-	Moor Grit
		Scarborough Formation		
GW101A	489153	505651	206.7	10.8 - 13 m
GW105	489449	505667	197.4	8 - 10 m
GW109	489610	505120	193.4	4.2 - 6.6 m
GW112	489843	504759	197.2	8.75 - 6.2 m
GW115	489453	504645	209.3	11 - 14 m
GW117	489237	505103	208.7	14.2 - 16.5 m
GW121B	488921	505605	211.6	4.0 - 14.0 m
GW126A	489128	505165	203.4	6.5 - 10.0 m
GW136C	489402	504121	224.3	11.0 - 16.8 m
SAC_6	489210	504948		Scarborough
SAC_7	489218	504863		Scarborough
SAC_8	489242	504692		Scarborough
		Spring Flows		
MF2	489151	504746	210	Moor Grit
DNS1	489510	505070	199	Moor Grit
SP04	489290	505995	195.6	Moor Grit
SP01	Distributed along western model border		Variable	Moor Grit
SF2	490239	504325	196.8	Scarborough
SP02	488336	505814	145	Cloughton
SP03	488473	506115	162.4	Cloughton
NHF	488866	504006	174.3	Cloughton

6.2 Calculation Details

All groundwater modelling results presented in the subsequent sections are calculated groundwater level differences between the pre-development base case and the post-development Phase 3 Works scenario. The base case model has been run for the same period and levels have been compared for each time step. Negative values are representative of a post-development decline in groundwater levels, whilst positive values indicate a post-development increase in groundwater levels. The same calculation has been performed for simulated flows in the modelled springs. Negative values represent a decrease in spring flow whilst positive values are indicative of an increase in spring flow relative to base case.

6.3 Transient Model Results

6.3.1 Effects on groundwater levels

Transient results are presented in the following manner:

- Contour plots and a cross section to show groundwater level change after 12 months (i.e. when changes are at a maximum);
- Time series graphs for the critical monitoring locations in a transect between the Phase 3 Works and the Spring Flush area of the SAC; and
- Tabulated results (Table 6.2) to provide a summary of the maximum groundwater level alterations for target points listed in Table 6.1.

Figure 6.3 and Figure 6.4 show contour plots of changes in groundwater level after 12 months in the Moor Grit and Scarborough formations respectively. Figure 6.5 shows a north-east to south-west cross section through the model that passes through the Production Shaft and towards the Spring Flush area of the SAC. Results shown in these figures correspond to the end of May in the year following the initiation of the construction works and temporary dewatering that commenced in the preceding June. Generally, this is when groundwater level changes are greatest and most extensive; however, locally there are areas where groundwater level changes can be greater at other times of the year. These areas tend to be around springs (see below).

Figure 6.3 and Figure 6.5 show that the greatest changes in groundwater level in the Moor Grit are centred on the Production and Service shafts. This is partly caused by the presence of the dewatering wells in this area, and partly because this area is at the centre of the no recharge zone. Decreases in groundwater level reach 5.5 m around the dewatering wells, and around 3.5 - 4 m beneath the shafts. The magnitude of changes in groundwater level decreases away from the shafts as the edge of the no recharge zones approaches and the radius of influence of the dewatering wells is reached. The cone of groundwater level decline in the Moor Grit is broadly orientated north-north-west to south-south-east, coincident with the orientation of the outcrop and the surrounding outcrop boundaries.

Around the eastern edge of the Wet Heath area of the SAC (closest to the western boundary of the Phase 3 Works) the decline in groundwater level in the Moor Grit reaches 0.7 m. Around the Spring Flush and Moorside Farm Spring area, this effect reduces to < 0.1 m.

In the Scarborough Formation (Figure 6.4 and Figure 6.5), the pattern of changes in groundwater level is more complex than the relatively uniform patterns observed in the Moor Grit. This is because, other than a small area in the east of the Scarborough Formation, the no recharge zones and dewatering wells only directly affect the Moor Grit Formation in Layer one. The effects of these features are transmitted to the Scarborough Formation (Layer three) through the upper layer of Mudstone (Layer two). Where this layer is thinner and/or the decline is greater, the effect can be transmitted more readily. The effect of a thinner Mudstone layer increasing the effect in the Scarborough Formation is demonstrated in Figure 6.5 (at around 900 m distance).

The greatest decline in the Scarborough Formation is to the west of the Production and Service shafts, where the decline in groundwater levels reaches around 3.1 m. This reduces to around 0.3 m at the edge of the Wet Heath area of the SAC and to around 0.05 m close to the Spring Flush area and Moorside Farm Spring.

Using the modelled drain elevations (analogous to pumping level) of 196 m AOD around the Production and Service shafts, and the base of the modelled Moor Grit around the MTS Shaft, the time to reach thee required levels in Section 5.1 can be calculated. These times have been calculated based on the required drawdown, rather than the absolute levels predicted by the model. This is because calibrated absolute levels around the shafts are generally overestimates. The required drawdown has been conservatively calculated by subtracting the required level from groundwater levels in February 2015 (FWS drawing 1433Dev0D248). February is when groundwater levels are naturally high, and levels in June 2017 will likely be lower than this. Therefore, the calculated required drawdowns are still overestimates (but more realistic). Based on a required drawdown of 1.5 m at the Production Shaft, 1 m at the MTS shaft and 0.5 m at the Service Shaft, the required levels will be reached in less than a week.

In the model, groundwater levels are generally overestimated around the shafts, and therefore higher gradients will be directed towards the modelled dewatering wells. This will induce greater flows out of the model than would be expected, and hence underestimate the required dewatering times. However, this effect is compensated by the overestimated required drawdowns (being based on high observed levels). The reported dewatering times are therefore considered realistic based on the pumping levels modelled.

The extents of the groundwater level declines shown in the contour plots are likely to be upper bounds. In reality, recharge during summer will likely be close to zero. This will mean that the no recharge zones will have no effect (as recharge would be zero anyway) and only the dewatering wells would act to decrease groundwater levels. Around October, background recharge will likely increase to be above zero, and the no recharge zones will begin to affect levels. The consequence of using a steady state recharge for the summer months is to increase the level of groundwater decline earlier in the model run meaning that the extent and magnitude of drawdown after 12 months will likely be an overestimate.

The spring and groundwater collection drainage system located in the north-east of the model does not drain groundwater in the model. This is because heads remain below the drain stage throughout the model run.

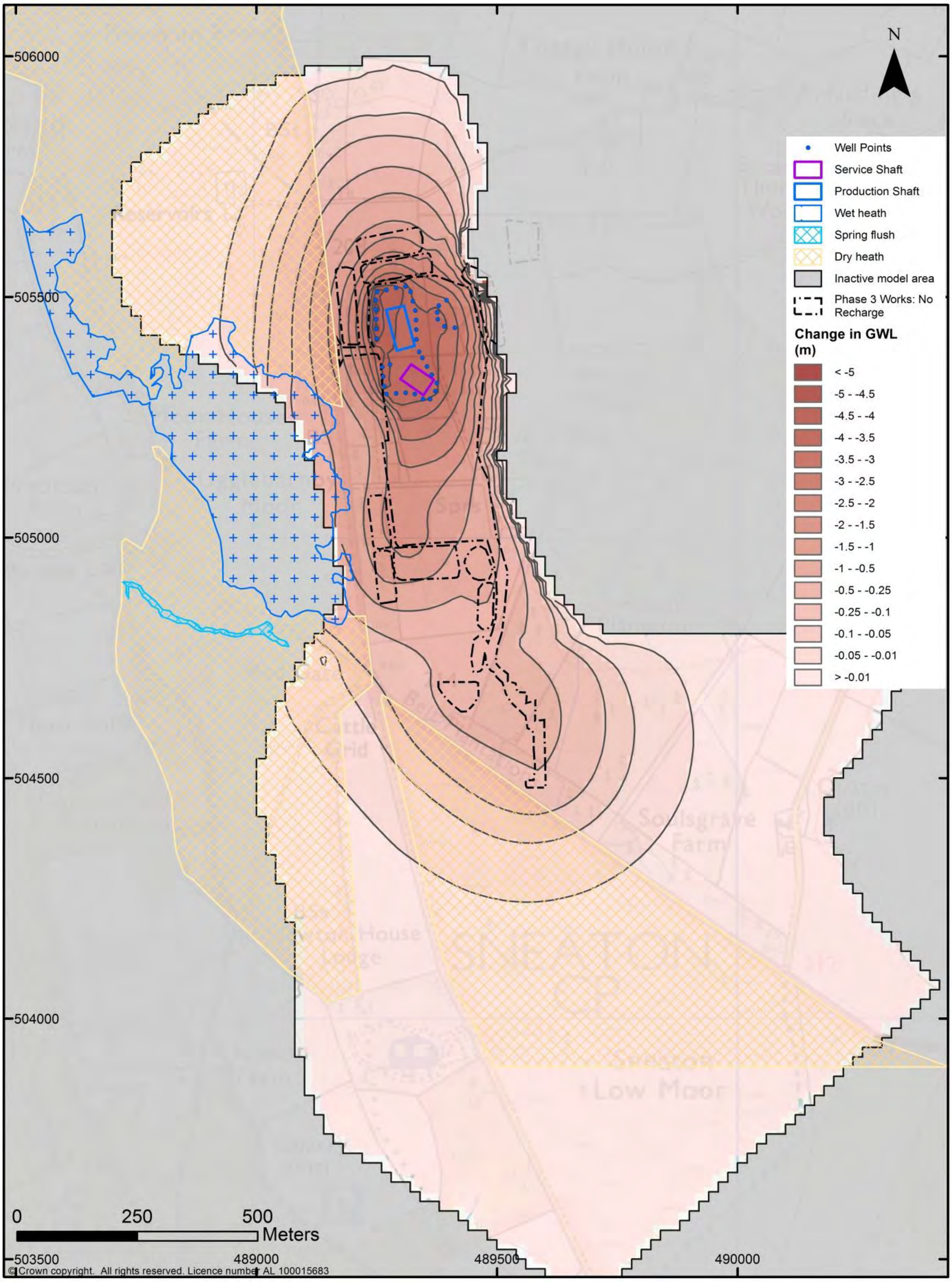


Figure 6.3 Contour plot of groundwater level changes in the Moor Grit Formation after 12 months

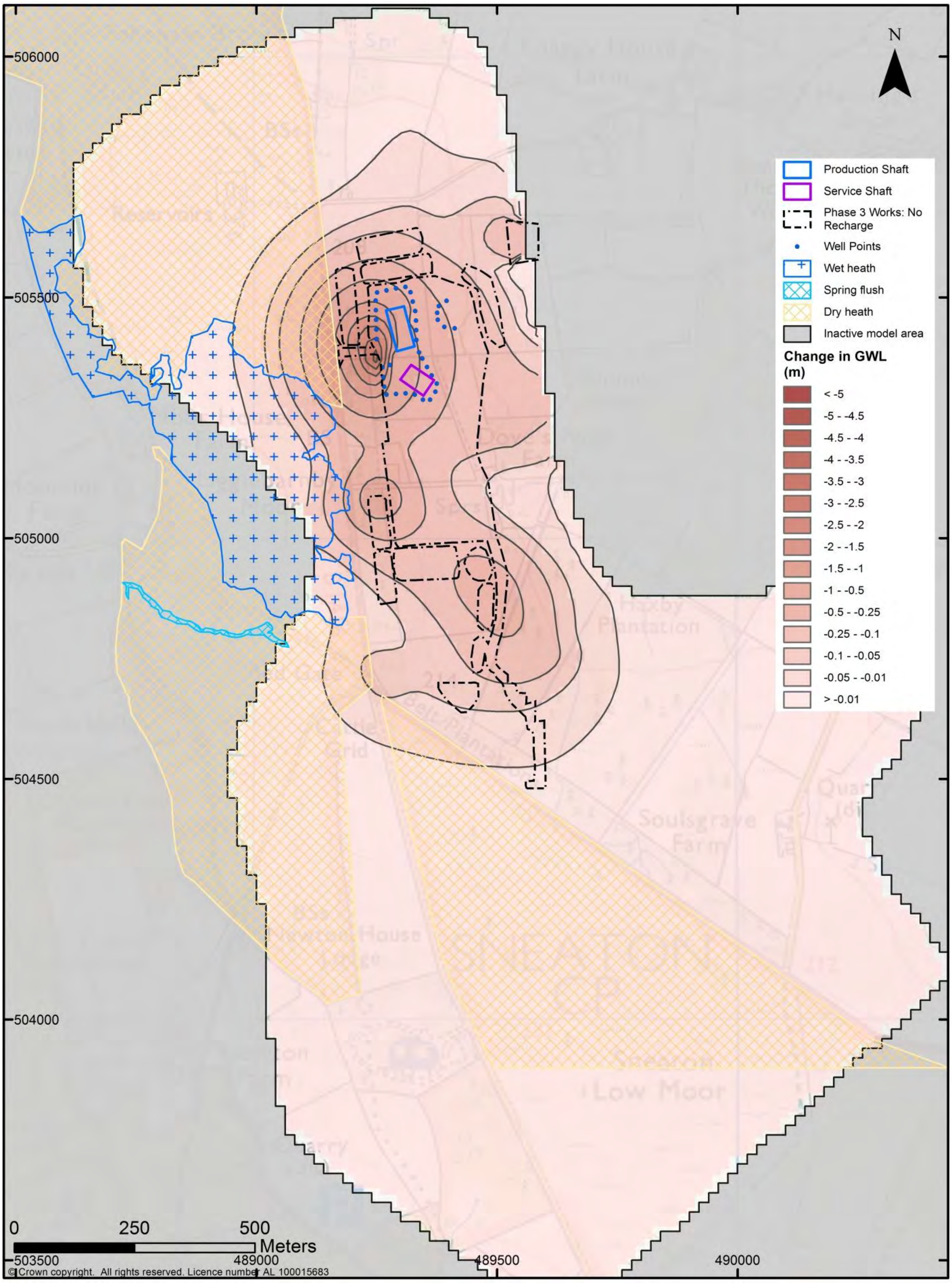
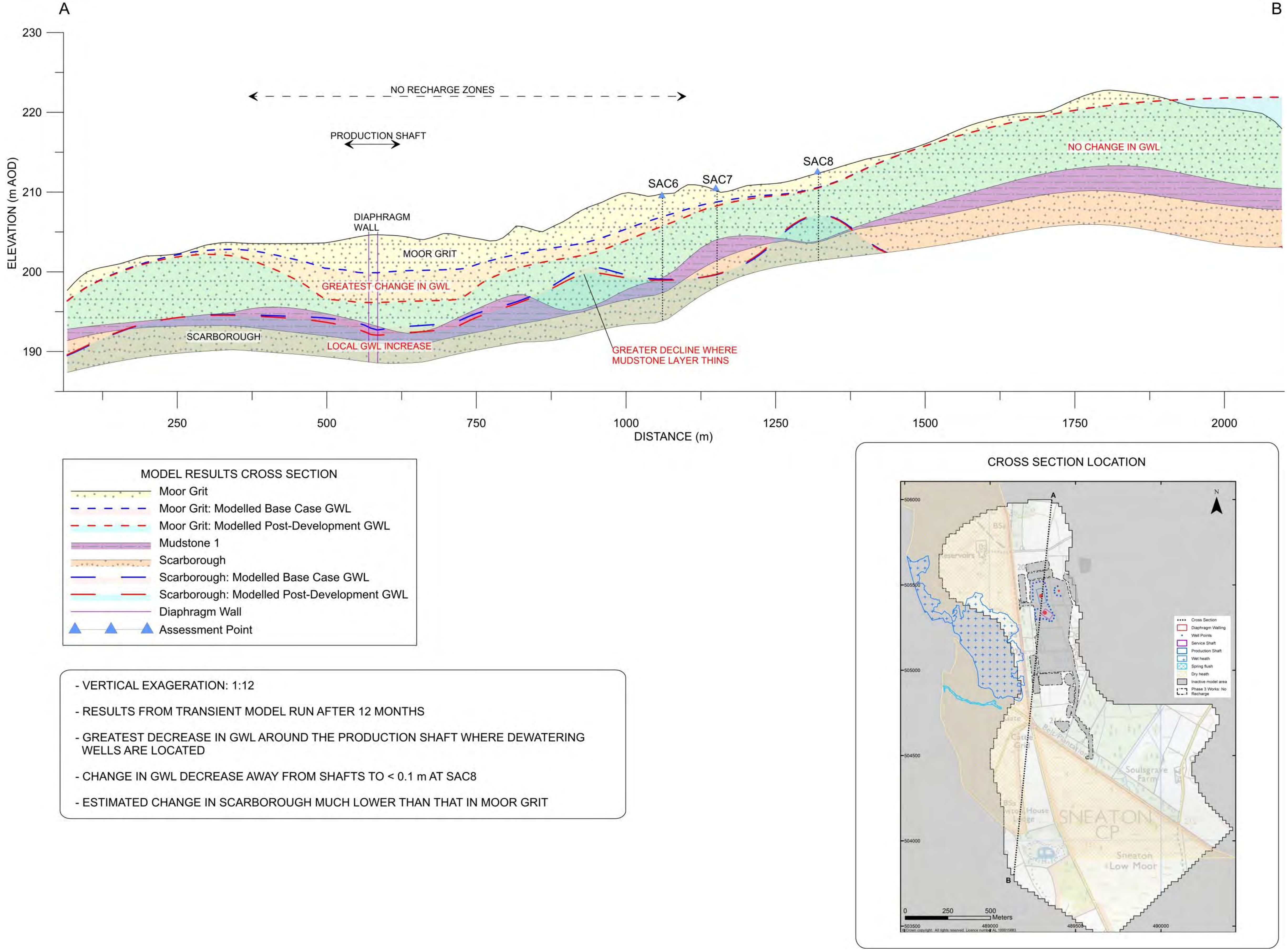


Figure 6.4 Contour plot of groundwater level changes in the Scarborough Formation after 12 months



- VERTICAL EXAGERATION: 1:12
- RESULTS FROM TRANSIENT MODEL RUN AFTER 12 MONTHS
- GREATEST DECREASE IN GWL AROUND THE PRODUCTION SHAFT WHERE DEWATERING WELLS ARE LOCATED
- CHANGE IN GWL DECREASE AWAY FROM SHAFTS TO < 0.1 m AT SAC8
- ESTIMATED CHANGE IN SCARBOROUGH MUCH LOWER THAN THAT IN MOOR GRIT

Figure 6.5 Cross section showing groundwater level changes in the Moor Grit and Scarborough formations after 12 months

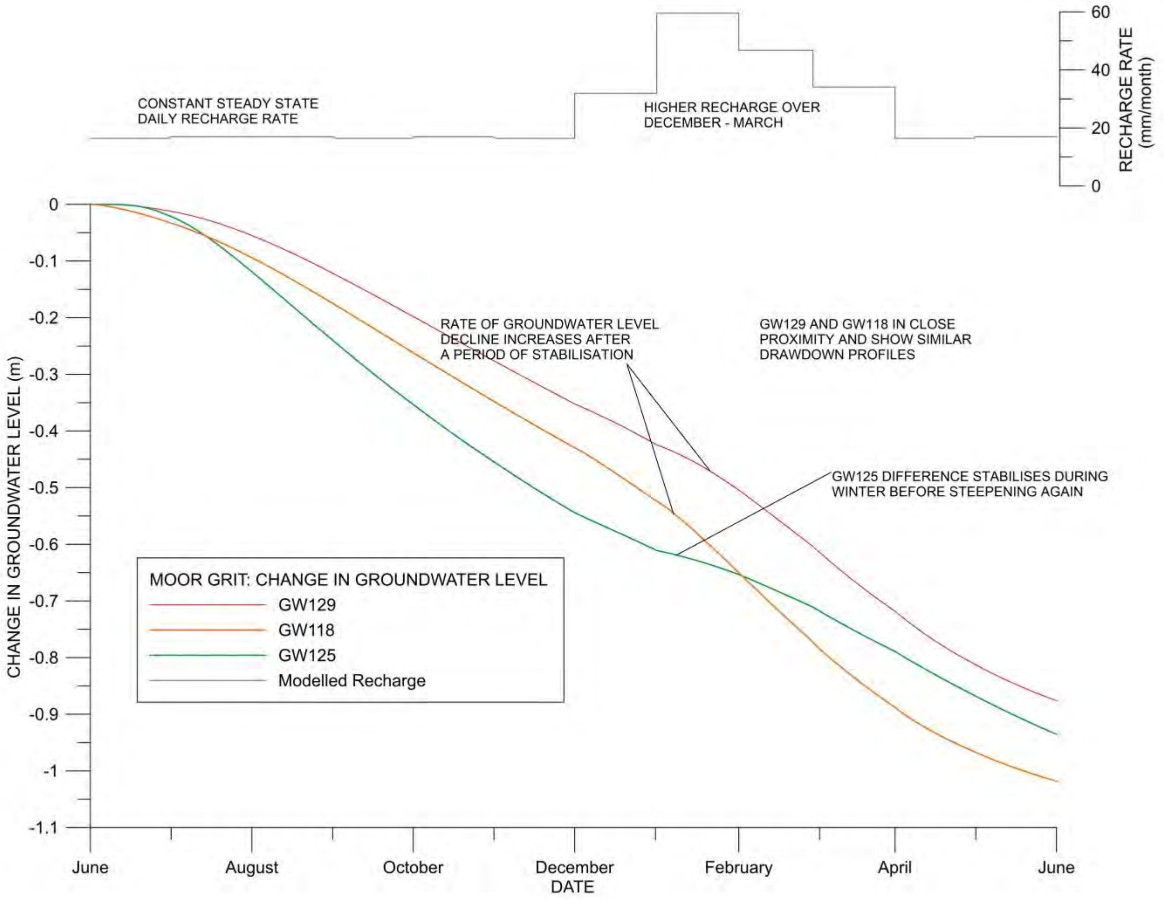


Figure 6.6 Transient model simulated change in groundwater level at GW118, GW125 and GW129 in the Moor Grit Formation

Figure 6.6 - Figure 6.8 show time series of changes in groundwater levels over a transect between the Phase 3 Works and the Moorside Farm Spring.

Groundwater levels in the Moor Grit Formation decline throughout the run period (figures 6.6 and 6.7). However, the rate of that decline and the way that decline varies temporally is dependent on location. The rate of decline in groundwater level between the post-development and base case runs is generally greatest over the winter months (December – March) when recharge in the model is raised above the steady state recharge rate.

After the onset of high recharge during winter, the rate of decrease in groundwater levels is initially buffered, but the rate of decrease subsequently increases. The times at which these changes occur varies spatially and will in part be related to the proximity of the observation points to dewatering wells and areas of background recharge.

The groundwater level drop at SAC8, closest to the Spring Flush area of the SAC, is < 0.1 m after 12 months (Table 6.2). Changes at MF2 reach a maximum 0.02 m drop in January. This maximum change occurs during, rather than at the end of, the 12 month run because of the effect of the Moorside Farm Spring. The spring will fix groundwater levels at the spring level when the spring is flowing and hence there will less of a difference in level between the two runs when this occurs (although there may be a difference in flow).

Time series plots in the Scarborough Formation show a much more uniform decrease in groundwater levels compared to those in the Moor Grit Formation. This is for the same reasons that cause the spatially more complex patterns of groundwater level changes between the Moor Grit and Scarborough formations (see above).

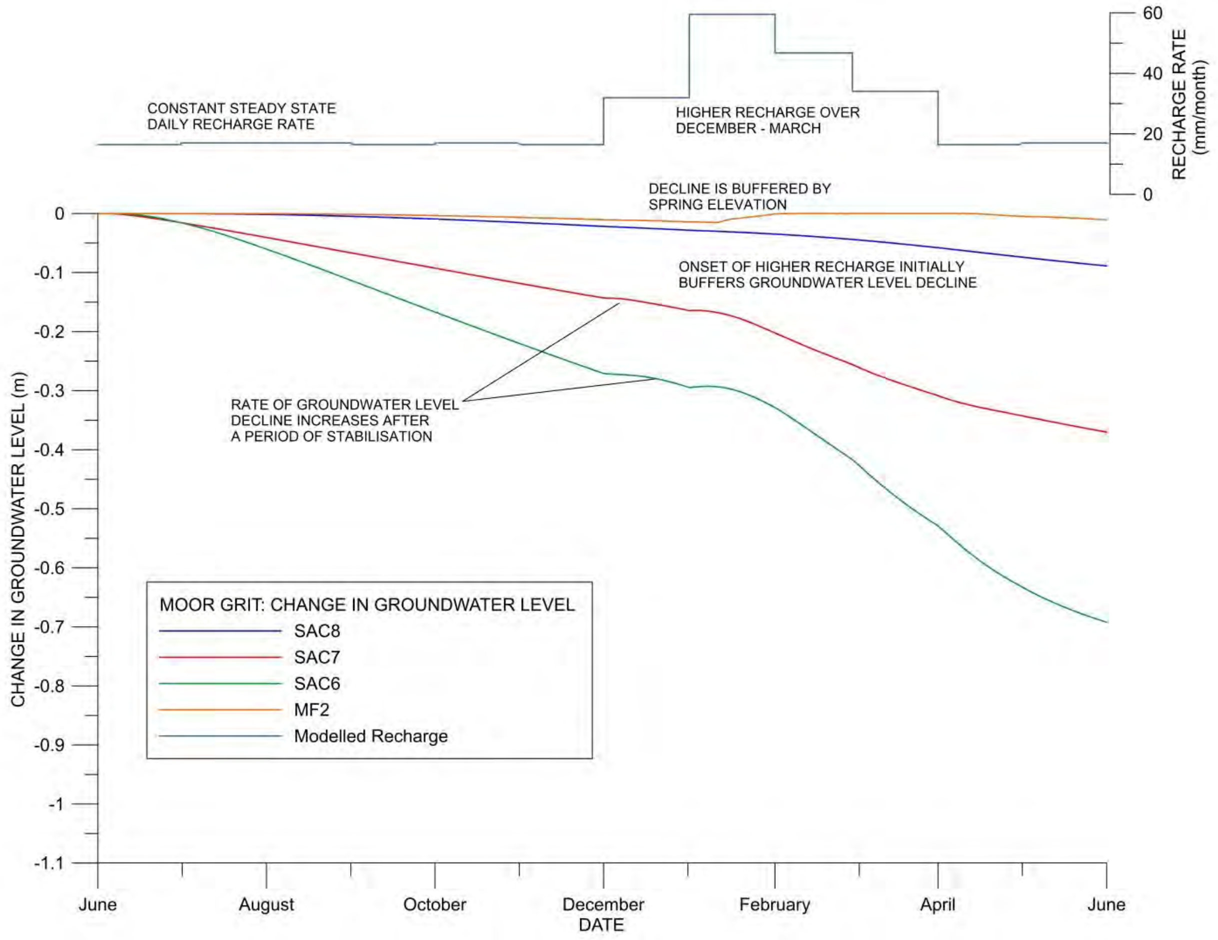


Figure 6.7 Transient model simulated change in groundwater level at SAC6 – SAC8 and MF2 in the Moor Grit Formation

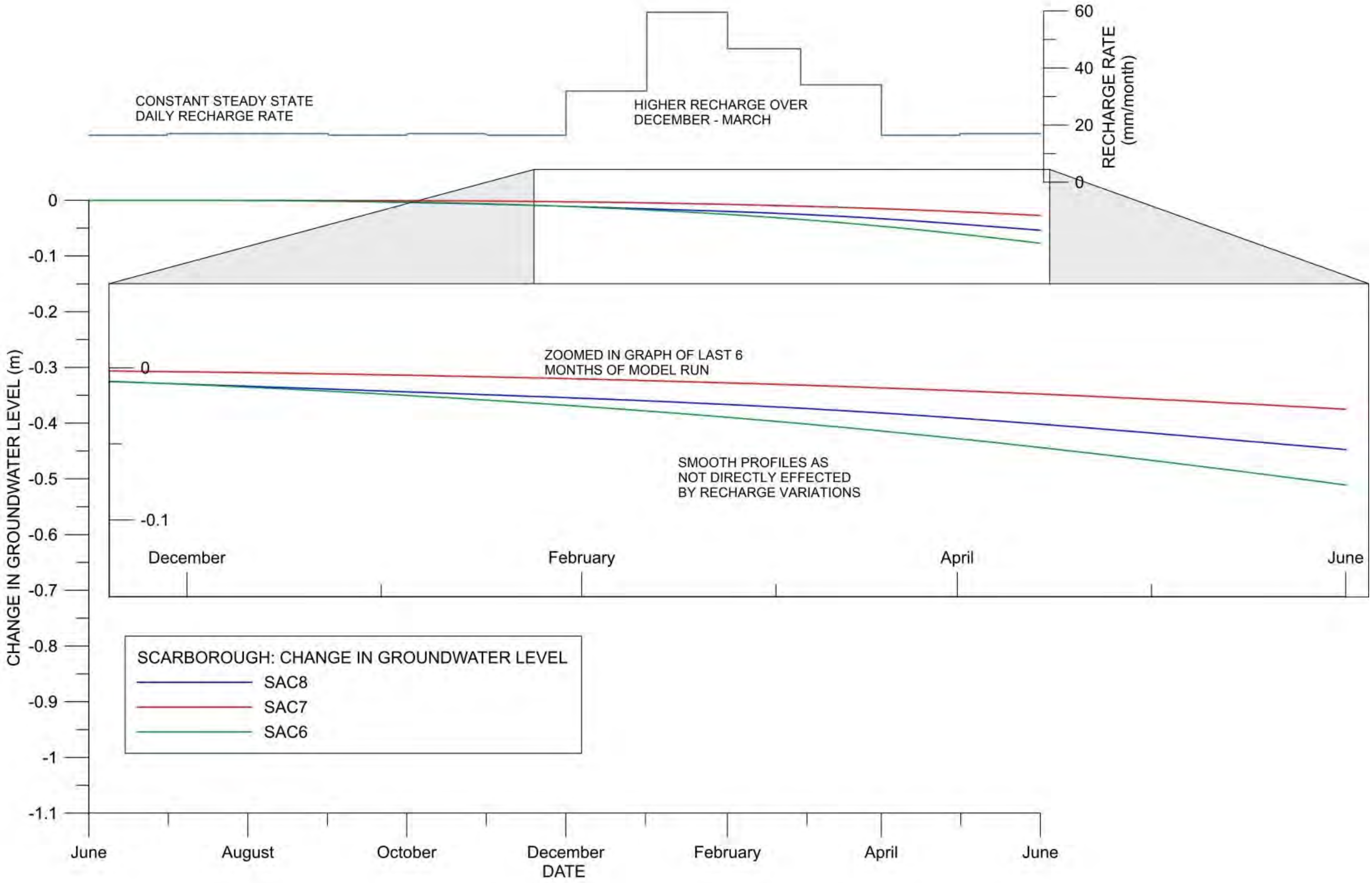


Figure 6.8 Transient model simulated change in groundwater level at SAC6 – SAC8 in the Scarborough Formation

Table 6.2 Maximum change (to nearest cm) in groundwater level (m) at assessment points for each transient simulation

Name	Easting	Northing	Maximum Change (m)
Moor Grit Formation			
GW101	489153	505657	-0.37
GW103	489343	505679	-0.65
GW116	489271	504712	-0.13
GW118	489230	505095	-1.02
GW121A	488929	505614	-0.01
GW122A	489139	505494	-0.78
GW123	489177	505427	-1.59
GW124	489184	505377	-1.63
GW125	489216	505222	-0.94
GW129	489219	505118	-0.88
GW130	489236	504929	-0.87
GW131	489247	504815	-0.28
GW133A	489211	504706	-0.07
GW135	489487	505052	-0.82[1]

Name	Easting	Northing	Maximum Change (m)
GW136A	489401	504126	0.00
SAC_6	489210	504948	-0.69
SAC_7	489218	504863	-0.37
SAC_8	489242	504692	-0.09
MF2	489150	504745	-0.02[1]
	Scarborough Formation		
GW101A	489153	505651	-0.04
GW105	489449	505667	-0.07
GW109	489610	505120	-0.01
GW112	489843	504759	0.00
GW115	489453	504645	-0.05
GW117	489237	505103	-0.61
GW121B	488921	505605	0.00
GW126A	489128	505165	-0.07
GW136C	489402	504121	0.00
SAC_6	489210	504948	-0.08
SAC_7	489218	504863	-0.03
SAC_8	489242	504692	-0.05

[1]Maximum change during or following winter, all other maximum changes are taken from after 12 months.

6.3.2 Effect on spring flows and pumping rates

Changes in transient spring flows at MF2 and SP01 between the pre-development base case model and the post-development model including the Phase 3 Works are shown in Figure 6.9. Figure 6.9 also the modelled spring flows in MF2 over the run time of the base case and post-development model runs. Maximum changes in spring flow in the model are summarised in Table 6.3.

Spring flow changes in MF2 are greatest over the winter period when the spring is flowing due to higher absolute groundwater levels. Changes in spring flow at MF2 decrease by up to 0.25 m^3/day (3 x 10^{-3} l/s) during April. Thereafter, the difference in flow between the two models decreases. The pattern of change in flow at MF2 is non-uniform. The pattern in spring flow at MF2 is similar in both models and the non-uniformities are due to variations in the rate of response to recharge changes in each of the individual models. These non-uniform changes are not significant, instead the trends (greater effect in winter, reducing in spring) are of greater importance.

SF2 and SP01 show gradual uniform declines in flow rate with time. These springs are located within the Scarborough Formation, and this uniformity is likely due to the same reasons which result in complexity in the spatial pattern of groundwater level decline (as discussed in Section 6.3.1). Flow from SP01 decreases by a maximum of 0.04 m^3/day (5 x 10^{-4} l/s) at the end of the model run.

Figure 6.10 shows the changes in pumping rate through time for the MTS Shaft wells, those around the Production and Service shafts and for all wells combined. Initially, the dewatering rate is > 1,200 m^3/day (13.9 l/s) but this rapidly reduces to < 500 m^3/day (5.8 l/s) after a week and to < 90 m^3/day (1 l/s) after 12 months. Pumping rates increase in response to the greater recharge over the winter months. This greater recharge increases the gradient directed towards the wells and means more groundwater must be removed from the aquifer to maintain the same groundwater level. Following winter, pumping rates reduce as the recharge rate decreases.

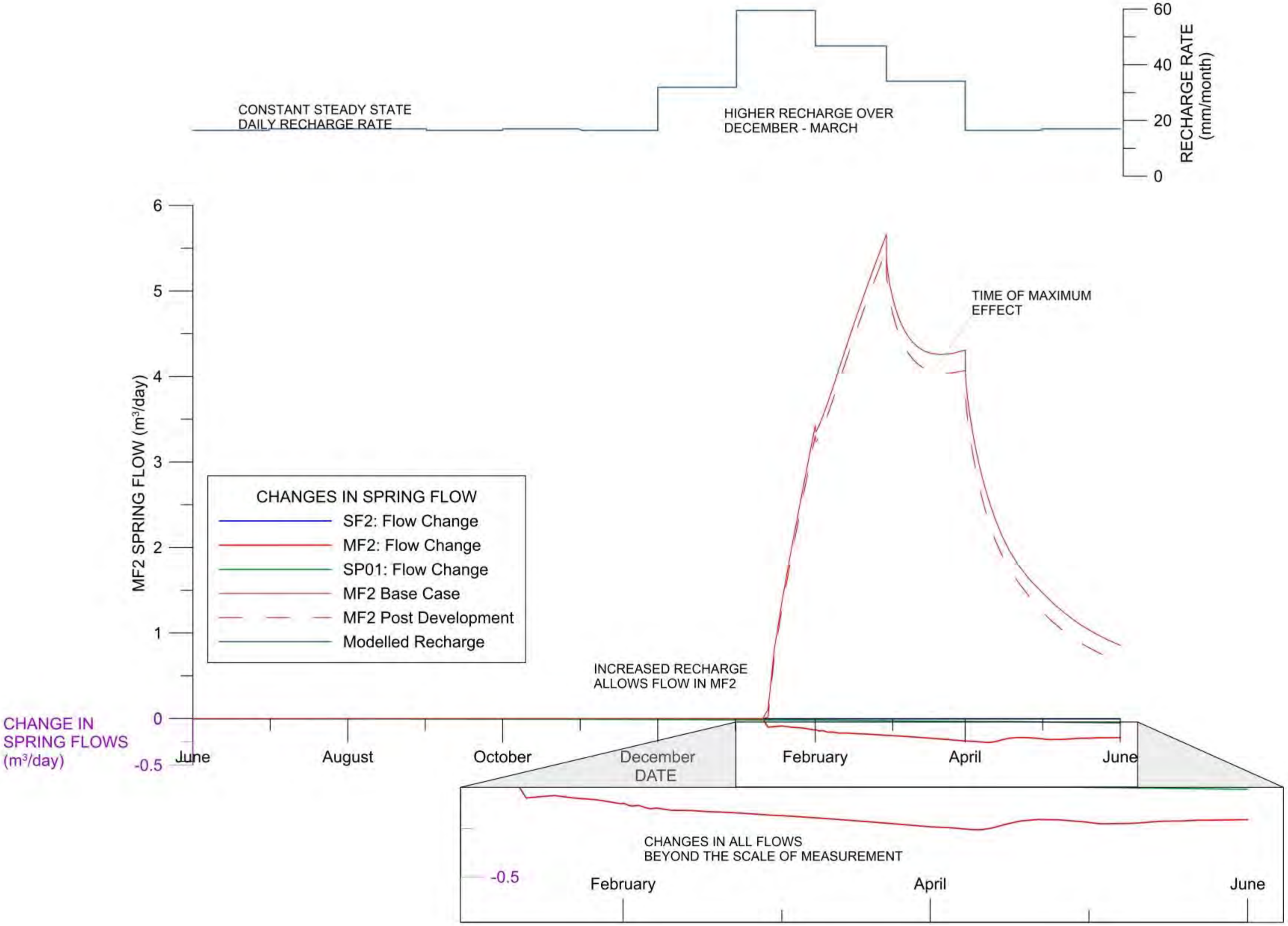


Figure 6.9 Changes in spring flows at MF2, SP01 and SF2 between transient pre- and post-construction models

Table 6.3 Maximum modelled decreases in simulated spring flows

Name	Easting	Northing	Maximum difference in spring flows (m^3/day)
	Moor Grit Formation		
MF2	489151	504746	-0.25
SP04	489290	505995	0
	Scarborough Formation		
SF2	490239	504325	0
SP01	Distributed along western model border		-0.04
	Cloughton Formation		
SP02	488336	505814	-0.01
SP03	488473	506115	-0.01
NHF	488866	504006	0

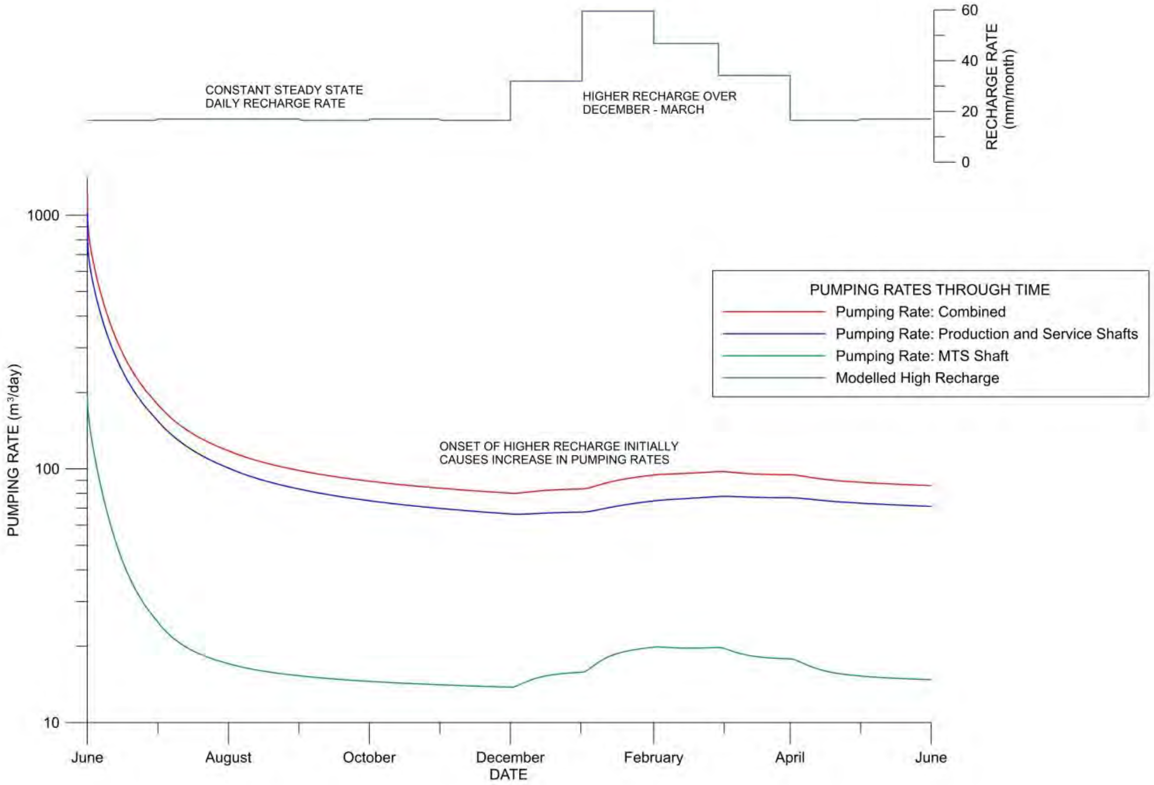


Figure 6.10 Changes in pumping rates from dewatering wells through time

6.4 Sensitivity and Uncertainty Analysis

Sensitivity and uncertainty analyses have been completed to test issues of model equivalence and the sensitivity of the model to changes in recharge. Appendix A contains the full results of these analyses.

Results of the sensitivity analysis indicate that under high annual recharge conditions the predicted groundwater level declines at the SAC will be greater, with the opposite being true with a low recharge run. However, this effect is not seen at SAC8, where high and low recharge runs both produce a lesser decline in groundwater levels. This is thought to be due to the proximity of SAC8 to the Moorside Farm Spring, which moderates the decline in groundwater levels at this location. The magnitude of groundwater level decline generally does not increase (i.e. the effect does not worsen) by > 0.05 m, and these changes are always < 0.08 m. The magnitude of the changes in level of effect decreases with respect to depth. Spring flows at MF2 show an additional decrease of 1.4 m^3/day (0.016 l/s) in the high recharge sensitivity run compared to the calibrated model. This decrease in flow would be beyond the scale of measurement. The sensitivity to recharge does not detract from the predictions of the calibrated model presented in the above sections.

Uncertainty analyses are used to assess equivalence in the model, and examine uncertainties in the model predictions. For groundwater levels, changes in the predicted level of effect were always < 0.02 m, indicating that uncertainties in the result due to the non-uniqueness of the model calibration are very small. This provides confidence in the results of the calibrated model that are presented in the preceding sections.

7 CONCLUSIONS

Following the most recent update of the baseline hydrogeological report (FWS, 2016a), the existing multi-layer groundwater model of the York Potash mine head development has been reviewed and updated. The model is calibrated to transient conditions over the 2013 - 2015 period of groundwater level and spring flow monitoring. Calibrated model results are consistent with measured spring flow and groundwater levels to March 2016. The objective of the model calibration focussed on achieving a model that is fit for assessing the effects on groundwater levels in the Moor Grit and Scarborough aquifers underlying Ugglebarnby Moor SAC. Potential impacts on flows from Moorside Farm Spring and to the Spring Flush area are of greatest interest.

In calibrating the model, it was necessary to deviate slightly from field parameters. Non-uniform zones of hydraulic conductivity and anisotropy are used to simulate the spatial variability in heads. The K_h values used for each of the aquifer units are consistent with the results obtained from the pumping tests carried out in late 2013/early 2014 (ESI, 2014a).

Pumping tests demonstrated that the K_v of the aquitards was very low. The K_v of each of the aquitards layers was further constrained by model calibration. The vertical leakage through these layers must be sufficiently low to support the observed steep vertical hydraulic gradients. Despite the permeability being very low (of the order of 10^{-9} and 10^{-10} m/s) the K_v values of the aquitards are still sufficient to allow a reasonable vertical groundwater flux under free-draining conditions (30 mm/a for a K_v of 10^{-9}). It is therefore possible to support the groundwater levels in each of the aquifer units by allowing a certain amount of the recharge at the surface to exit through the base. By comparison, the flux through the southern boundary is relatively small.

A review of simulated groundwater levels and spring flows has been undertaken against the extended hydrogeological baseline data series. This review served as a check and no significant changes in the quality of the calibration were identified. Changes to model calibration in terms of aquifer properties or boundary conditions were therefore not considered necessary. Fluctuations in groundwater levels beyond the model run period (after October 2015 and before April 2016) are consistent with groundwater levels predicted by the model.

In summary, the model is considered to be appropriately calibrated for the purposes required:

- The model simulates the steep vertical hydraulic gradients observed between the various thin aquifer layers on Site accurately; and
- The model simulates the flashy, intermittent flows in the key springs effectively.

The model does not capture all the spatial variability in groundwater levels within individual horizons accurately due to local heterogeneity. However, this is not considered to be a significant limitation on its predictive use as models are generally considered to represent the differences between two scenarios (e.g. baseline and predictive) more reliably than the simulation of absolute flow and groundwater level. The model is thus considered to be an appropriate tool for use in assessing the likely effect of the proposed development on the local groundwater systems.

The calibrated model has been used to simulate the proposed Phase 3 Works as detailed in (FWS, 2017). Results of a transient post-development model run which incorporates these works has been compared to the pre-development base case model. The transient model run undertaken incorporates an unlikely, but conservative, high recharge sequence to estimate effects around the Spring Flush area of the SAC. Given the conservative nature of the model run, it is expected that the results represent upper bounds in terms of the extent and magnitudes of the changes in groundwater level.

The decrease in groundwater levels and spring flows is predicted to be greatest during the winter months, when groundwater levels in the base case model are naturally higher due to recharge. Around the Spring Flush area of the SAC, the decrease in groundwater level is expected to be < 0.1 m and < 0.05 m in the Moor Grit and Scarborough formations respectively. The greatest changes in groundwater level are predicted to occur over the winter months. Spring flows at the Moorside Farm spring are predicted to decrease by a maximum of 0.25 m^3/day and those at SP01 by 0.04 m^3/day. These maximum changes are anticipated to occur over the winter months, with minimum changes predicted over the summer period, when natural spring flows are typically intermittent. Such small reductions in flow are unlikely to be measurable in the field.

Uncertainty and sensitivity analyses have been undertaken to determine the possible uncertainties in predicted effects due to model equivalence and long term variations in recharge. The variations in the level of effect calculated from the uncertainty model runs are small and this increases confidence in predictions of the calibrated model. The model results are sensitive to long term variations in recharge, with slight (< 0.1 m) increases in the level of effect however, this sensitivity does not detract from model predictions presented in this report.

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APPENDICES

APPENDIX A

York Potash Model: Phase 3 Works Sensitivity and Uncertainty Analyses

York Potash Model: Phase 3 Works Sensitivity and Uncertainty Analyses

Prepared for York Potash Limited

Report reference: 61415 TN3 Rev1, March 2017

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1 SENSITIVITY AND UNCERTAINTY ANALYSES

1.1 Overview

Given the uncertainties involved in modelling an area of complex hydrogeology, it is important to undertake sensitivity and uncertainty analyses to validate the conclusions reached using the calibrated York Potash model. These conclusions are presented in the accompanying Phase 3 Works modelling report (ESI, 2017), and this technical note should be read in conjunction with that report. Pairs of steady state model runs both pre- and post-development have been used to check the changes in groundwater level along the SAC boundary at points SAC1 to SAC8.

Results from these analyses can then be used to identify where the groundwater model results could be most uncertain and what the nature of that uncertainty might be. Model runs were carried out using a steady state model and the conclusions are therefore considered to be more reliable for groundwater level changes than for spring flows (due to the intermittent nature of the springs).

The main sources of model equivalence, and uncertainty in the calibrated values, are related to the interplay between hydraulic conductivity and recharge in the seven model layers. These parameters were therefore the focus of this analysis. Results of these model runs only look at the impact attributed to the development (i.e. differences between pre-construction and post-construction scenarios) rather than absolute groundwater levels predicted by the model. Groundwater levels under low recharge conditions and high recharge conditions will be predicted to be lower and higher in the model respectively. The difference between the pre-construction and post-construction runs could be more or less depending on how the model adjusts to changes in recharge and hydraulic conductivity.

1.2 Model Runs

A summary of the model runs undertaken is provided in Table 1.1. Run A and Run B represent high and low annual recharge based on monthly rainfall at Whitby for the period 1971 – 2000 (representative of a typical long term average period). The purpose of these runs is to test the sensitivity of the results predicted by the model to changes in recharge. During this period of time, the lowest rainfall was recorded in 1972 (325 mm) and the highest in 2000 (744 mm). Low and high annual recharge was calculated by assuming that a recharge of 200 mm/year (recharge used in the calibrated model) is equivalent to long term average rainfall at Whitby (558 mm/year). The calibrated recharge was then factored up and down based on the differences between long term average rainfall and high and low annual rainfall. This produced recharge estimates ranging from 116 – 267 mm/year. However, the groundwater model encountered numerical stability issues with a low annual recharge of 116 mm/year. Therefore, Run B was completed using the lowest recharge with which convergence was possible (180 mm/year).

Runs C and D represent an uncertainty of + 20% and - 10% respectively in the calibrated long term average recharge of 200 mm/year. The principle purpose of these runs is to test potential uncertainties in the model results arising from model equivalence. The reason for the reduced decrease in the hydraulic conductivity and recharge values for Run D was to ensure numerical stability in the model. In any groundwater flow model, there is some equivalence between recharge and hydraulic conductivity and hydraulic conductivity has therefore also been changed by the same factor. Horizontal and vertical hydraulic conductivity for all model layers have been modified however, the ratios remain the same.

Table 1.1 Model uncertainty and sensitivity runs

Run	Description	Recharge (mm/year)	Change in recharge and k (%)
Calibrated model	Calibrated model described above	200	0
Run A	High annual recharge	267	+33%
Run B	Low annual recharge	180	-10%
Run C	High annual recharge and high hydraulic conductivity	240	+20%
Run D	Low annual recharge and low hydraulic conductivity	180	-10%

The steady state post development models include all of the Phase 3 construction features discussed in Section 5.1. This is so that the all of the Phase 3 features can be tested in unison. As discussed in Section 5.2, steady state results are not considered appropriate for predicting effects; however, the changes in results can be used to infer likely uncertainties in the results presented in Section 6.

Results of the uncertainty analyses in the following sections are presented as a series of bar charts showing ‘absolute difference’. This absolute difference has been calculated using the following equation:

$$Absolute\ difference\ (m) = Change_{Run\ X} - Change_{Calibrated\ Model}$$

Where:

Change refers to the change in groundwater levels or spring flows between the base case and post development model pairs for each of the sensitivity/uncertainty and calibrated model runs; and
Run X refers to each of the uncertainty and sensitivity runs (i.e. Run A etc.).

A negative absolute difference means that the uncertainty run predicts a greater decline in groundwater levels or spring flows than the calibrated model (i.e. a greater effect). A positive absolute difference means that the uncertainty run predicts a smaller decline in groundwater levels or spring flows than the calibrated model (i.e. a lesser effect). An absolute difference of zero means that the same change is predicted by the uncertainty run and the calibrated model.

Absolute differences in Runs A and B provide an indication of the sensitivity of the model results to long term fluctuations in seasonal recharge. Runs C and D give an indication of the uncertainty of the model results with regard to issues of model equivalence.

1.3 Groundwater Levels

Figure 1.1 and Figure 1.2 present the predicted absolute differences in changes seen in the sensitivity/uncertainty run pair and the calibrated model run pair. Differences in the level of effect between the sensitivity/uncertainty run pairs and the calibrated model run pair are greatest for Run A and Run B and for the shallower layers. Absolute differences for Run pairs C and D are all smaller than ±0.02 m. This shows that uncertainties in results due to non-uniqueness of the model calibration are small. However, the model results are sensitive to long term recharge variations.

The maximum increase in effect is at SAC6 in the Run A pair in the Moor Grit Formation, where the predicted groundwater level decline is 0.06 m greater in the high recharge sensitivity run pair. Such an increase is small, especially as this is a long term steady state run and the results presented in Section 6 are for a one year transient run. Given the conservative nature of the predictive transient model run, it is likely that the results presented in Section 6 account for any uncertainties.

Generally, under high (Run A) and low (Run B) annual recharge conditions, the absolute difference between the sensitivity run pair and the calibrated model run pair is lower for the high recharge run pair (i.e. greater effect) and higher for the low recharge run pair (i.e. lesser effect). In the Moor Grit, SAC8 is an exception to this generalisation. This could be due to the proximity of SAC8 to the Moorside Farm Spring which, due to the higher recharge, is active in Run A. The level at which this spring is set will moderate the decline in groundwater level at this location. In Run C the spring is not activated, and the absolute difference is lower, and therefore the effect is predicted to be greater. However, this increase in effect is predicted to be much less than 0.01 m.

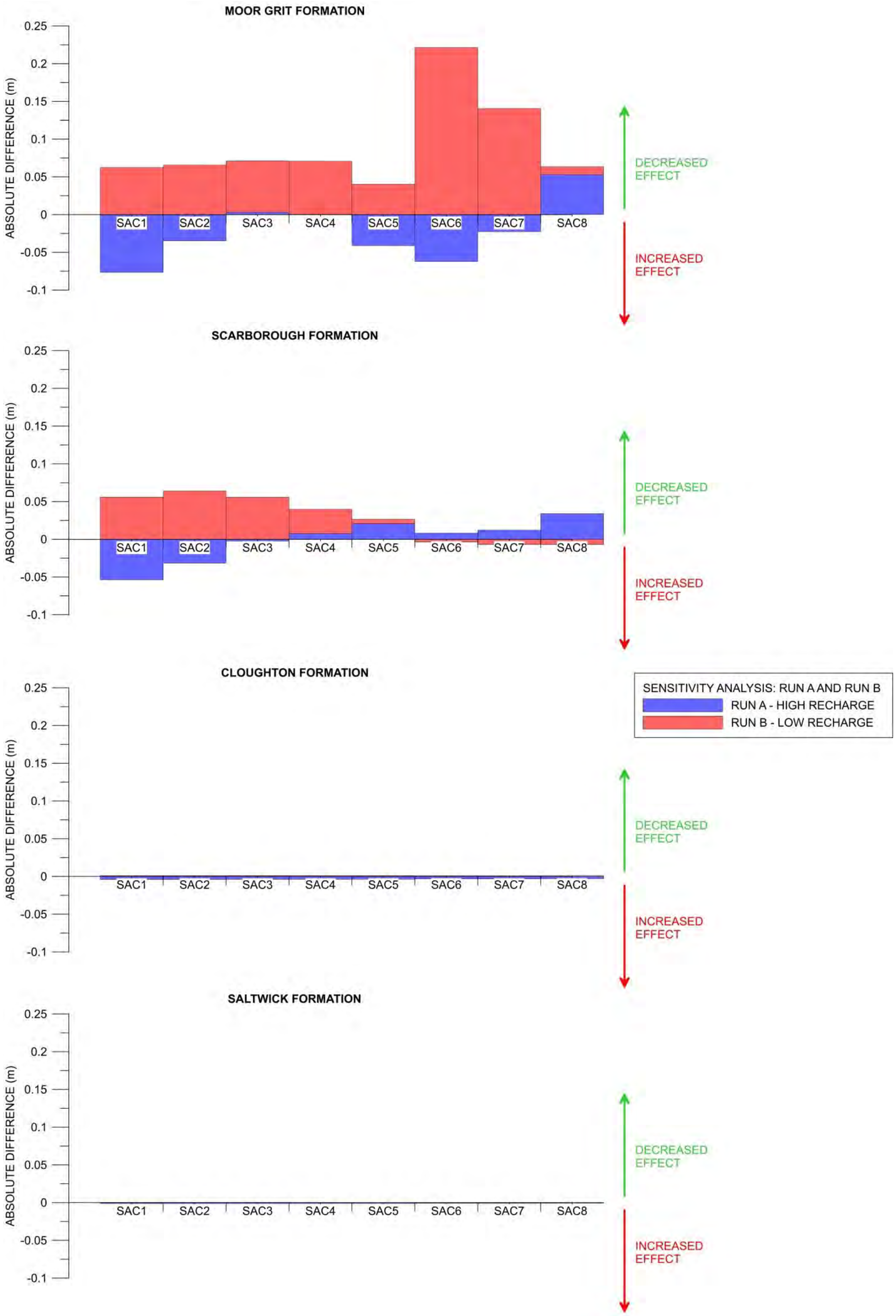

Figure 1.1 Groundwater level sensitivity analysis results for Run A and Run B

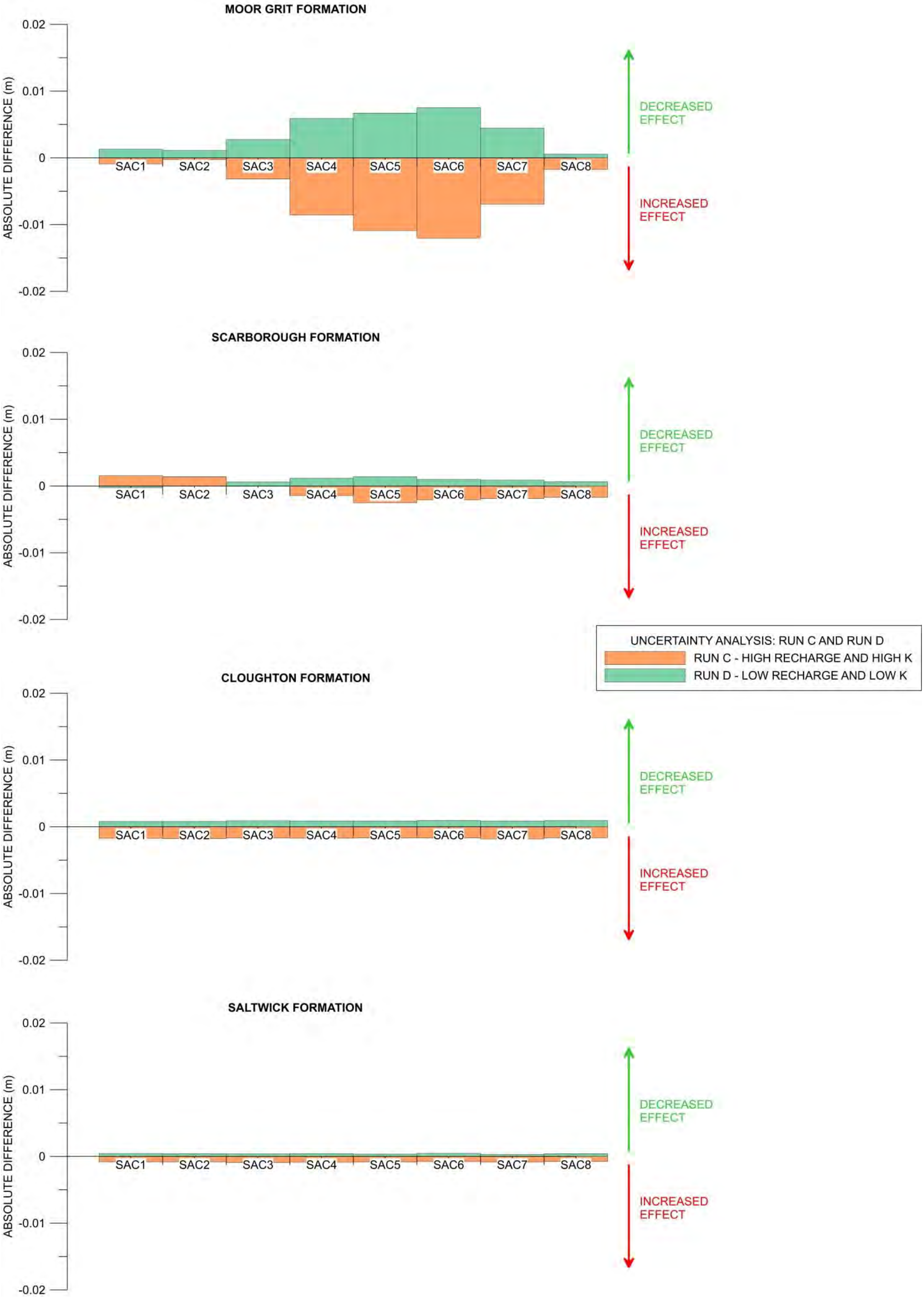

Figure 1.2 Groundwater level uncertainty analysis results for Run C and Run D

1.4 Spring and Boundary Flows

The conclusions of this analysis with respect to spring flows are considered less reliable than for groundwater levels because the steady state model rather than the transient model has been used to test sensitivity. Figure 1.3 shows the sensitivity analysis results for spring flows.

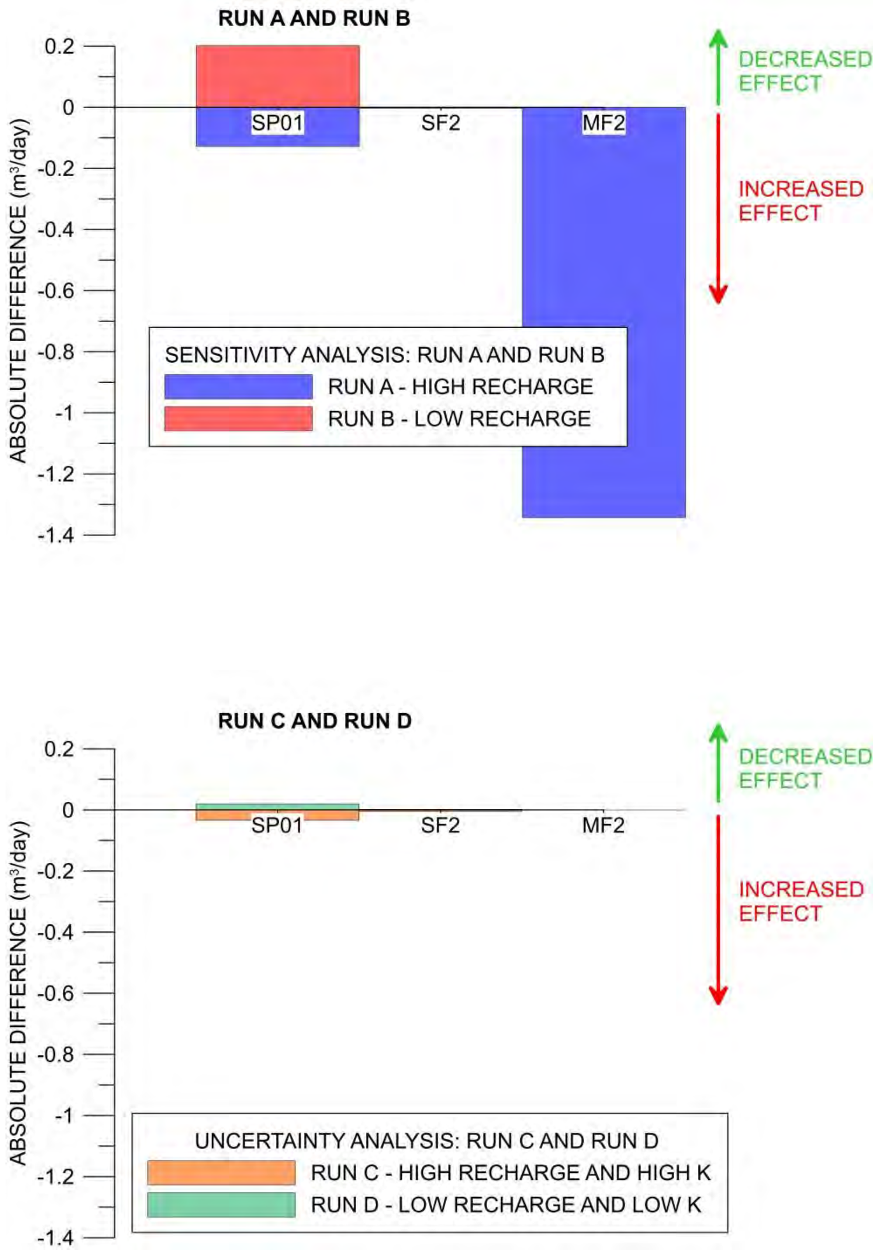

Figure 1.3 Spring flow analysis results

Figure 1.3 shows that, as for groundwater levels, only negligible absolute differences were identified in Runs C and D. This demonstrates that uncertainties in the model results regarding model equivalence are small. An increase in effect of 1.34 m^3/day (0.016 l/s) was predicted by high recharge Run A at the Moorside Farm Spring. Such a decrease in flow would be beyond the scale of measurement. These results indicate that during periods of high recharge, such as over winter, the decrease in spring flow is likely to be greater, with the opposite being true over summer. Given the conservative nature of the high recharge model run, it is likely that this decrease in spring flow over winter has been appropriately accounted for.

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