Oxford Flood Alleviation Scheme: Groundwater Model Update

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1 INTRODUCTION

1.1 Background

A Flood Alleviation Scheme (FAS) is proposed for Oxford (Illustration 1.1) and includes a flood relief channel, referred to as the Western Conveyance or Oxford Relief Channel (Fugro Engineering Services, 2014). In 2015/16 a groundwater model was constructed to inform both the outline design of the scheme and the associated Project Appraisal Report (PAR) (ESI, 2016).

The model represents the river terrace sand/gravel deposits of the Thames Valley near Oxford. Across most of the area of interest (the floodplain) these deposits are overlain by lower permeability alluvium, which can act as a confining layer (ESI, 2016). However, the alluvium does not occur everywhere (there are gaps or “windows” through to the sand/gravel) and made ground is present locally (ESI, 2016). The sand/gravel aquifer is underlain by low permeability mudstone bedrock (Oxford Clay and West Walton Formations), the top of which forms an effective base to the near-surface groundwater system; the model represents only the sand/gravel aquifer layer (ESI, 2016).

The model was built using the United States Geological Survey (USGS) open source code MODFLOW (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996; Harbaugh *et al.*, 2000; Harbaugh, 2005), which uses a finite difference approach to solve the groundwater flow equations. Specifically, MODFLOW-NWT (a Newton formulation of MODFLOW-2005, see Niswonger *et al.*, 2011) was used with the Graphical User Interface (GUI) Groundwater Vistas (Environmental Simulations Inc., 2000-2011). The outputs of a Flood Modeller (ISIS) river model were taken as boundary conditions. The model was calibrated to the July 2007 flood event and then used to simulate the effects of the scheme on groundwater levels under various flood scenarios and also in a dry year (ESI, 2016).

As a result of ongoing ground investigation and monitoring, new information is available on ground conditions, groundwater levels and groundwater recharge. Further, there have been updated surveys of existing channels (affecting bed levels) and the geometry of the scheme design has also been updated. The model needs to be reviewed in light of these new data and amended if necessary to ensure that the effects of the scheme on groundwater levels and potential for groundwater flooding in the modelled aquifer are simulated as accurately as possible.

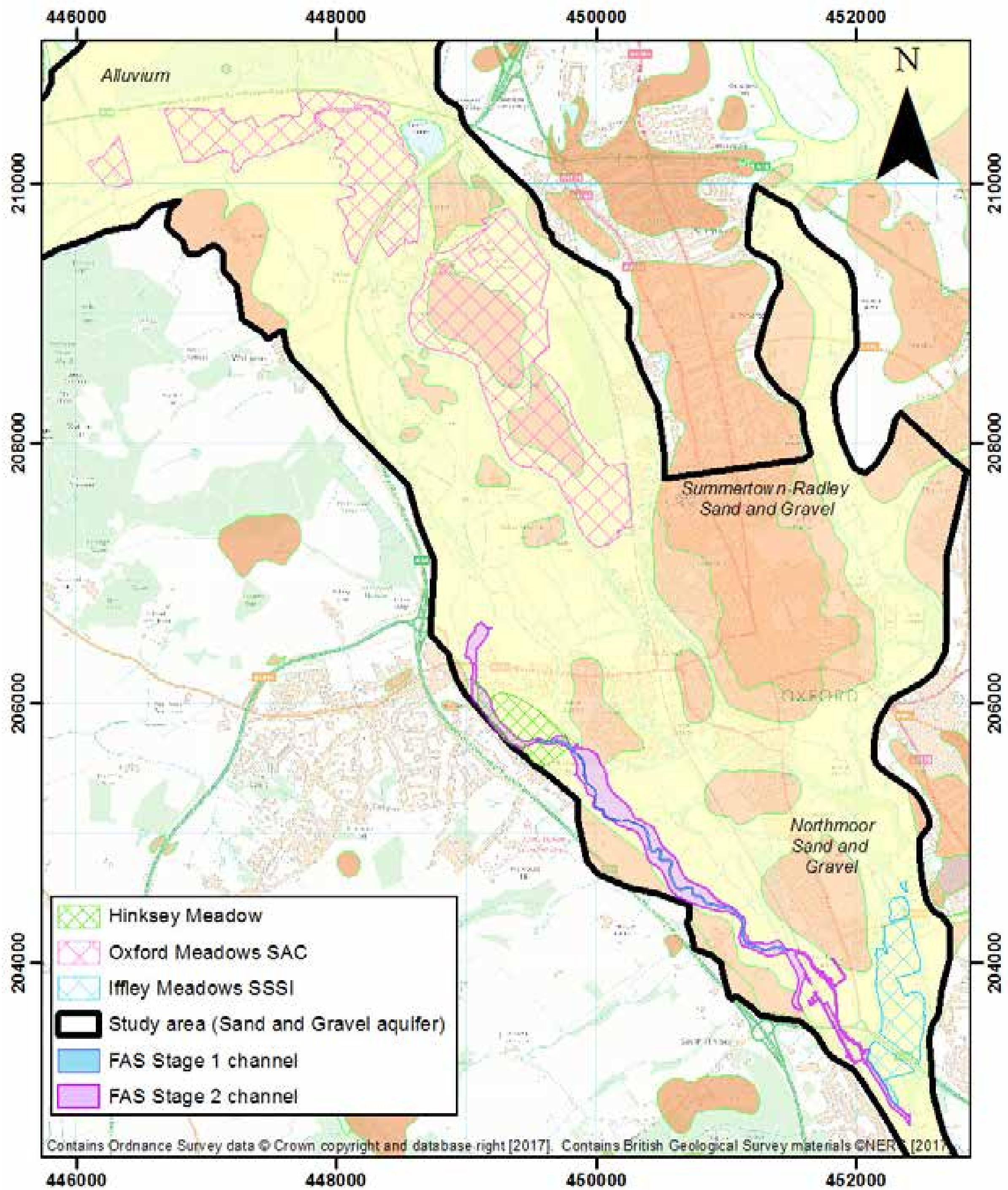


Illustration 1.1 FAS location and protected sites

1.2 Scope and Objectives

The original scope of works is detailed in the Proposal (Ref: 63294P3, 23 June 2017) and summarised below:

1. Obtain and review ground condition, groundwater level, scheme geometry, and recharge data against the current conceptual model.
2. Review and amend the existing model construction in the light of the above.
3. Validate the amended model against the original groundwater calibration targets (July 2007)
4. Carry out scenario runs as follows:
    a. 1 in 20 year flood event scenario run pair (with and without scheme) and assessment of impacts of the FAS on groundwater flood risk.
    b. Dry period run pair (with and without scheme) and assessment of impacts of the FAS on sites of ecological interest: Oxford Meadows SAC, Iffley Meadows SSSI and the Hinksey Meadow MG4 grassland area (Illustration 1.1). Hinksey Meadow was not considered explicitly in the original modelling work (ESI, 2016) and has been targeted in response to concerns about the potential impact of the scheme in this area.
5. Reporting.

In response to requests from the Environment Agency (EA), the following additional tasks were added to the original scope as the work progressed:

6. An additional dry period run representing weirs in Bulstake Stream (proposed mitigation measures designed to help maintain groundwater levels beneath Hinksey Meadow)
7. Additional baseline and dry period runs with the following changes having been made to the fluvial model by CH2M:
    a. Correction of river levels downstream of Sandford Lock.
    b. Update of the rule applied to the operation of weirs at Sandford.
    c. Update to weirs on Bulstake Stream to raise water levels in the MG4 grassland area of Hinksey Meadow (8 cm rise).
    d. Update to water levels in fishing ponds near South Hinksey (3 cm rise).
8. Preparation of three Technical Notes, which are included as appendices to this report:
    a. 63294 TN02: Investigation of apparent groundwater level anomaly (Appendix B)
    b. 63294 TN03: Review of modelling approach at Hinksey Meadow and Hogacre Park (Appendix C)
    c. 63294 TN04: Hydraulic connectivity between rivers and groundwater (Appendix D).

1.3 This report

This report is based on the information from the previous model (ESI, 2016). The conceptual and numerical model are reviewed, and updated if necessary, in light of the new data. The reader is referred to ESI (2016) for full details of the original model set-up and scenarios. Section 2 presents additional data, available since the issue of ESI (2016), that are relevant to the groundwater model construction and calibration. Section 3 discuss the implications of the new information on the conceptual understanding of the area that was described in ESI (2016). Section 4 describes how the new datasets were included in the calibrated groundwater model. Section 5 describes and presents the results of the flood scenarios carried out to assess the impact of the revised FAS. Conclusions are summarised in Section 6. Additional information is provided in appendices (see Contents list).

2 DATA REVIEW

This section presents additional data, available since the issue of ESI (2016), that are relevant to the groundwater model construction and calibration. The model is calibrated to the July 2007 flood event. The reader is referred to ESI (2016) for full details of model development.

2.1 Data Sources

The new datasets provided by CH2M are (Figure 2.1a and 2.1b):

- 0.5 m LIDAR Digital Terrain Model (DTM) along the FAS (Section 2.2)
- Geological information gathered from several sources (detailed in Section 2.5).
- Groundwater levels in September / October 2015 and May / June 2017 (Section 2.4).
- Pumping test data results (Section 2.6)
- 2016 Thame and Ock Soil Moisture Model data (Section 2.7).

This chapter reviews the new datasets and their implications for the calibrated groundwater model. River levels resulting from the revision of the FAS design are discussed in Section 5.

2.2 Topographical Survey

In the groundwater model, topography data are used to:

- Assign the top elevation of the sand/gravel aquifer where it crops out. Previously, the model used a combination of a 5 m DTM provided by CH2M and OS Terrain 50 DTM (ESI 2016, Section 3.4.1). At the scale of the model grid (20 m), the new 0.5 m LIDAR DTM would have a minimal impact as the DTM would need to be resampled to the resolution of the model grid.
- Identify areas where the scheme may change the risk of groundwater flooding (ESI 2016, Section 3.10, Figures 3.17, Figures 3.30 to 3.35, Figure 3.50). In ESI (2016), the depth to groundwater was calculated based on the simulated groundwater levels (20 m grid) and the DTM provided by CH2M (5 m grid). A conservative approach was adopted in which the ground elevation attributed to each model cell was taken as the minimum of the 5 m DTM cells covered by the model cell. In this report, depth to simulated groundwater was calculated on the resolution of the DTM (5 m and 0.5 m) (see Section 4.3.2). This is a less conservative but more accurate approach than in ESI (2016).

2.3 River channel survey

The river channels of reaches of the Seacourt Stream, Hinksey Stream and Weirs Mills Stream were surveyed between September 2016 and April 2017 (Illustration 2.1). The survey results were used by CH2M to inform the fluvial modelling. This resulted in revised river level and river bed elevations for some of the river cells present in the groundwater model. Additionally, the Triangulated Irregular Network (TIN) interpolation was refined by CH2M. The Flood Modeller TIN tools were used by CH2M to provide the surface water model input data for the MODFLOW model. The TIN was defined from 1D-model surveyed river cross sections, which were joined to form a network of triangles. Within this network, bed and water levels were converted into continuous surfaces, which were then intersected/sampled by the MODFLOW grid to provide the fluvial model and channel inputs for each individual MODFLOW river cell.

The scenarios presented in Section 5 incorporate these changes. However, the re-calibration to the July 2007 event does not. The changes were reviewed with the following findings:

- The changes in river water level are still within the error of the existing calibration (as measured by the groundwater level residuals in the steady-state model). This means that the impact of changing river levels would be insignificant on the model calibration and that other model parameters (such as hydraulic conductivity of the sand and gravel or conductance of the river bed) would not have required additional adjustment to allow for these slightly different river levels.

- The changes in bed level are unlikely to have a significant effect on the results. The river bed levels are represented in MODFLOW through the RBOT parameter. This is used to control the equation that MODFLOW uses for calculating fluxes from losing river reaches (depending on whether or not there is an unsaturated zone beneath the river). In practice, the strong connection between groundwater and surface water means that groundwater levels in river cells will effectively be fixed by the specified river level (which is itself always above the river bed). It is therefore unlikely that the groundwater head in a river cell will fall below RBOT – in other words, it is unlikely that the river will become "perched". Furthermore, a check was carried out for the start of the model run, when groundwater levels are low, to compare the updated river bed levels to the modelled groundwater levels. This showed the perched condition to be rare (10 cells out of 73,712 active model cells).

Therefore, incorporation of the recent changes to the river bed and water levels would have an insignificant impact on the calibration.

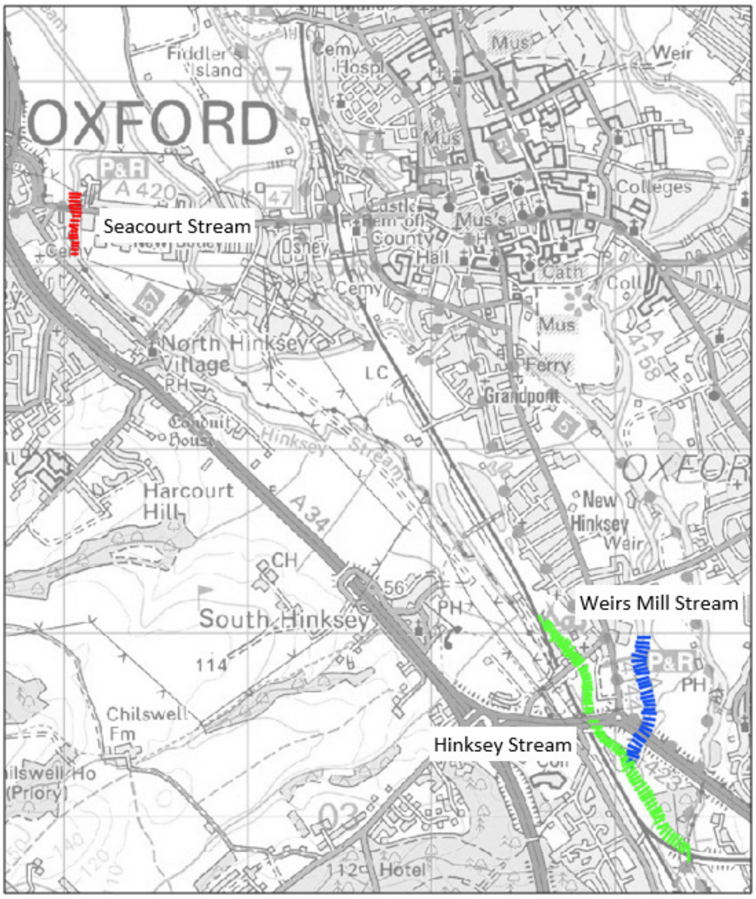


Illustration 2.1 Location of river channel survey (From CH2M, 2017b[1])

[1] © Crown Copyright. Ordnance Survey data. Licence number 10024198

2.4 Groundwater levels

Figure 2.1a shows the monitoring boreholes for which groundwater level data are available. Additional data (not used in the original modelling project – ESI, 2016) are available for September to November 2015 and May to June 2017. These data have been reviewed to check their consistency with the existing conceptual understanding of the groundwater system. However, they have not been used to calibrate the updated model as they post-date the calibration event (July 2007).

Groundwater contours were calculated for the days where the most extensive datasets were recorded and are presented in Figure 2.3. The July 2007 groundwater level targets used in the calibration of the steady-state model are also presented in the Figure for comparison.

The conceptual understanding of river-groundwater interactions is detailed in Section 2.5 of ESI (2016); further details are also presented in Appendix D. In general, the sand/gravel aquifer is well-connected to the river network and so, close to rivers, groundwater levels are similar to river levels. However, river levels were not available over the same period as the groundwater monitoring dates and so could not be used to constrain the groundwater contours.

A groundwater level low point is shown in the southern part of the area, between borehole SH1 and the historical landfill to the south east. It is likely that in reality the minimum groundwater level is located further to the east, along the river (which is understood to be receiving groundwater discharge, as shown by the groundwater flow paths in the inset maps). However, the contour plot does not reflect this as river levels are not accounted for.

The range and flow direction of the 2017 groundwater levels are generally consistent with the levels used as calibration points in the steady state model (i.e. levels at the start of the July 2007 flood event), apart from the area in the south west where the calculated groundwater contours are about 2.5 m higher than the calibration target at SH1. ESI 2016 notes that the groundwater levels at SH1 are known to respond to runoff recharge.

Time series at locations with the greatest number of records are presented in the illustration below. Between September and November 2015, the groundwater levels measured at any one location show little variation (< 0.5 m). Note that this is a fairly short record which does not allow assessment of seasonal variations.

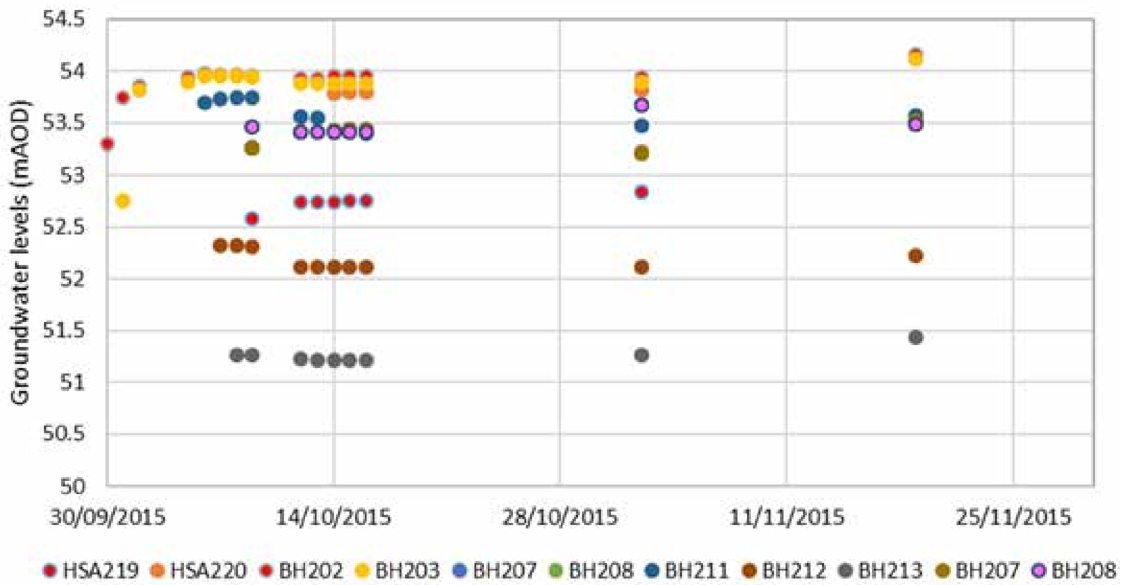


Illustration 2.2 Groundwater levels time series, autumn 2015

2.5 Geological Data: Layer Top/Base

As shown in Figure 2.4, the record of geological logs in the area is extensive and comes from various sources:

Table 2.1 Source of geological borehole records

Contractor	Consultant	Client	Date	Purpose
WYG	CH2M	EA	2017	Oxford FAS Ground Investigation (GI)
Oxford Archaeology	Mackley	EA	2017	Geoarchaeology for Oxford FAS
WYG	CH2M	EA	2015	Oxford FAS design investigation
Fugro	Black & Veatch		2011	
Fugro	Black & Veatch	EA	2008	Geotechnical and Contaminated Land Assessment
Twistell Reinforcement Ltd, G.K.N. Reinforcement Ltd		Oxford City Council	1956 to 1961	A34 A423 Road building
Technotrade		Oxford City Council	1999	Bridge design
Jacobs		Oxford City Council	2007	Bridge repair design
EA			various	GW monitoring and modelling
BGS borehole records			various	various

The top and bottom elevations of the original single-layer model were based on a BGS 3D geological model (Kessler *et al.*, 2007; Newell, 2008), with additional data points taken from the BGS online borehole database (BGS website). At the time that the BGS 3D model was built, many of the geological records listed in Table 2.1 were available (Illustration 2.3). The main new source of geological information is provided by the investigations carried out for the Oxford FAS in 2015 and 2017 by WYG for CH2M (Illustration 2.3). Amongst these, the top of the sand and gravel formation is recorded in 225 logs and the bottom in 81 logs across the model area (Figure 2.1b). The top of the sand and gravel is generally defined as the base of the Alluvium, except for 12 boreholes where sand and gravel was recorded directly below a clay-lined landfill. In these cases, the sand and gravel is likely to have been partly, or wholly, removed prior to landfilling and the engineered landfill liner will form a barrier to flow, effectively confining the aquifer much more effectively than the natural Alluvium.

Figure 2.1b compares the top and bottom elevations of the model with elevations of the top and bottom of the sand/gravel aquifer given in the recent borehole logs. There is no distinctive pattern in deviation of the aquifer model top from the WYG GI results. In the southern part of the model area, the GI results suggest the gradient of the bottom of the sand/gravel aquifer is steeper than previously simulated in ESI (2016).

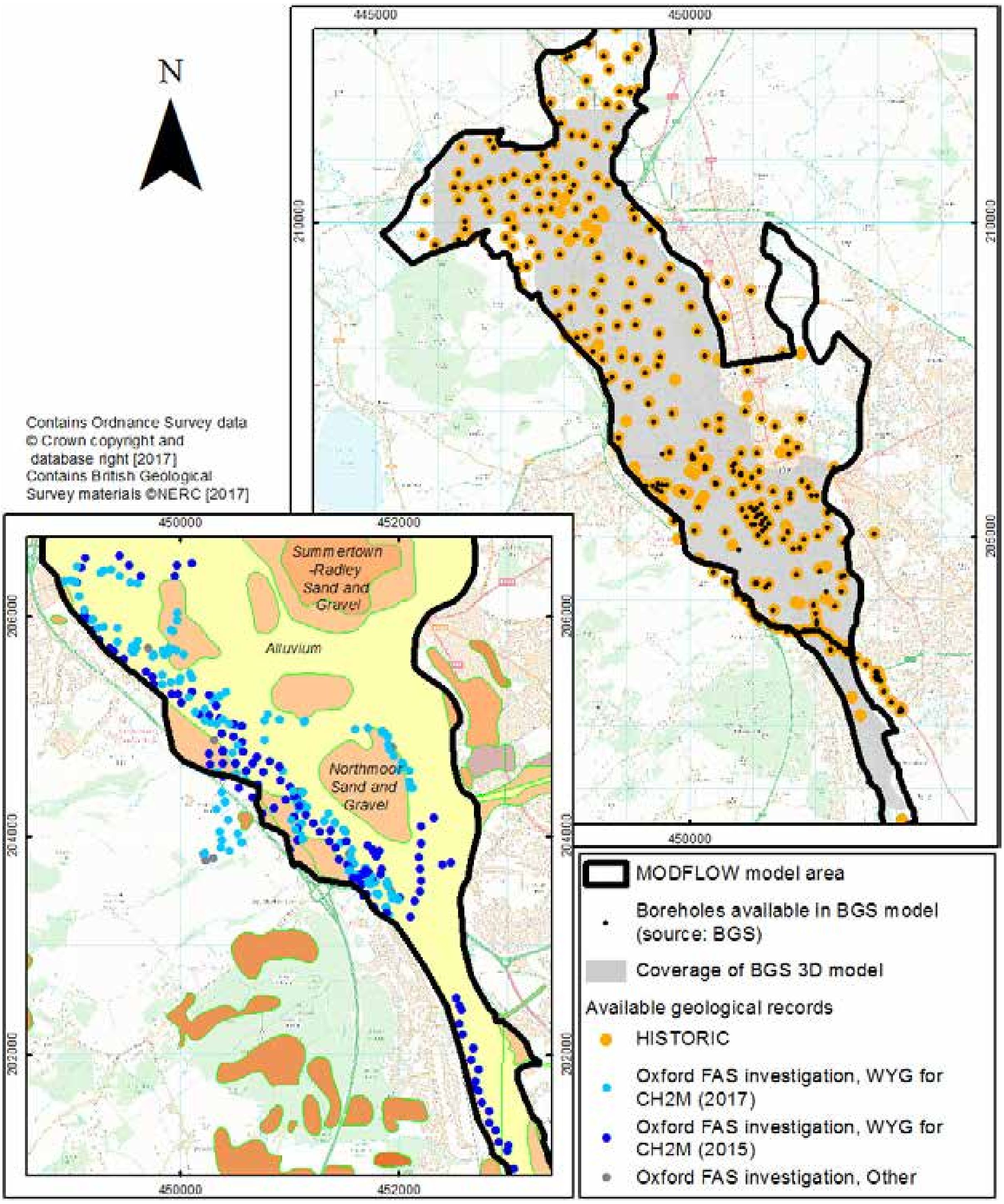


Illustration 2.3 Borehole records

2.6 Aquifer Properties

Three pumping tests were carried out in the sand/gravel aquifer in May 2017. Results were provided by CH2M (2017b). The test locations and main results are presented in Figure 2.1a and summarised in the Table below.

Table 2.2 Pumping tests results (summarised from CH2M, 2017a)

	Date (May 2017)	Pumping rate (l/s)	Data used	Transmissivity (m^2/d)	Hydraulic conductivity (m/d)*	Storativity
New Hinksey	3rd – 4th	8.5	Early	1529	200 to 500	0.01
			Middle/ late	640		0.56
South Hinksey	8th – 9th	2.5	Early	588	125 to 200	0.07
			Middle/ late	374		0.32
North Hinksey	5th – 6th	10	Middle/ late	3164	1000	0.000396

*based on an aquifer thickness of about 3 m.

The test carried out at North Hinksey appears to provide significantly different results to those at the other two sites, and the high values obtained may reflect the apparent occurrence of recharge to the aquifer during the test due to the proximity of the test site to the Hinksey Stream. The test is therefore considered to be unrepresentative of the aquifer as a whole. The other two tests are more consistent, particularly with respect to derived transmissivity and (hence) hydraulic conductivity values. The storativity values derived at New Hinksey and South Hinksey appear to reflect a transition from near-confined (early data) to unconfined conditions (later data), although the storativity values derived (particularly at New Hinksey) for the later data appear unrealistically high. Given the relatively short duration of the test (c.24 hours) and the constraints in undertaking the test (testing had to be curtailed as drawdown in the pumping well was close to the base of the screened section), the storativity results are considered to be less reliable than those for transmissivity. The geometric mean of hydraulic conductivity values is 300 m/d, and 200 m/d if the outlier at North Hinksey is excluded. This is higher than (although the same order of magnitude as) the 100 m/d used in the existing groundwater model presented in ESI (2016), which was based on literature values of 100 to 1000 m/d and calibration to observed groundwater levels.

2.7 Rainfall Recharge

Daily recharge ("effective rainfall") data were provided by the EA from its Soil Moisture Model (Figure 2.5). Two Soil Moisture Model areas cover virtually the whole of the MODFLOW model domain: Thame and Ock areas (Figure 2.1a). On average, about 25-30% of rainfall is effective for recharge (Table 2.3).

Table 2.3 SMD summary

Area	Data period	1961-2016 effective rainfall average (mm/d)	Proportion of rainfall that is effective
Thame	Jan 1920 – Jul 2017	0.514	29%
Ock	Jan 1961 – Jul 2017	0.45	26%

2.8 Revisions to Fluvial Model Runs

Topographic survey, DTM and river bed level survey updates had led to a number of significant changes to the fluvial model runs subsequent to the development of the original (2016) groundwater model. There were also changes to some elements of the scheme design (compared to that previously modelled), including incorporation of a two-stage channel. The updated fluvial model runs (for both dry weather and flood scenarios) have been fully incorporated into the updates of the groundwater model presented in this report. Furthermore, there have been two further simulations (ref. scope items 6 and 7 in Section 1.2) corresponding to some minor corrections to the fluvial model and further iterations (adding weirs) of water level mitigation measures identified for Hinksey Meadow and other parts of the scheme.

3 IMPLICATIONS OF NEW DATA FOR THE MODEL

3.1 Summary of Previous Conceptual Model

ESI (2016) presents a detailed account of the hydrogeological conceptual model for the superficial sand/gravel aquifer of the Thames Valley, Oxford. Only a very brief summary is given here.

- The floodplain is underlain by a river terrace sand/gravel aquifer (Northmoor Sand and Gravel Member) that is typically 2 to 4 m thick (locally up to 8 m).
- The sands and gravels are highly permeable, with estimated horizontal hydraulic conductivities being of the order of 10 to 1000 m/d.
- Stratification (including the presence of silt/clay layers) imparts anisotropy to the aquifer, with the vertical hydraulic conductivity being lower than the horizontal. However, the silt/clay layers are probably not very persistent laterally, and so are unlikely to provide an effective barrier to vertical flow.
- The sand/gravel aquifer is underlain by low permeability mudstone bedrock (Oxford Clay and West Walton Formation), the top of which forms an effective base to the near-surface groundwater system.
- Across most of the study area the sand/gravel aquifer is overlain by low permeability alluvial deposits that are typically about 1 m thick (locally up to 8 m). The alluvial deposits commonly confine the sand/gravel aquifer so that groundwater levels in boreholes penetrating the aquifer rise above the aquifer top.
- Along the edges of the floodplain the aquifer is bounded by low permeability mudstone bedrock, effectively providing no-flow boundaries. Exceptions to this occur where the river terrace deposits beneath the floodplain are in contact with higher terrace deposits or (in the south) with bedrock aquifers of the Corallian Group.
- There is a good hydraulic connection between the groundwater and surface water systems, and the groundwater flow system is strongly influenced by the management of surface water levels using locks and weirs. The impoundments generally create local groundwater recharge zones in the upstream areas, with lock bypass channels often forming lines of discharge. The resulting groundwater flow pattern is relatively complex.
- Parts of the floodplain are prone to groundwater flooding. Properties with basements are likely to be at particular risk.

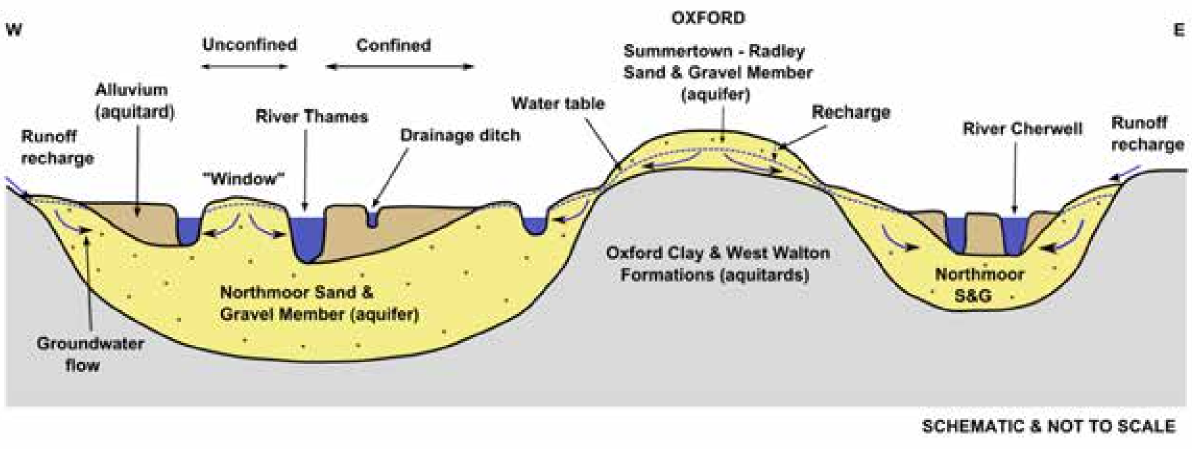


Illustration 3.1 Hydrogeological conceptual model

3.2 Updates to Conceptual Model

The new data do not provide grounds to significantly alter the conceptual understanding of the area, although they provide information to refine the groundwater model:

- Model layer elevations from borehole logs from the WYG investigations carried out for CH2M FAS investigations in 2015 and 2017.
- Long-term average model recharge from 1961-2016 SMD data.
- Hydraulic conductivity of the sand/gravel aquifer from pumping tests.

New stream surveys were also carried out and although the new survey data were not incorporated in the calibrated groundwater model (see Section 2.3), they were incorporated, through the Flood Modeller outputs, in the scenarios run to assess the impact of the FAS (see Section 5).

4 NUMERICAL MODEL UPDATE & VALIDATION

This section presents the amendments made to the calibrated groundwater model in light of the new data presented in Section 4. The reader is referred to ESI (2016) for full details of model development. Like the original model presented in ESI (2016), the updated model is calibrated to the July 2007 flood event.

From the calibrated flood model, scenario models were developed to assess the impact of the FAS. A "dry-year" version was set up to assess the potential impact of the scheme on ecologically sensitive sites and a "1 in 20 year flood scenario" version was built to assess potential impacts on groundwater flooding. These scenario models are detailed in Section 5

4.1 Model approach summary

The original flood model (ESI, 2016) was calibrated to groundwater levels observed at 20 locations during the July 2007 groundwater flooding event. The river levels of this event correspond to somewhere between a 1 in 5 and 1 in 20 year return period. A steady-state model, corresponding to the beginning of the flood event, provided the initial conditions to a transient model and was calibrated to groundwater levels at the beginning of the flood events.

The newly available data presented in Section 2 (recharge, hydraulic conductivity, elevation of the top and bottom of the sand/gravel aquifer) were taken into account to refine the calibrated model presented in Sections 4.2 and 4.3 below. It should be noted that the river levels used in the original July 2007 calibration were not changed.

4.2 Model Update

4.2.1 Geometry

Note that the full geological dataset contains approximately 1000 geological records gathered from various sources (Section 2.5, Table 2.1) and includes historical records. The update of the model geometry was targeted to reflect the newly available geological information and to preserve the existing geometry in areas where no new data were available. Therefore, CH2M provided ESI with a subset of the geological records dataset containing only the results of investigations carried out for the FAS. These c. 350 records were used to update the top and bottom elevations of the sand/gravel layer in the model in the FAS area (Illustration 4.1). As no new geological information was available outside of this area, the elevations elsewhere were kept as processed in ESI (2016). These original elevations (ESI, 2016) were based on the BGS 3D model surfaces and are assumed to be a good representation of the aquifer geometry.

From the data subset provided by CH2M, the bottom of the sand and gravel was recorded at 81 locations and the top of the formation at 225 locations. Interpolation was undertaken using Spatial Analyst (ArcGIS) and Natural Neighbour analysis. To constrain the interpolation, the layer elevations from the previous model (ESI, 2016) were extracted at the boundary of the area where elevations needed to be updated and some additional points were added (based on the BGS 3D model) to infill significant gaps in coverage. Checks were performed to ensure that interpolation did not result in computing the aquifer bottom above the aquifer top.

The model top, bottom and thickness are presented in Figures 4.1, 4.2 and 4.3 respectively, along with the differences between the new and previous layer elevations, and the locations of data points used. The pattern of differences between the new and previous models reflects the density of new borehole data available.

In MODFLOW-NWT, the simulation stops when the head specified in boundary conditions such as river cells falls below the base of the model. Therefore, checks were made to ensure that in those cells containing boundary heads (e.g. river cells) the defined minimum head (for the time series) was not below the base of the model. If it was then the base was dropped to 0.1 m below the minimum boundary head.

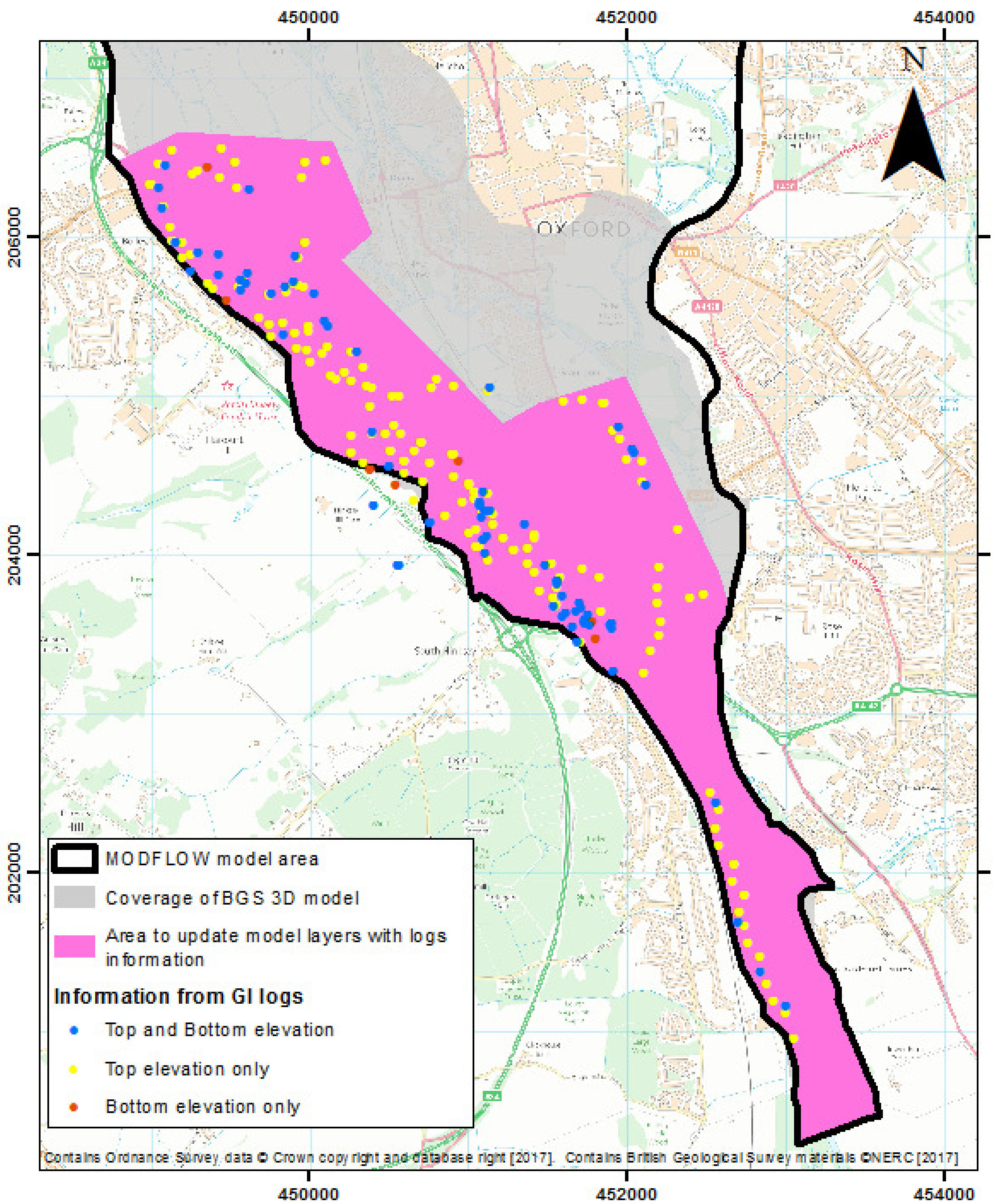


Illustration 4.1 Model layer update area

4.2.2 Recharge

Two recharge zones are defined in the model:

- sand and gravel outcrop, where rainfall recharge is directly available to the aquifer.
- Alluvium outcrop where rainfall recharge is attenuated by a factor of 0.2, following the reduction factor approach of Rushton, 2003 (ESI, 2016). This reflects the presence of low permeability silty/clay overlying the sand/gravel aquifer.

Certain areas of open water (larger ponds and lakes) are represented in the model as areas of very high hydraulic conductivity, as discussed in Section 3.6 of ESI (2016), and the recharge is set according to the mapped geology as discussed above, i.e. attenuated on Alluvium outcrop. The depth of these waterbodies is not known and nor is the nature and thickness of any lake bed sediment, artificial lining or underlying alluvial deposits. The ponds/lakes may be well-connected to the sand/gravel aquifer, in which case the sand/gravel recharge rate would be appropriate. Alternatively, low permeability linings or bed sediment may limit connectivity with groundwater. This will limit direct rainfall recharge; however, overall recharge may increase if the surface water is "perched" and leaking to ground. The model does not represent perching of lakes or ponds (these surface water features are represented simply by the simulated groundwater level being above ground; they are not explicitly represented using River cells). The recharge rate assigned to lakes and ponds in the model is not considered to be of great importance because (i) lakes/ponds occupy only a very limited portion of the area of interest and (ii) river levels are the main control on simulated groundwater levels in the model.

<u>Flood model</u>

In the original flood model, the recharge was based on the Flood Estimation handbook (FEH) which gives the Standard Average Annual Rainfall (SAAR) within the model area as 620 to 636 mm for the period 1961-1990 and 650 mm for the period 1941-1970 (CEH, 2009). The recharge was set constant throughout the simulation, at 15% of SAAR (i.e. 3% on Alluvium outcrop after the reduction factor 0.2 is applied). The EA's Soil Moisture Model suggested that this was an underestimate, with 25 – 30% being more likely[2] (ESI, 2016). Although the model is transient, the timeframe is fairly short (three weeks) and the variations in recharge conditions would not affect the groundwater model, especially during a fluvial flood event where fluctuations in groundwater levels in the permeable superficial deposits are completely controlled by the fluctuations in river levels.

The simulated groundwater levels are mainly controlled by the river levels. However, the model is also sensitive to the recharge – hydraulic conductivity combination. This is especially evident in observation boreholes that are located further away from the influence of the rivers. Increasing the recharge to a more realistic (and defensible) value of about 27% of SAAR leads to a general increase in groundwater levels and worsens the calibration, especially in observation boreholes away from the rivers (WR3, PTM11, PTM1). A higher hydraulic conductivity of the sand/gravel aquifer is theoretically needed to maintain a good calibration (Section 4.2.3).

In the flood model presented here, daily recharge ("effective rainfall") data derived from Soil Moisture Model were provided by the EA for the period 1961 - 2016. Two Soil Moisture Model areas cover virtually the whole of the MODFLOW model domain: Thame and Ock areas, which cover respectively 23% and 77% of the model area (Figure 4.4). The recharge was maintained constant throughout the simulation and calculated as follows:

Sand and gravel = $(\text{Ock}_{1961\text{-}2016} \times 0.77) + (\text{Thame LTA}_{1961\text{-}2015} \times 0.23)$

Alluvium = $0.2 \times [(\text{Ock}_{1961\text{-}2016} \times 0.77) + (\text{Thame LTA}_{1961\text{-}2016} \times 0.23)]$

Table 4.1 compares the recharge in the updated model with that in the previous model. Figure 4.4 presents the recharge used in the calibrated flood model.

[2] The 25 – 30% of long-term average rainfall is applied to the areas of Sand and Gravel outcrop. In areas of alluvium the recharge is reduced by a reduction factor as described in the text.

Table 4.1 Updated model recharge

	Previous model recharge		Updated recharge		Change in recharge
	mm/d	mm/a	mm/d	mm/a	
sand and gravel	0.26	94.9	0.465	169.7	+79%
Alluvium	0.053	19.3	0.093	33.9	+75%

Dry year model

The original dry year model recharge was already based on the 1961 - 2015 EA's Soil Moisture Model (which became available after the flood model was constructed). In the model presented here, the data period was extended with additional data to 1961 – 2016. Monthly transient recharge for the two defined recharge zones (sand/gravel and alluvium) was calculated as follows:

1st year (Sand and gravel) = ($Ock_{\text{Monthly LTA 1961-2016}}$ x 0.77) + ($Thame_{\text{Monthly LTA 1961-2016}}$ x 0.23)

1st year (Alluvium) = 0.2 x [($Ock_{\text{Monthly LTA 1961-2016}}$ x 0.77) + ($Thame_{\text{Monthly LTA 1961-2016}}$ x 0.23)]

2nd year (Sand and gravel) = ($Ock_{\text{Monthly 2011}}$ x 0.77) + (Thame $LTA_{\text{Monthly 2011}}$ x 0.23)

2nd year (Alluvium) = 0.2 x [($Ock_{\text{Monthly 2011}}$ x 0.77) + (Thame $LTA_{\text{Monthly 2011}}$ x 0.23)]

where 0.2 is the recharge reduction factor for areas of alluvial outcrop and the factors 0.77 and 0.23 are areal weighting factors for calculating the average recharge.

Figure 4.4 shows the recharge used in the dry year model.

An initial model run with these higher recharge values showed an increase in groundwater levels (poorer calibration) at the targets located further away from the rivers while the calibration remained unchanged at targets near the rivers. This is expected as groundwater levels at targets located near the rivers are controlled by the river levels and those points most distant from discharge zones will show greatest sensitivity to changes in recharge.

4.2.3 Aquifer Properties

The aquifer properties of the original calibrated model were as follows:

- Horizontal hydraulic conductivity, K_{xy} 100 m/d
- Vertical hydraulic conductivity, K_z 10 m/d
- Specific yield, S_y 0.3
- Specific storage, S_s 0.00075 m^{-1}

[Storage coefficient, S = S_s x b where b = saturated thickness; e.g. for b = 4 m, S = 0.003]

The results of the pumping tests suggest that the hydraulic conductivity is higher than previously used and give a geometric mean hydraulic conductivity of 200 to 300 m/d for the sand/gravel aquifer (Section 2.6). The updated model uses a value of 200 m/d. Increasing the hydraulic conductivity is conceptually justified by the pumping test results and consistent with the increase in recharge (Section 4.2.2) to achieve a calibration very similar to that of the previous model (see Section 4.3). Indeed, a simple increase of the hydraulic conductivity would have lowered the simulated groundwater levels away from the rivers, worsening the calibration. However, as the recharge was increased based on newly available data (Section 4.2.2), a quality of calibration very similar to that of the previous model was achieved, using more realistic parameters. The model calibration is discussed in Section 4.3

Due to constraints in the pumping test procedure, the storage information given by the pumping tests is considered to be less reliable than the hydraulic conductivity. Furthermore, the model is not sensitive to the storage parameters (ESI, 2016, Section 3.8.2). On this basis, no changes have been made to the storage parameters used in the model.

4.2.4 Other model parameters

This section presents a brief overview of the model parameters that have not been updated in the calibrated model. The justification of the model set up is fully detailed in ESI (2016) (Section 3) and not repeated here.

- Modelling code and software: MODFLOW–NWT used through the Groundwater Vistas user interface.
- Solver and convergence criteria: GMRES solver (Niswonger et al., 2011) with the convergence criteria: Head Change Criterion for Outer Iterations (HEADTOL) = 0.01 m, Flux Change Criterion for Inner Iterations (FLUXTOL) = 500 m^3/d.
- Model Grid: extends across 700 rows and 500 columns of 20 m x 20 m cells from the origin located at NGR SP 440 000
- Time frame:
    - Initial flood steady-state model (Calibrated to 20 July 2007 groundwater levels)
    - Transient flood model (Calibrated to the July 2007 flood event): initial heads provided by the above steady-state model. One long (10 year) stress period followed by 173 three-hourly stress periods, each split into three time steps that are increased as a geometric progression of ratio 1.41 (see ESI, 2016 for further details; the long initial stress period was to ensure that the model stabilised before simulation of the flood peak).
- External boundary conditions (Figure 4.5):
    - No-flow along edges where the sand/gravel aquifer is bounded by low permeability bedrock.
    - No-flow where the Upper Terrace ceases to be in contact with the Lower Terrace, immediately north of the main urban area of Oxford.
    - Oxford Canal not represented.
    - General Head Boundaries (GHB) specified where the edges of the model cross a river valley, to represent the exchange of groundwater between the modelled aquifer and the (connected) aquifer outside the model:
        - In the transient flood model, the specified heads follow the fluctuations of the levels in nearby rivers and are specified 500 m outside the boundary. This represents the fact that groundwater levels outside the modelled area will rise in a flood event, like those inside the model
        - In the dry –year model, the heads are maintained at the constant low level of 1 mbgl, 500 m outside the boundary. This represents a theoretical worst-case drought in which groundwater levels are at their lowest.
- Internal boundary conditions (Figure 4.5):
    - Rivers represented using MODFLOW river cells. The river stage, bed level, width and length of the channel within each model cell are based on Flood Modeller outputs and interpolated from Flood Modeller nodes to MODFLOW model cells by CH2M. The model calibration is based on the July 2007 groundwater flooding event, with the river levels of this event corresponding to a 1 in 5 to 1 in 20 year return period (ESI, 2016). The river bed hydraulic conductivity, K, was set at 10 m/d, with a bed thickness of 1 m.

- In the transient flood model, the stage of each river cell varies for each time step, following the progression of the flood.
- In the steady state model, the stage of each river cell is kept constant throughout the simulation, at its Q_{95} level which represents low flow conditions.

No changes have been made to the river boundary condition representing the July 2007 event (Section 3.2).

4.3 Validation of the July 2007 model

4.3.1 Calibration of flood model

The flood model is calibrated to the July 2007 flood event. Groundwater level data presented in Section 2.3 cover periods in 2015 and 2017 and are therefore not useful to assess the model calibration. The calibration of the updated model is evaluated based on the targets presented in Section 3.8 of ESI (2016,).

Figure 4.6 presents the Steady-State groundwater contours, target locations and simulated residuals[3]. As shown in Illustration 4.2 and Illustration 4.3 below, the calibration is almost identical to that of the previous model. Figures 4.7 a, b, c, d present the transient calibration to the observed groundwater levels during the July 2007 event. Table 4.2 compares the model to the observed timing and value of peak groundwater levels during the flood event. The calibration is also very similar to that of the previous model.

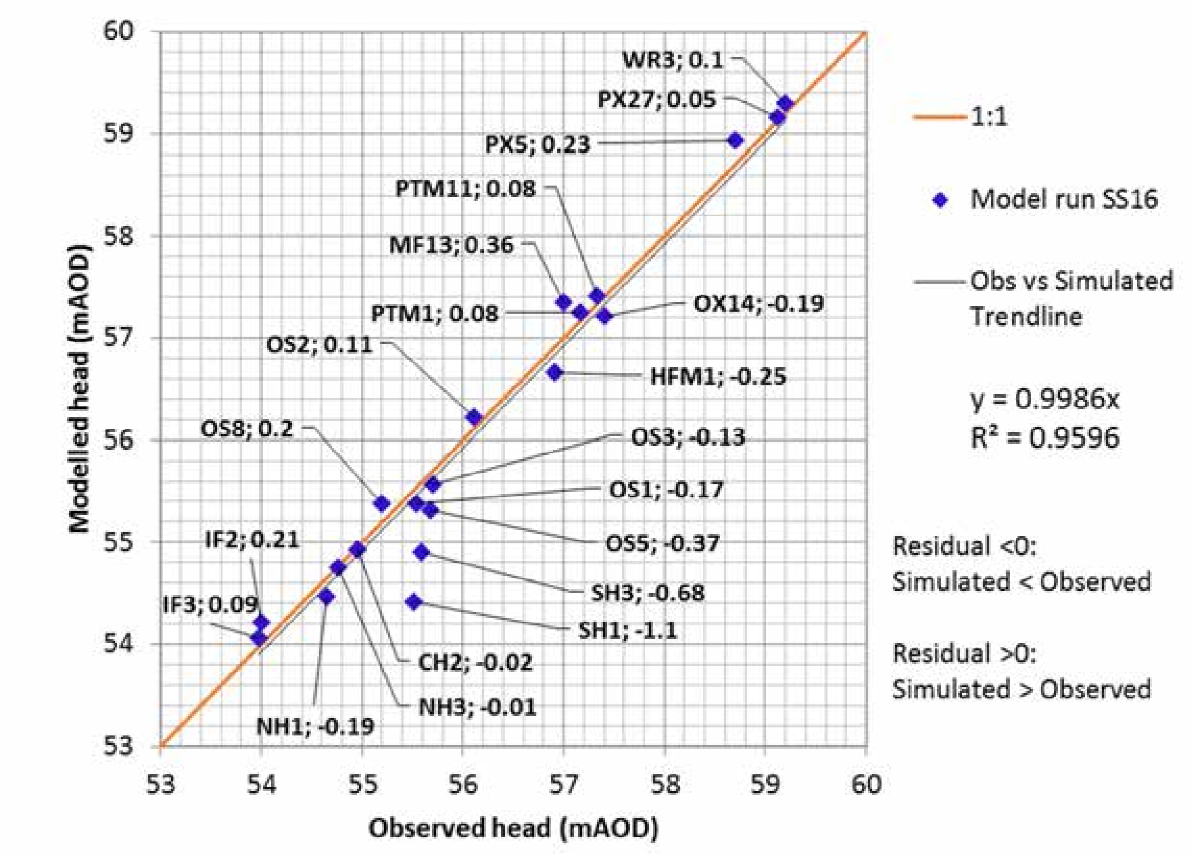


Illustration 4.2 Steady-State calibration

[3] Residual is defined as Simulated minus Observed head, i.e. positive residual means the simulated head exceed the observed head (and vice-versa)

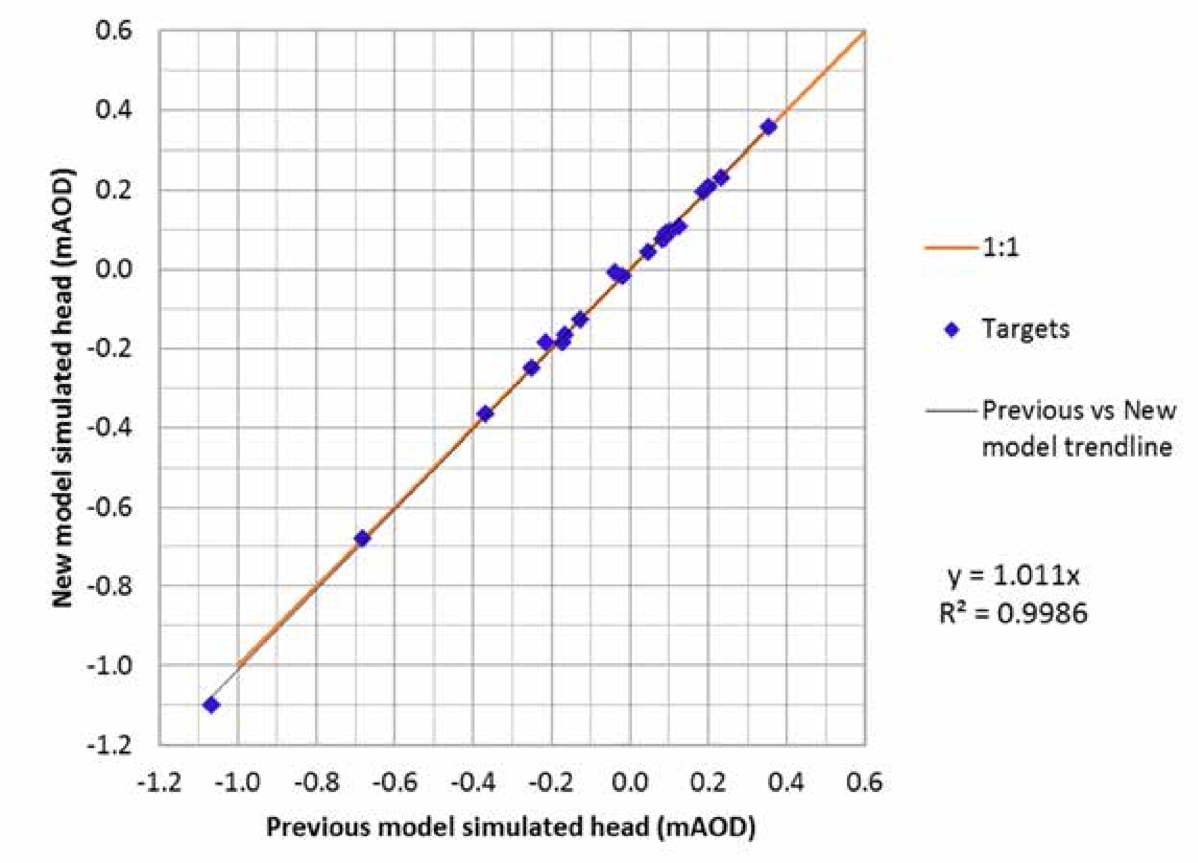


Illustration 4.3 Comparison to previous steady-state calibration

Table 4.2 Transient calibration to peak groundwater levels (mAOD)

	Observed	**Simulated**		**Previous model**		**Difference with previous model**		**Comment on revised calibration**
	Peak level (mAOD)	Peak level (mAOD)	Time (d)	Peak level (mAOD)	Time (d)	Peak level (m)	Peak time (hours)	
CH2	55.76	55.90	3.15	55.90	3.15	0.00	0.00	No significant change on calibration
HFM1	58.10	58.19	4.64	58.19	4.64	0.00	0.00	No significant change on calibration
IF2	55.19	55.07	4.77	55.07	4.77	0.00	0.00	No significant change on calibration
IF3	54.94	54.90	4.93	54.90	4.87	0.00	1.64	No significant change on calibration
MF13	57.31	57.90	4.81	57.89	4.77	0.01	0.96	No significant change on calibration
NH1	55.54	55.84	5.12	55.84	5.31	-0.01	-4.63	Peak slightly earlier
NH3	56.13	56.04	5.06	56.04	5.12	0.00	-1.35	No significant change on calibration
OS1	56.67	56.45	4.89	56.45	4.89	0.00	0.00	No significant change on calibration
OS2	57.40	57.13	4.93	57.13	4.93	0.00	0.00	No significant change on calibration
OS3	57.33	57.06	4.99	57.06	4.99	0.00	0.00	No significant change on calibration
OS5	56.74	56.44	4.93	56.43	4.93	0.00	0.00	No significant change on calibration

	Observed	**Simulated**		**Previous model**		**Difference with previous model**		**Comment on revised calibration**
	Peak level (mAOD)	Peak level (mAOD)	Time (d)	Peak level (mAOD)	Time (d)	Peak level (m)	Peak time (hours)	
OS8	56.74	56.67	4.99	56.64	5.06	0.02	-1.64	Peak slightly earlier and higher (closer to observed GWL)
OX14	57.48	57.44	7.18	57.41	8.30	0.02	-26.95	Calibration remains poor
PTM1	57.87	57.64	5.36	57.63	5.56	0.01	-4.63	No significant change on calibration
PTM11	57.83	57.78	5.52	57.77	5.93	0.01	-9.94	No significant change on calibration
PX5	59.35	59.36	4.52	59.36	4.62	0.00	-2.31	No significant change on calibration
PX27	59.88	59.62	4.52	59.62	4.52	0.00	0.00	No significant change on calibration
SH1	56.11	55.97	5.49	56.03	5.56	-0.07	-1.64	Peak slightly earlier (closer to observed GWL) and lower (the previous calibration was already lower than the observed GWL, although observed GWL are unusually high (Section 2.4))
SH3	56.41	56.17	5.02	56.20	5.06	-0.03	-0.96	No significant change on calibration
WR3	59.95	59.61	5.24	59.60	5.68	0.02	-10.62	No significant change on calibration

4.3.2 Model outputs

Figure 4.8 compares the initial heads with the 5 m resolution ground surface elevation. The depth to simulated groundwater was calculated on the resolution of the DTM (5 m). This is a less conservative but more accurate approach than in ESI (2016), where the calculations were carried out on a 20m grid, using the minimum DTM elevation in each 20m grid cell. Groundwater levels are within half a metre of the ground surface over most of the model area. Greater depths to groundwater occur in areas of sand and gravel outcrop or areas of higher topography. To the north and south of Oxford Meadows, groundwater levels are simulated 15 to 25 cm above ground level

Figure 4.9 compares the initial heads to the elevation of the top of the aquifer, and highlights those areas where the aquifer is confined, i.e. where the head is above the top of the aquifer (it also includes some lakes in the north, where the aquifer is unlikely to be confined – unless the lakes have low permeability beds). This map suggests that the aquifer is generally confined and that the response of groundwater levels to changes in river level will therefore be rapid. Confined storage is much lower than unconfined storage, with head changes reflecting changes in pressure rather than changes in the degree of saturation; a pressure pulse can move more rapidly than a wetting or drying front. It is apparent that confined conditions (at least, groundwater heads above the top of the model layer) are indicated even within the “window” areas that are mapped by the BGS as sand/gravel outcrop[4], and where the aquifer should be unconfined. In such areas, one of the following may apply:

- The aquifer is actually confined:

[4] Re-mapping of the geology was not within the scope of this study.

  - The geological mapping has limited resolution: the BGS will have applied a minimum thickness for mapping alluvium (David Macdonald, BGS, pers. comm. 10th December 2015), and so some thin lower permeability alluvial deposits may be present in areas mapped as sand/gravel outcrop. The aquifer may therefore be confined, or semi-confined, in some of these areas.

- The aquifer is unconfined with groundwater emergence:
  - Groundwater emergence is not represented in the model, except as baseflow to the river network. Heads are allowed to rise above the ground surface without water being removed by overland flow. As Figure 4.9 relates to "non-flood" conditions (the steady-state run used to provide initial heads for transient model runs), groundwater flooding is unlikely, and any genuine groundwater emergence would be expected to correspond to a feature such as a spring or lake.
- The aquifer is unconfined:
  - Groundwater levels may be over-predicted by the model and/or the aquifer top elevation (where interpolated between data points) may locally be underestimated.

Figure 4.10 presents the simulated transmissivity (i.e. hydraulic conductivity times saturated thickness) at the start of the model (i.e. for the initial heads).

Figure 4.11 compares modelled peak groundwater levels with the elevation of the ground surface. Potential groundwater flooding is indicated where modelled groundwater levels rise above the ground surface as defined by the DTM. However, whether or not groundwater flooding occurs in reality depends on several other factors that are not captured by the model: artificial ground (basements, building foundations, etc.) can enhance or reduce the flood risk, and the presence low permeability alluvial deposits can reduce the risk, although seepage may occur through thin alluvial deposits. There are also uncertainties in the DTM and simulated groundwater levels presented. Attributing a flooding incident to groundwater is also not always straightforward, as groundwater can mix with floodwater from other sources (e.g. fluvial or pluvial). For example, potential groundwater flooding is simulated to the south of Oxford Meadows, around Medley Manor Farm, immediately west of Osney village. These areas are not known to have suffered groundwater flooding in 2007 although as no major road or habitations are present, flooding may have occurred but been unreported. The approximate areas where groundwater flooding was reported in 2007 are discussed below:

- Botley Road underneath the railway Bridge (Illustration 4.4): very locally, groundwater levels are simulated above ground levels. Although the geological map does not show sand and gravel outcrop in this location, groundwater could potentially seep through a thin layer of alluvial deposits. Another possibility is that alluvial deposits have been locally excavated to construct the road under the railway bridge, thus connecting the road to groundwater in the aquifer. The 5m DTM indeed shows the area to be about 3 to 4m below the surrounding land.

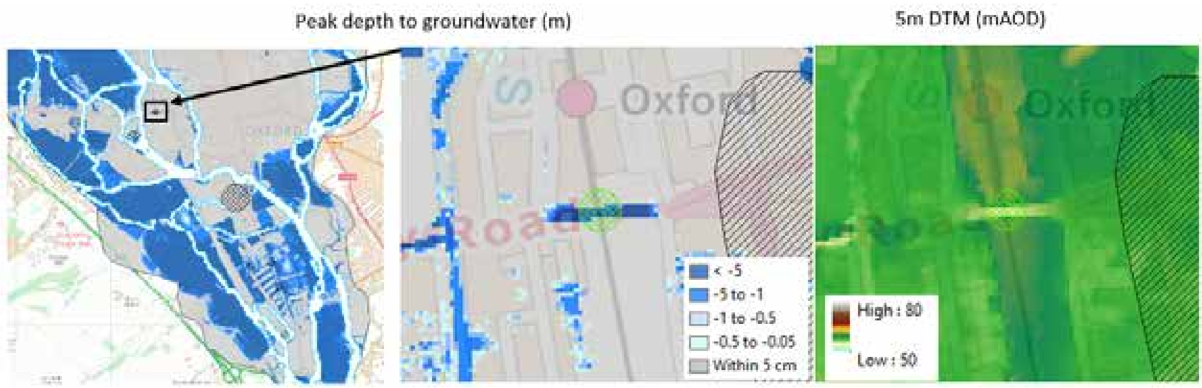


Illustration 4.4 Simulated groundwater flooding (July 2007), Botley Road railway bridge[5]

- Osney village, south of Botley Road (Illustration 4.5). In this area, groundwater levels are indeed simulated above ground level, suggesting a potential higher risk of groundwater flooding. The sand/gravel aquifer is not mapped as cropping out in this location. Although the presence of the relatively low permeability layer of Alluvium is expected to reduce flood risk, the effect is only partial (Macdonald *et al.*, 2012). Upward seepage through the Alluvium could have led to groundwater flooding, especially where the alluvium is thin or where urbanisation has resulted in its partial or total excavation.

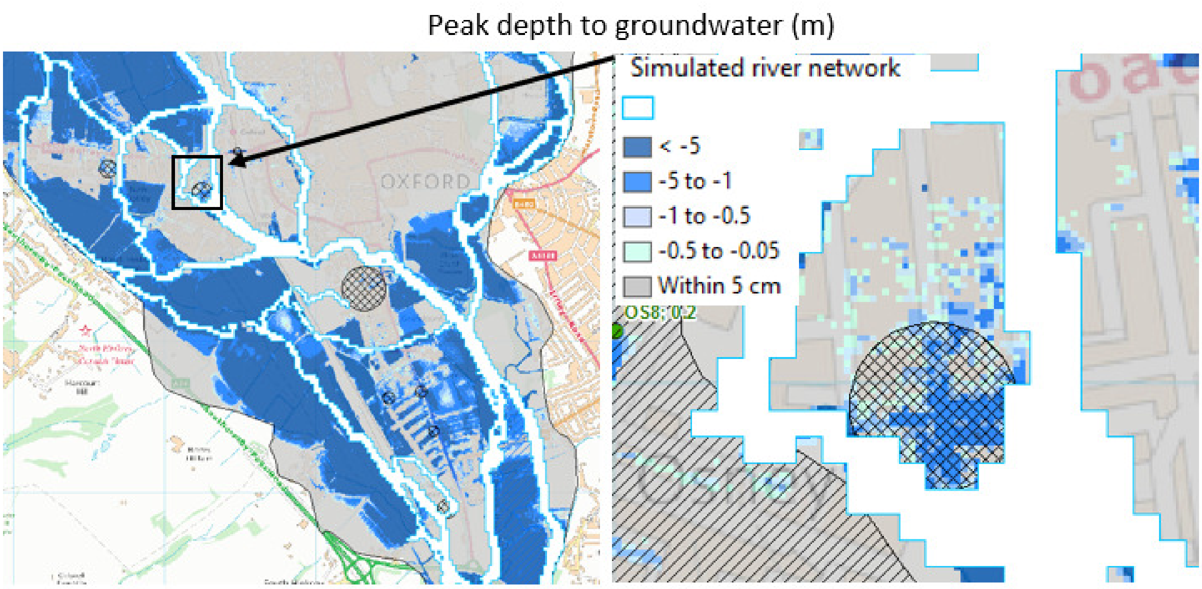


Illustration 4.5 Simulated groundwater flooding (July 2007), Osney village[5]

- Housing to the west of Grandpont and Christchurch Meadow (Illustration 4.6). sand and gravel are mapped at outcrop. Locally, groundwater levels are simulated to rise above ground level. Flooding is also simulated to the west of Abingdon Road, on sand and gravel outcrop. It is possible that flooding occurred but was not reported as the area is uninhabited (according to OS mapping).

[5] Contains OS data © Crown copyright and database right 2017. Single-hatched areas are Sand and Gravel outcrop (based on BGS mapping © NERC); double/cross-hatched areas are areas of groundwater flooding (ESI, 2016).

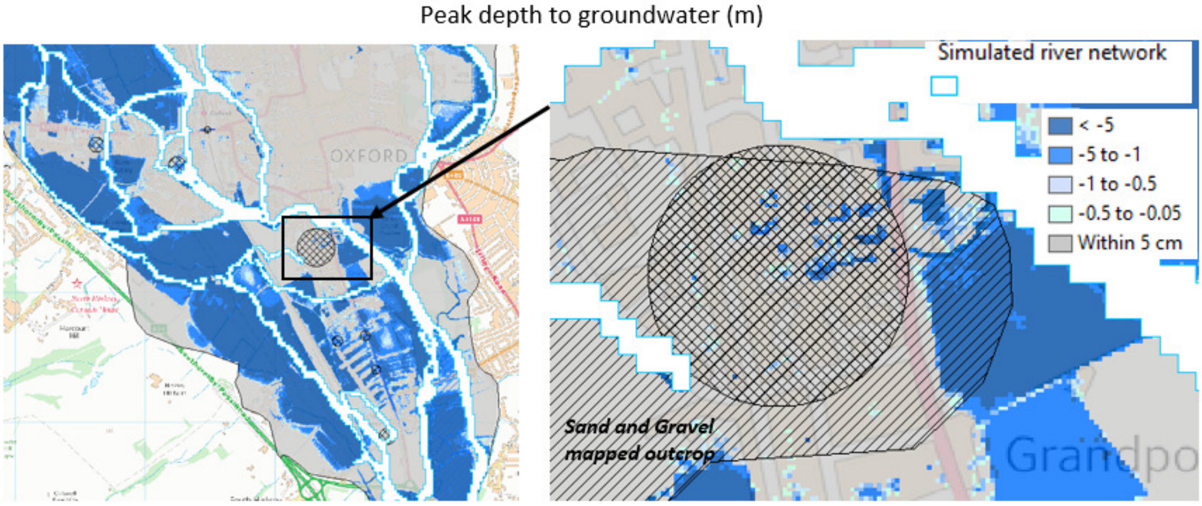


Illustration 4.6 Simulated groundwater flooding (July 2007), Grandpont[6]

- At New Hinksey (Illustration 4.7), potential groundwater flooding is simulated to be more extensive than reported. However, for the reasons noted above, areas of *potential* groundwater flooding (groundwater head above ground level) will be more extensive than those areas that actually flood.

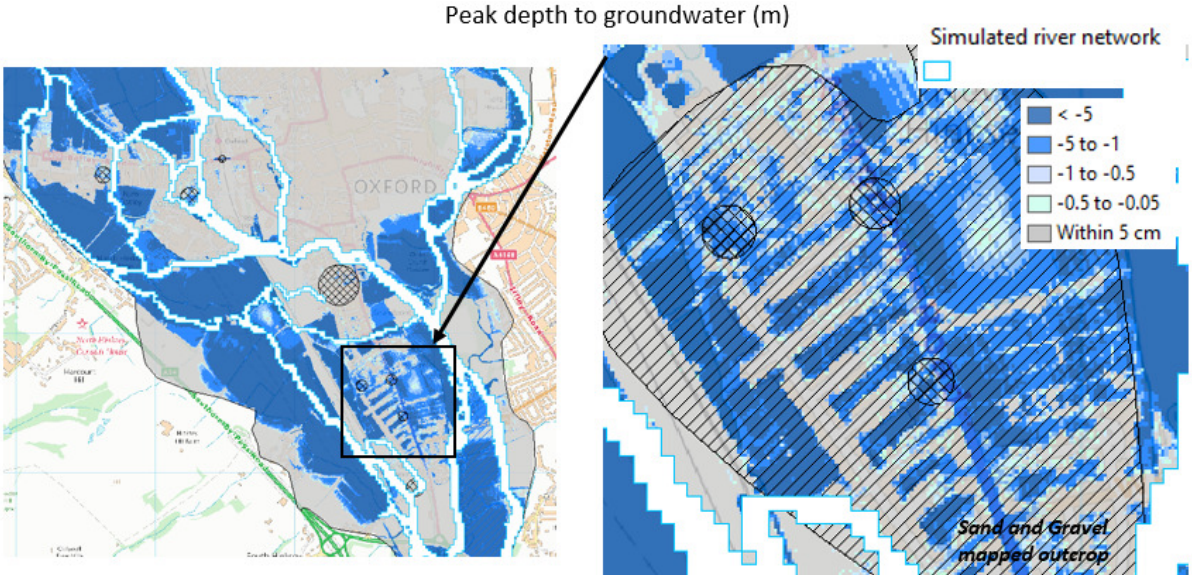


Illustration 4.7 Simulated groundwater flooding (July 2007), New Hinksey[7]

[6] Contains OS data © Crown copyright and database right 2017. Single-hatched areas are Sand and Gravel outcrop (based on BGS mapping © NERC); double/cross-hatched areas are areas of groundwater flooding (ESI, 2016).

5 NUMERICAL MODEL SCENARIO RUNS

The geometry of the proposed scheme is presented in Figure 5.1. This has been updated from the previous model (in both fluvial and groundwater models) and now includes a first stage channel (deeper and present in both the 1 in 20 year event and the dry Q95 scenario) and a second stage channel (as the second stage is shallower, it is dry in the Q95 scenario and only represented in the 1 in 20 year event scenario, as illustrated in the schematic cross section below). This provides a much more realistic replication of the scheme in both dry weather and "operational" flood scenarios.

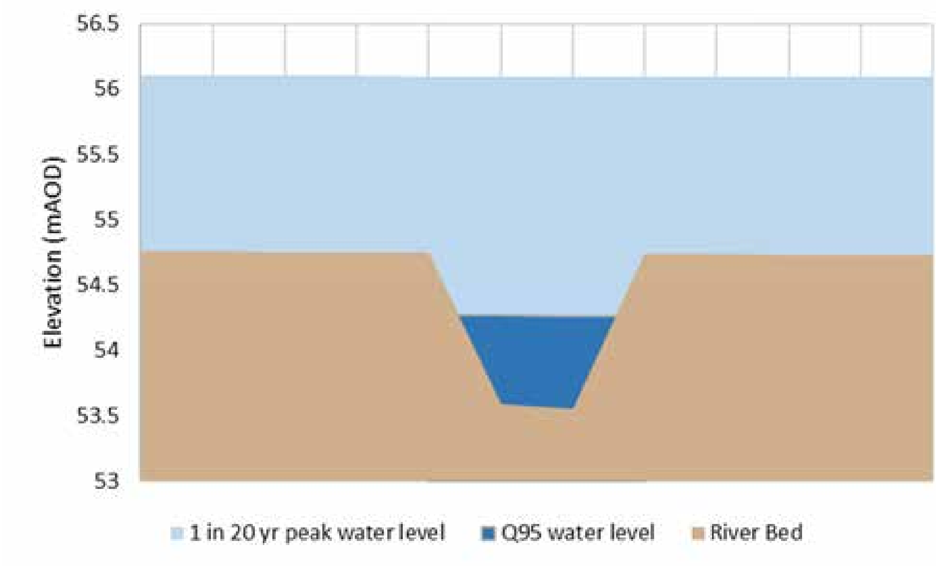


Illustration 5.1 Example cross section through FAS (model row 460)

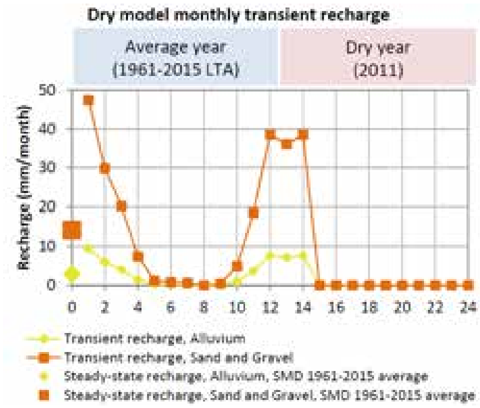
5.1 Flood Scenario Runs

From the model parameters set in the flood model calibrated to the July 2007 flood event (Section 4), a series of scenarios were carried out to simulate the impact of the FAS channel on two sets of conditions: the 1 in 20 year flood event and a "dry year" event. The "dry year" model uses the recharge conditions presented in Section 4.2.2.

The 1 in 20 year flood event aims to assess the impact of the FAS scheme on potential increase or reduction of the groundwater flood risk in the area while the dry year model aims to assess potential impacts on areas of ecological interest (Oxford Meadows SAC, Iffley Meadows SSSI, Hinksey Meadow). For this purpose, the scenarios were run in pairs to compare the model results: a "baseline" scenario without the scheme and a scenario where the FAS channel is represented. The river (and river bed) levels were derived from the Flood Modeller model and provided by CH2M. They incorporate the stream channel surveys undertaken between September 2016 and April 2017 (Section 2.3).

Table 5.1 Scenario model set up

<table>
<tr><th rowspan="2"></th><th colspan="2">1 in 20 year flood event</th><th colspan="2">“Dry year” model</th></tr>
<tr><th>baseline</th><th>FAS</th><th>baseline</th><th>FAS</th></tr>
<tr><td>Timeframe[7]</td><td colspan="2">12.5 day model of 100 three-hour stress periods</td><td colspan="2">2 year model of 24 monthly stress periods</td></tr>
<tr><td>FAS channel</td><td>no</td><td>yes</td><td>no</td><td>Yes</td></tr>
<tr><td>River levels, derived from the Flood Modeller model, provided by CH2M[8]</td><td colspan="2">Transient levels[9]</td><td colspan="2">Constant levels equivalent to the Q_{95} event</td></tr>
<tr><td>Recharge</td><td colspan="2">Constant long-term average recharge[10]
<table>
<tr><td>Sand and gravel</td><td>0.465 mm/d</td></tr>
<tr><td>Alluvium</td><td>0.093 mm/d</td></tr>
</table>
</td><td colspan="2">Transient recharge: year 1 representing average conditions, year 2 represents dry conditions



</td></tr>
</table>

Part of the Western Conveyance Channel is proposed to be lined and is therefore assumed to be impermeable. This was represented in the model (Illustration 5.2) by:

- Deleting the river boundary condition from the cells representing the lined section (reflecting a lack of aquifer-river interaction).
- Adjusting the hydraulic conductivity of the corresponding aquifer cells to reflect the lowering of aquifer transmissivity by partial, or complete, penetration of the aquifer layer by the lined channel. For each cell a reduced horizontal hydraulic conductivity (K=Kx=Ky) was calculated from:

$$K_{reduced} = K\left(1 - \frac{d}{b}\right)$$

where d = depth of penetration of the aquifer by the channel (model top elevation minus bed level) and b = thickness of aquifer layer. This changes the transmissivity T=Kb.

[7] In each of the model runs, an additional first stress period is set as steady-state to ensure groundwater levels have stabilised prior to the transient period.
[8] In areas unaffected by the scheme, checks were made to ensure the level of the river bed was identical in all the scenarios. This ensures any change in groundwater levels the model may show are the result of the scheme rather than numerical artefacts from river bed interpolation. A few river cells showed inconsistencies in bed levels across the scenarios. In these cases, the “without” level was preferred to the “with” and the Q_{95} was preferred to the 1 in 20 years. These decisions were taken following discussions with CH2M.
[9] Some river cells on the second stage FAS channel are dry at the beginning of the simulation. In the Flood Modeller outputs, this is translated by a river level falling below the river bed. These events were removed from the groundwater model.
[10] Note that the 2007 flood event was not related to rainfall over Oxford but to rainfall further upstream, which led to a flood pulse travelling downstream to Oxford. For this reason it was not necessary to represent enhanced rainfall recharge in the flood model.

In reality, it is b that changes, but the effect of changing K is the same because MODFLOW uses T when solving the groundwater flow equations.

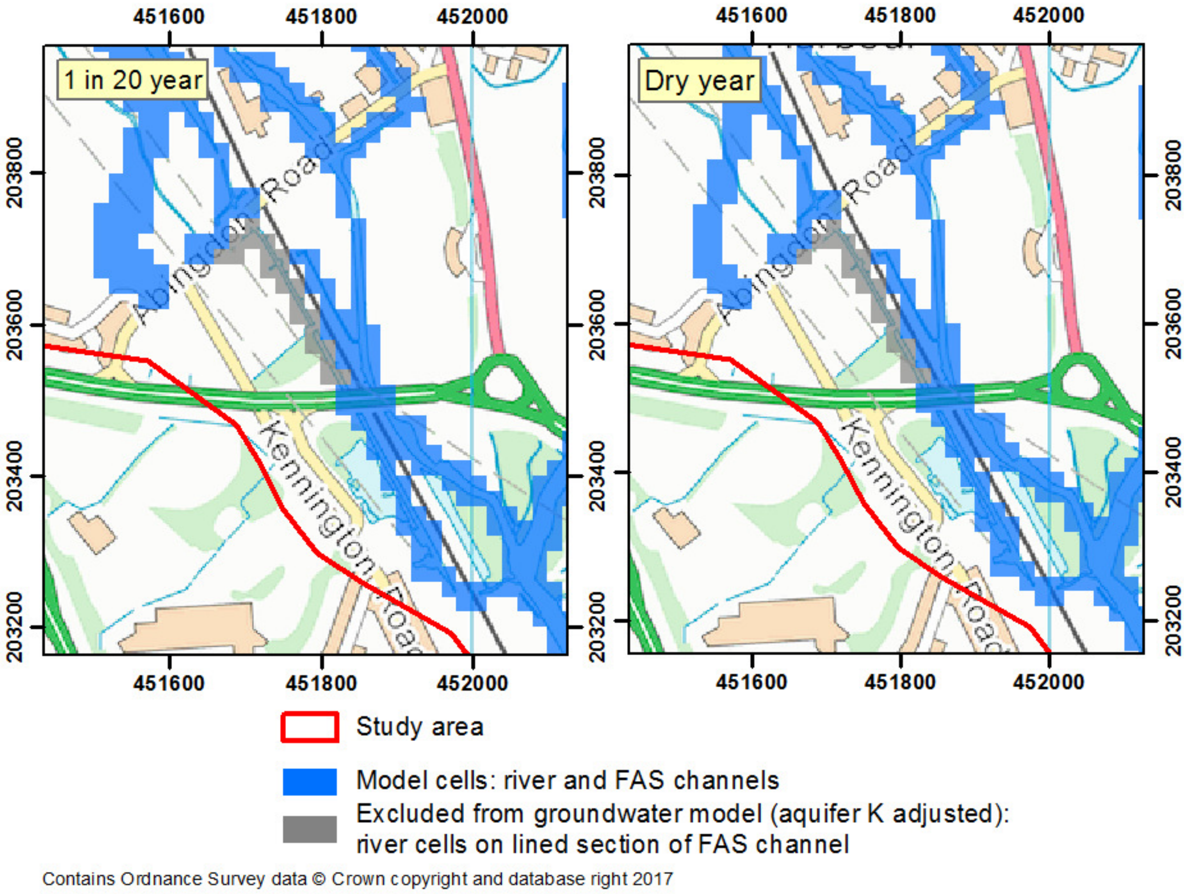


Illustration 5.2 Representation of lined section of FAS Channel

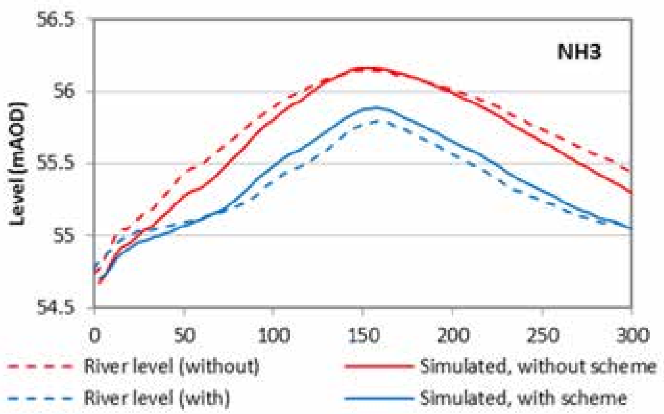
5.2 Model results

The model results are presented in the Table 5.2 below for the 1 in 20 year flood and the dry year scenario. The associated Figures (named in the table) show:

- Time series of groundwater levels at observation boreholes comparing results "with FAS" to the "without FAS" baseline ("existing") situation
- Spatial groundwater levels and a comparison plot "with FAS" to the baseline situation:
    - For the 1 in 20 year flood, the maximum simulated groundwater levels[11] are compared. This allows assessment of the areas where the model predicts the FAS to reduce or increase the risk of groundwater flooding.
    - For the dry year scenario, the groundwater levels at the end of the simulation are compared. By this time, groundwater levels are expected to have reached their lowest point. This allows assessment of the potential impact of the scheme on the areas of ecological interest (Oxford Meadows SAC, Iffley Meadows SSSI and Hinksey Meadow, Illustration 1.1)
- Spatial depth to groundwater and a comparison plot "with FAS" to the baseline situation.

[11] This does not represent a specific time step. The maximum groundwater level was extracted from each model cell time series.

Table 5.2 Scenario model results

	1 in 20 year event	**Dry year**
Simulated groundwater heads at the monitoring boreholes for both the "with scheme" and "without scheme" (baseline) scenarios The response of the OBHs depends on their proximity to the FAS and to a river boundary condition. This is summarised on Figure 5.2 and detailed here	Figure 5.2, 5.3a to 5.3d The presence of the FAS does not affect the timing of the simulated peak groundwater levels at any of the observation Boreholes (OBHs). In the model, a number of OBHs are not significantly affected by the scheme: - HFM1, MF13, PX5, PX27, WR3: located in the northern part of the model area where the scheme is not expected to have an impact. - OX14, PTM1, PTM11: located east of the Thames and away from the river. - IF3 located on the river, east of Iffley Meadows. SIF2 is also located on the river, west of Iffley Meadows so simulated groundwater levels are controlled by Weirs Mill Stream. The OBHs indicated as most affected are: - CH2 on the River Cherwell (c. 9 cm reduction in groundwater levels with the FAS), reflecting a change of water level in the associated river cell. - NH1, OS1, OS5, SH1, SH3, SNH1, SOS5 are located close to the FAS. - NH3, which is located between a river and an area of open water.  	Figure 5.2, 5.4a to 5.4d The OBHs show different patterns of response: - OBHs in which no response to the FAS is simulated (due to there being no significant local change in river level) and showing little to no seasonal variation: HFM1, IF3, MF13, OS2, PX27, PX5. These are located on or very close to the rivers (so groundwater levels are mainly controlled by the constant river levels) and in areas unaffected by the FAS. - OBHs in which no response to the FAS is simulated (due to no change in river level) but which display seasonal variations: OS8, OX14, PTM1, PTM11, WR3. These are located further away from the streams (so they respond to variations in recharge conditions) and in areas unaffected by the scheme. - OBHs in which a response to the FAS is simulated but no seasonal variations are shown: OS1, OS3, OS5, SOS5, SH3. These are located on or very close to the rivers (so groundwater levels are mainly controlled by the constant river levels, which are different with the FAS in place) and in areas affected by the FAS. - OBHs in which a response to the FAS is simulated as well as seasonal variations: SH1, NH1, SNH1, OS8. These are located slightly away from the rivers (so they respond to variations in recharge conditions) and in areas affected by the scheme. - The high conductivity area representing an area of open water next to NH3 causes groundwater levels to be simulated slightly lower than the rivers. The low groundwater levels in the dry year model (due to the low recharge conditions) are propagated to NH3 through the high K area. NH3 is also close to a river and responds to slightly lower river levels induced by the FAS.

	1 in 20 year event	**Dry year**
Spatial difference in groundwater level between the baseline and “with scheme” scenarios	Peak groundwater levels shown in Figure 5.5 The FAS channel results in slightly lower groundwater levels overall. This can potentially reduce the risk of groundwater flooding in the areas along Abingdon Road that have experienced it in the past (23 to 40cm reduction in groundwater levels). The greatest reduction (up to 62 cm) occurs around Cold Harbour. A slight increase in groundwater levels of about 10 to 15 cm is simulated to the south of North Hinksey, over the A34, on the sand and gravel outcrop. This apparent “anomaly” is a reflection of actual groundwater condition (i.e. not a modelling artefact) and is the subject of a review presented in Appendix B. These changes affect the hydraulic gradient from Osney to Cold Harbour. In the existing situation, a steep gradient towards the river is simulated. The FAS induces a lower gradient in a more southerly direction.	Groundwater levels at the end of the simulation shown in Figure 5.6 The FAS affects a much smaller area than the 1 in 20 year flood. Again, the most significant reduction is simulated around Cold Harbour (up to 47 cm). North of Cold Harbour, groundwater levels increase by about 10 to 15cm, reflecting higher water levels in the river with the FAS in place. In Oxford Meadows and Iffley Meadows, the change in groundwater level is less than 1cm
Spatial variations in the Depth to Water (DTW) from ground surface	Minimum groundwater depth shown in Figure 5.7a, 5.7b, 5.7c As the FAS induces a reduction in groundwater levels in areas that have experienced groundwater flooding in the past, the simulated levels mostly drop below ground levels. However, at OBH NH1, groundwater levels in the calibrated model are simulated 20 cm lower than observed. This is a similar range to the simulated reduction in groundwater levels in the area (Figure 5.7c). Therefore, the influence of the scheme on groundwater flooding incidence might actually be insignificant, with the apparent change reflecting error/uncertainty in the calibration.	Depth to groundwater at the end of the simulation is shown in Figure 5.8a, 5.8b, 5.8c. Note that these figures also show the calibration residuals (simulated groundwater level minus observed groundwater level) for the calibrated model (calibrated to the July 2007 flood event). These values are included to show how the quality of the calibration varies spatially. They provide a context for interpreting the results of the model scenarios. Around Hinksey Meadow (Figure 5.8b), groundwater levels are simulated to reduce by up to 33 cm, bringing the depth to groundwater to around 0.8 to 1.3 mbgl. In the baseline model, depth to groundwater is simulated to be around 0.7 to 1 mbgl, although the calibrated flood model is about 30 cm lower than observed. This suggests that under dry conditions, the grassland would receive very little to no inflow from groundwater under the current situation. The FAS may further reduce this inflow. At Iffley Meadows (Figure 5.8c), the depth to groundwater under current conditions is simulated around 30 cm below ground (ranging from the extreme 1 mbgl to slightly above ground level), which is about the range of the calibration residuals in the area (Figure 4.6, steady-state conditions, Figure 5.8c, 2007 peak conditions). The FAS channel is not simulated to significantly affect groundwater levels in the Meadows.

	1 in 20 year event	**Dry year**
Implications	**Implications for groundwater flood risk** In general, simulated peak groundwater levels are reduced by up to about 0.6 m in the area of the scheme. A reduction in peak groundwater level will tend to reduce groundwater flood risk. A slight rise in peak groundwater level (about 0.1 to 0.2 m) is predicted for a very localised area near North Hinksey Conduit House. This is not an urban area, although it does contain the A34 Southern Bypass. The apparent rise in peak groundwater level is addressed in Appendix B. Overall the modelling results suggest that the scheme will tend to reduce groundwater flood risk in the area. However, it should be emphasised that any impact on actual groundwater emergence will depend on site-specific factors not represented in the model (e.g. whether or not the confining layer of alluvium has been breached by building foundations) as well as on absolute water levels (modelled groundwater levels are subject to a degree of uncertainty because the calibration is imperfect).	**Implications for ecological habitats** At Iffley and Oxford Meadows, the model simulates a negligible change in groundwater levels (< 0.01 m, which is within the model convergence criteria, Section 4.2.4). The Floodplain Meadows Partnership[12] has suggested that the representation of the River Thames as being well-connected to groundwater may be leading to an underestimate of the effects of the scheme on Oxford Meadows. This concern is addressed in Appendix D. At Hinksey Meadow, the model simulates a groundwater level fall of up to 0.3 m with the scheme in place. Any ecological impact of such a fall would depend on the sensitivity of the grassland ecosystem to changes in groundwater level.
Additional model runs (Section 5.3) including, as a mitigation measure, new weirs on Bulstake Stream.	**Implications for groundwater flood risk** Not modelled. These additional runs were concerned with “dry year” groundwater levels beneath Hinksey Meadow.	**Implications for ecological habitats** The modelling suggests that the weirs will help to maintain groundwater levels beneath Hinksey Meadow. The simulated effect of the scheme is to cause a fall in groundwater levels beneath part of the Meadow area of up to 11 cm in scenario A and up to 2 cm in scenario B. In the remainder of the Hinksey Meadow area, a slight rise in groundwater level is simulated.

[12] A project focussing on research into, and management/restoration of, floodplain meadows in England and Wales. The Steering Group includes the following partners: The Open University, Natural England, the Environment Agency (EA), the Wildlife Trusts, the Centre for Ecology and Hydrology (CEH), the Field Studies Council, the Royal Society for the Protection of Birds (RSPB), the National Trust and People Need Nature (Floodplain Meadows Partnership website).

5.3 Additional scenarios

As presented in Table 5.2, the dry year scenario simulates the FAS to cause groundwater levels to reduce across Hinksey Meadows. Although the simulated reduction is, hydrogeologically speaking, fairly small, it may be considered significant from an ecological point of view. Therefore, two scenarios were carried out to explore whether weirs could maintain the water levels in the river, and therefore in the sand/gravel aquifer:

> **Scenario A:** new weirs represented on Bulstake Stream.
>
> **Scenario B:** update to weirs on Bulstake Stream to raise water levels in the MG4 grassland area (8 cm increase). Additional changes made to the Sandford weir structures and to river levels downstream of Sandford Lock. Water levels also adjusted upwards (by 3 cm) in the fishing ponds north west of Cold Harbour.

For these scenarios, rather than re-creating TIN interpolations (Section 2.3) between the fluvial and groundwater models, a simpler approach was adopted in which CH2M provided ESI with new river levels for the affected reaches. Changes to modelled river boundary conditions were restricted to these reaches, with reaches outside the area of influence left unchanged. Results are presented in Figure 5.9 (scenario A) and 5.10 (scenario B), along with the specified changes in river level. They can be compared to Figure 5.8b which presents the results of the original scenario described in Section 5.2.

It should be noted that the apparent groundwater level rise shown at the north western tip of Hinksey Meadow (indicated by a small blue patch in each of Figures 5.9 and 5.10) reflects an anomaly in the Q95 river levels. During processing of the fluvial model outputs into a form suitable for the groundwater model, some river cells were allocated , in the FAS scenario, a stage that was up to 0.25 m too high. This higher river stage results in nearby groundwater levels being simulated as higher than in the baseline. The effect is very localised and is not considered to present a problem with regard to the interpretation of the results.

In scenario A (Figure 5.9), the simulated drawdown across Hinksey Meadow is very small (1 to 11 cm). Drawdowns in excess of 5 cm are simulated across an area of about 0.5 km^2. A small rise in groundwater levels is simulated in the north west of the Meadows, although this was already simulated in the original scenario (Figure 5.8b).

In scenario B (Figure 5.10), the simulated drawdown is very minor, being between 1 and 2 cm and limited to the immediate vicinity of the FAS channel. The rise in groundwater levels originating in the north west of the area now extends to about 2/3 of the meadows (~1 - 5 cm). In New Botley, groundwater levels are simulated to rise by up to about 5 cm and although groundwater flooding has been reported in the area, the modelled scenario represents dry conditions.

The final row in Table 5.2 summarises the findings of the additional runs.

Appendix C explores the option of undertaking more detailed modelling in the area of Hinksey Meadow and nearby Hogacre Park.

6 CONCLUSIONS & RECOMMENDATIONS

6.1 Conclusions

The original Oxford FAS groundwater model was built in 2016 and calibrated to the July 2007 flood event. Since then, the design of the FAS scheme has evolved and additional data have become available; furthermore, additional ecological receptors have been identified. The model has been updated to incorporate these changes.

- The model top and bottom elevation of the sand/gravel aquifer were refined to account for geological data gathered from recent ground investigations.
- Results from pumping tests and data from the EA's Soil-Moisture model informed more realistic parametrisation of the model to the hydraulic conductivity of the aquifer and to the recharge conditions in the area.
- The results of revised fluvial model runs have been incorporated into the groundwater model.
- The quality of the revised model calibration to the July 2007 flood event is similar to that of the model presented in ESI (2016).
- The new scheme design was simulated for the 1 in 20 year flood event. The results suggest that for this flood event the scheme will result in a modest lowering of peak groundwater levels across the area (mostly around 10-20 cm and up to 62 cm at Cold Harbour). This may reduce the risk of groundwater flooding; however, groundwater flooding in urban areas is strongly influenced by local sub-surface conditions such as man-made structures and disturbance of natural ground conditions which locally affect groundwater flow. A small increase in groundwater levels of about 10 to 15 cm is simulated south of North Hinksey, on sand and gravel outcrop. However, this does not significantly alter the pattern of potential groundwater flooding in the area.
- The scheme was also simulated for a theoretical dry year with low river levels (Q_{95}). The modelling suggests that Oxford Meadows and Iffley Meadows will not be significantly affected by the scheme (the simulated change in groundwater levels induced by the scheme is < 0.01 m). The first model runs indicated a fall in groundwater levels of up to 0.3 m in the area of Hinksey Meadow. However, additional model runs including proposed weirs on Bulstake Stream suggest that such mitigation measures would be likely to reduce any drawdown effect beneath Hinksey Meadow to the order of a few centimetres.

6.2 Recommendations

- Given that the whole floodplain area is potentially susceptible to groundwater flooding, it is recommended that this source of flooding be considered carefully when planning any new development in the area. In particular, consideration should be given to the potential for any excavation work to create a new pathway for groundwater to emerge from the confined sand/gravel aquifer, potentially resulting in flooding.
- Following construction of the scheme, continued monitoring of groundwater should be undertaken. If, over a period of time, the monitored levels are not in line with the modelled predictions then further investigation could be undertaken of the influence of the new and existing weirs and locks on local groundwater levels, especially in the vicinity of Hinksey Meadows, Oxford Meadows (near Wolvercote) and Iffley Meadows. This could involve more detailed modelling of groundwater levels and flows in the vicinity of these structures and areas, e.g. by refining the MODFLOW model grid. It could also involve more detailed collection of field data such as groundwater and surface water levels from the ongoing monitoring, detailed ground conditions, and the nature of the channel bed/bank material. The aim of the investigations would be to

refine and improve the model and mitigation measures as more accurate long term field data become available.

7 REFERENCES

BGS (British Geological Survey) website:

http://www.bgs.ac.uk/geoindex/

CH2M, 2017a. Oxford FAS Groundwater Pumping Tests – Preliminary Determination of Permeability Values. Project number 684232, Revision 2, 18 August 2017.

CH2M, 2017b. Oxford Flood Alleviation Scheme Peer Review Handover Note. Draft. Prepared for Environment Agency. October 2017.

Environmental Simulations Inc., 2000-2011. Guide to using Groundwater Vistas: Version 6.

ESI, 2016. Oxford Flood Alleviation Scheme: Groundwater Flood Modelling. Final Report produced for CH2M, ref. 63294 R1 rev. 2, November 2016.

Floodplain Meadows Partnership website: http://www.floodplainmeadows.org.uk/

Harbaugh, A. W. and McDonald, M. G., 1996. User's documentation for MODFLOW-96, an update to the U.S. Geological Survey modular finite-difference ground-water flow model. U. S. Geological Survey Open-File Report 96-485, 56pp.

Harbaugh, A. W., Banta, E. R., Hill, M. C. and McDonald, M. G., 2000. MODFLOW-2000, the U.S. Geological Survey Modular Ground-Water Model – User guide to modularization concepts and the ground-water flow process. U.S. Geological Survey Open-File Report 00-92, 121pp.

Harbaugh, A. W., 2005. MODFLOW-2005. The U.S. Geological Survey modular ground-water model – the ground-water flow process. U.S. Geological Survey Techniques and Methods 6-A16.

Kessler, H., Mathers, S., Lelliott, M., Hughes, A. and Macdonald, D., 2007. Rigorous 3D Geological Models as the Basis for Groundwater Modelling. In: Three-dimensional geologic mapping for groundwater applications, Workshop extended abstracts, Denver, Colorado.

http://nora.nerc.ac.uk/4129/1/kessler.pdf,
http://www.isgs.uiuc.edu/research/3DWorkshop/2007/powerp/kessler.ppt

Macdonald, D., Hall, R., Carden, D., Dixon, A., Cheetham, M., Cornick, S. and Clegg, M., 2007. Investigating the interdependencies between surface and groundwater in the Oxford area to help predict the timing and location of groundwater flooding and to optimise flood mitigation measures. In: 42nd Defra Flood and Coastal Management Conference, York, UK, 3-5 July 2007.

Macdonald, D. M. J., Dixon, A., Newell, A. J. and Hallaways, A., 2012. Groundwater flooding within an urbanised flood plain. Journal of Flood Risk Management, vol. 5, p.68-80.

McDonald, M. G. and Harbaugh, A. W., 1988. A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 6, Chapter A1, 586pp.

Newell, A. J., 2008. Morphology and Quaternary geology of the Thames floodplain around Oxford. British Geological Survey Groundwater Resources Programme Open Report OR/08/030.

Niswonger, R. G., Panday, S. and Ibaraki, M., 2011. MODFLOW-NWT, a Newton Formulation for MODFLOW-2005. Chapter 37 of Section A, Groundwater Book 6, Modelling Techniques. Groundwater Resources Program, U.S. Geological Survey.

FIGURES

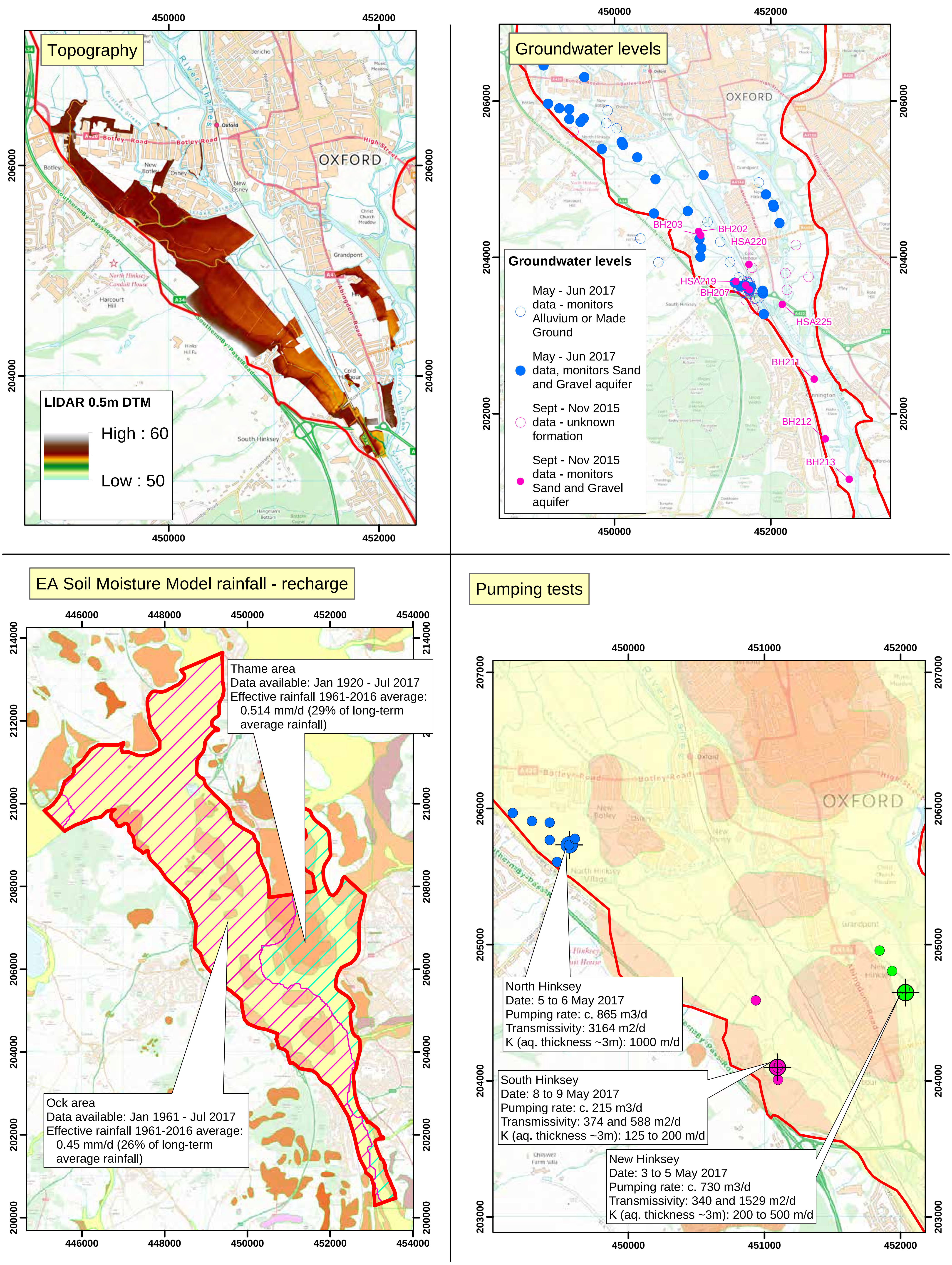


Figure 2.1a
Overview of available data

Study area

N

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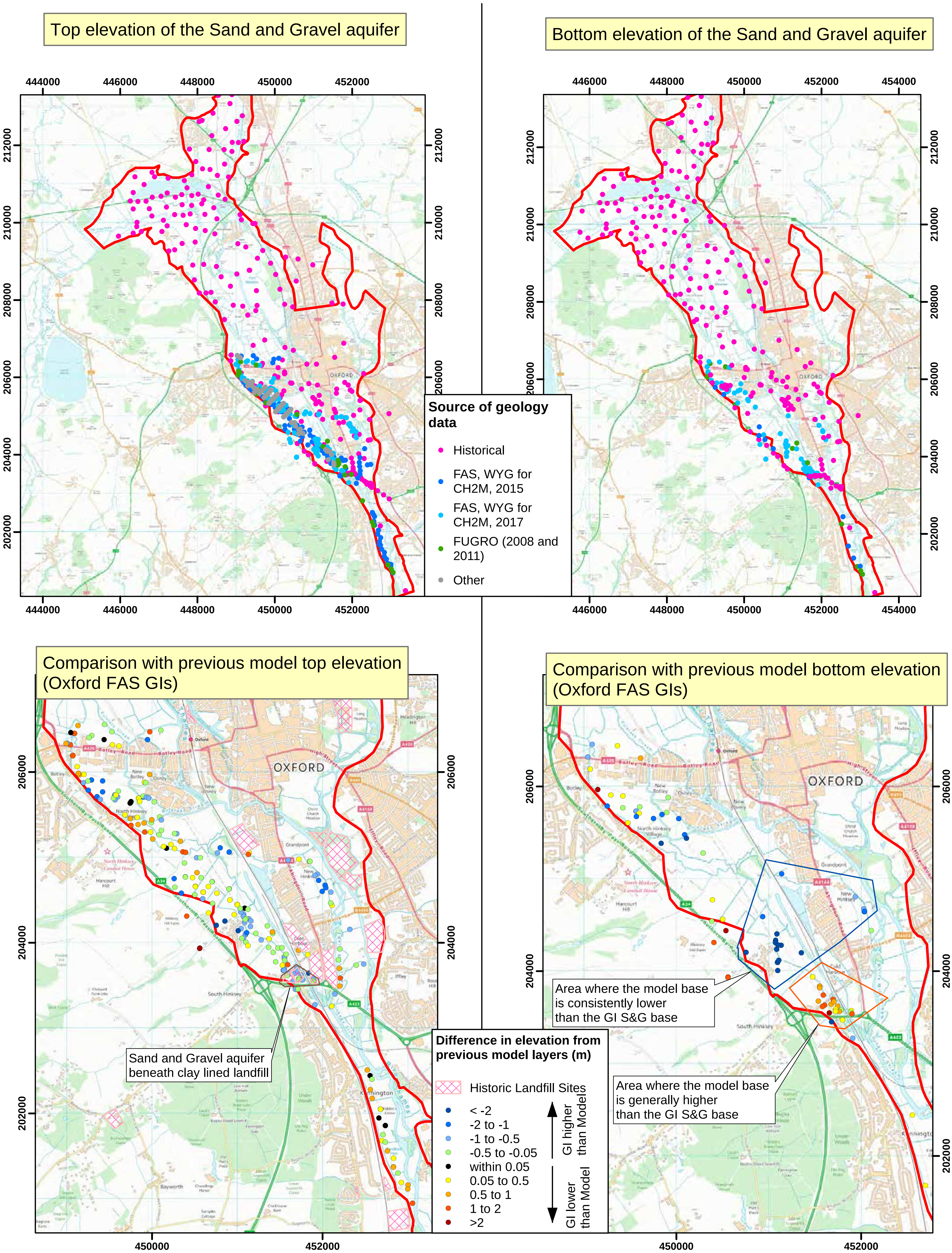

Figure 2.1b
Overview of available data

MODFLOW model area

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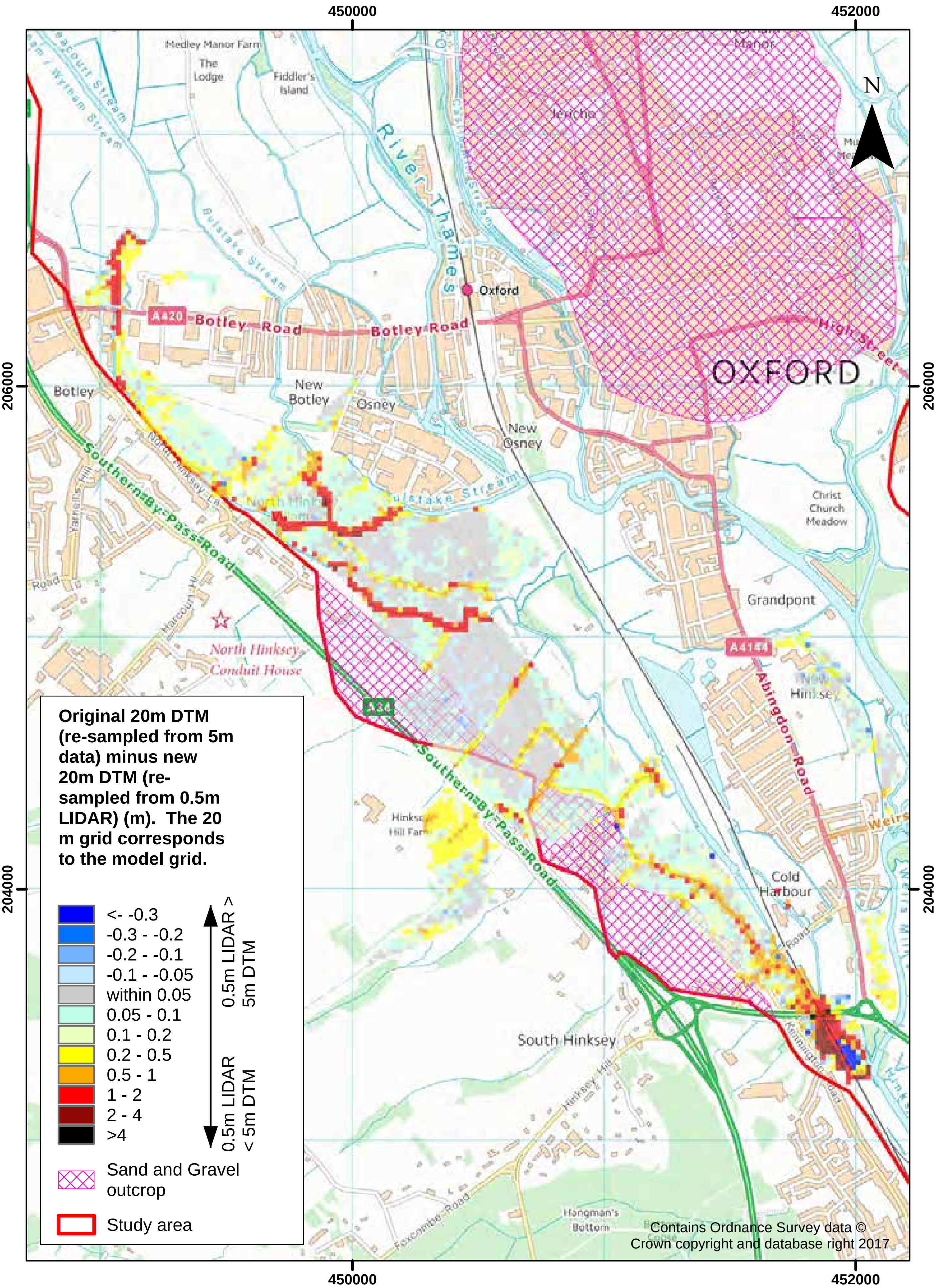

Figure 2.2 Comparison of DTM	Date: Aug 2017	Drawn: IJG
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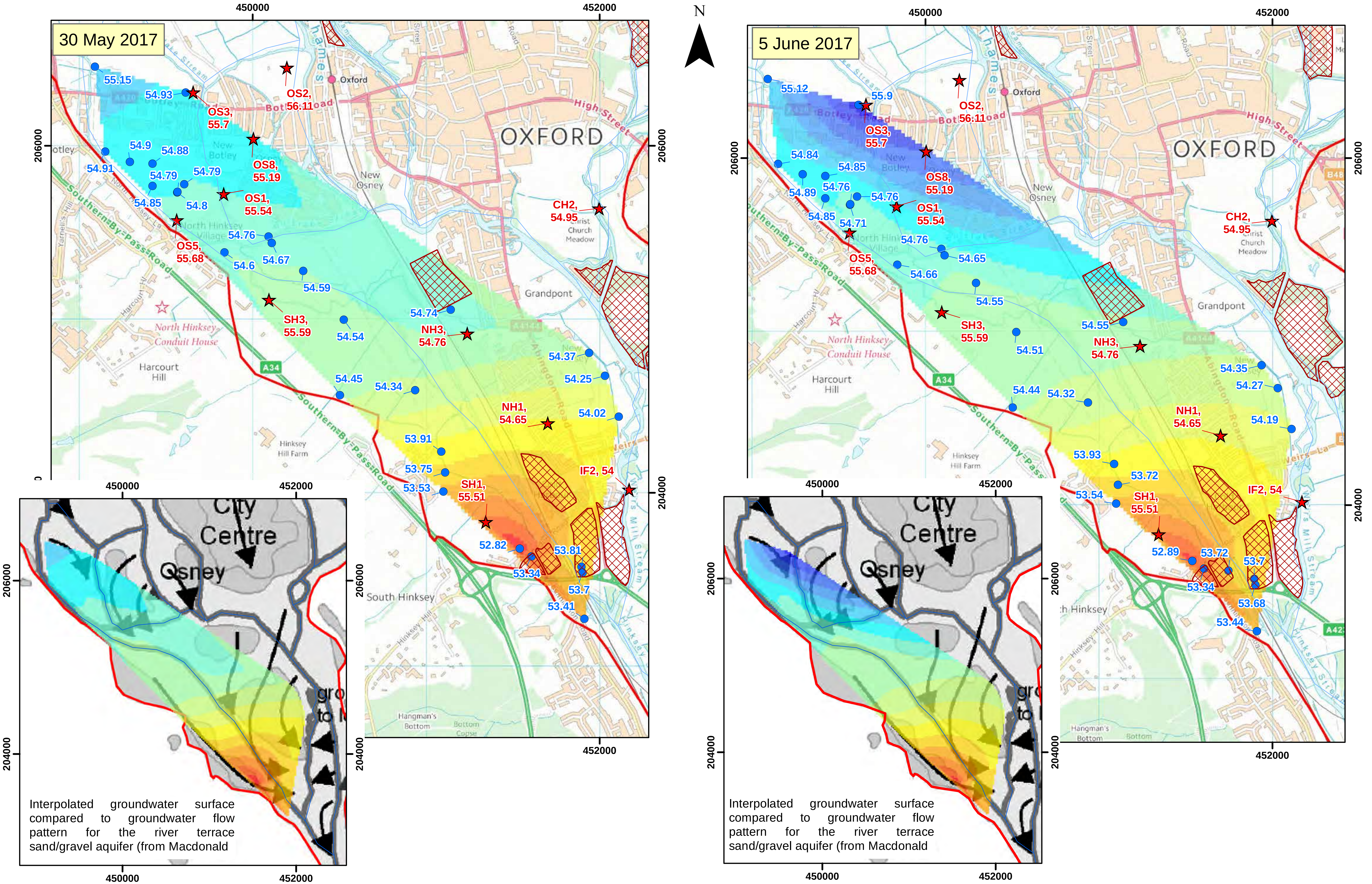

Figure 2.3
Interpolated groundwater surfaces

Legend	
Study area	
Rivers	
Historic Landfill Sites	
Previous steady state targets (Start of July 2007 flood event, GWL in mAOD)	
Groundwater levels (mAOD)	

Interpolated groundwater contours (mAOD)

<53	53.4 - 53.6	54.8 - 55
53 - 53.2	53.6 - 53.8	55 - 55.2
53.2 - 53.4	53.8 - 54	55.2 - 55.4
	54 - 54.2	55.4 - 55.6
	54.2 - 54.4	55.6 - 55.8
	54.4 - 54.6	55.8 - 56
	54.6 - 54.8	

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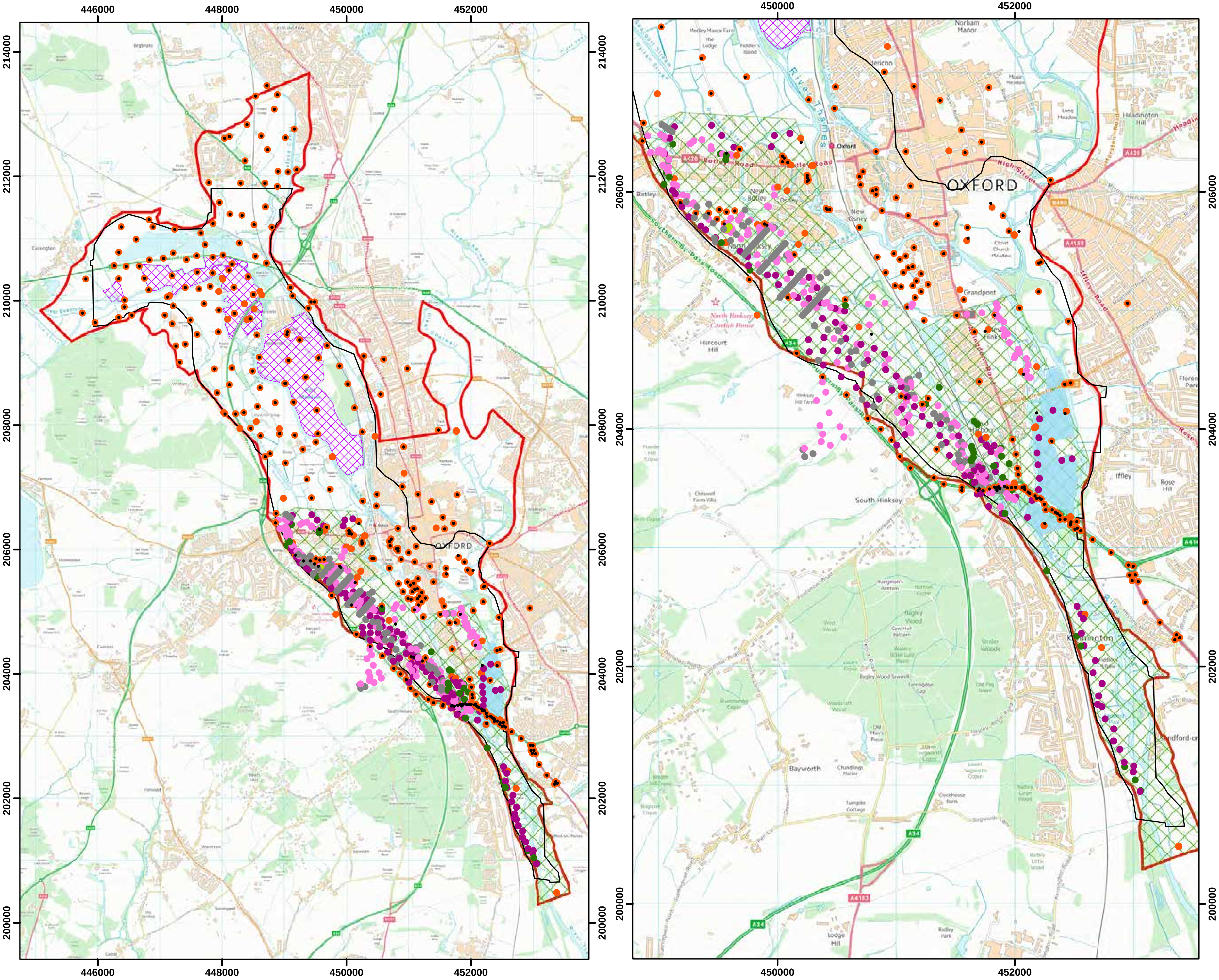

Figure 2.4
Locations of geological logs

Legend

- Boreholes used in BGS 3D model

Available logs

- HISTORIC
- FUGRO 2008
- FUGRO 2011
- PRELIM
- WYG 2015
- Unknown
- Coverage of BGS 3D model
- Oxford Meadows SAC
- Iffley Meadows SSSI
- Area with new geological information
- Study area

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\\Win2012\e\Projects\63294 Oxford FAS\GIS\UPDATE JULY_AUGUST 2017\Map documents\Figures for report\Superseded\Fig 2.4 Geological records.mxd

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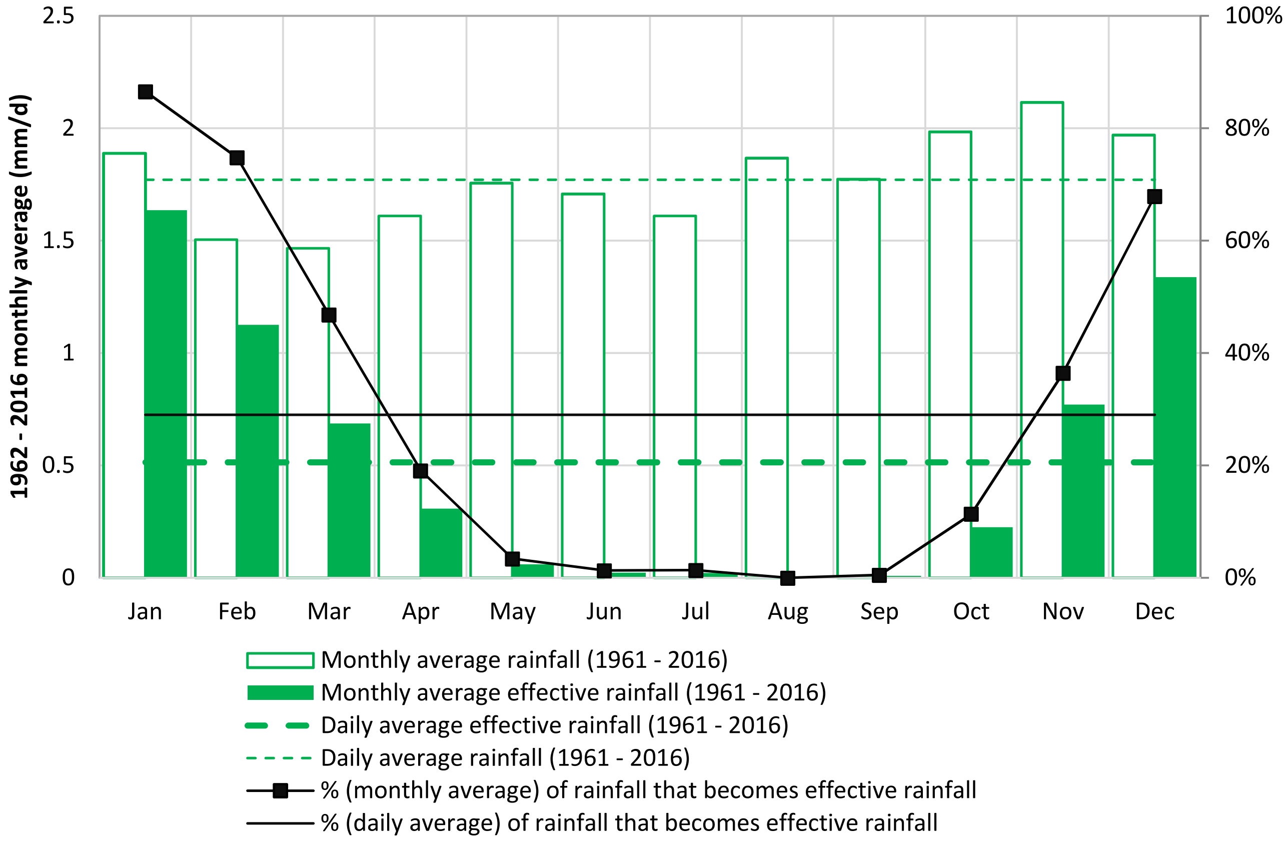

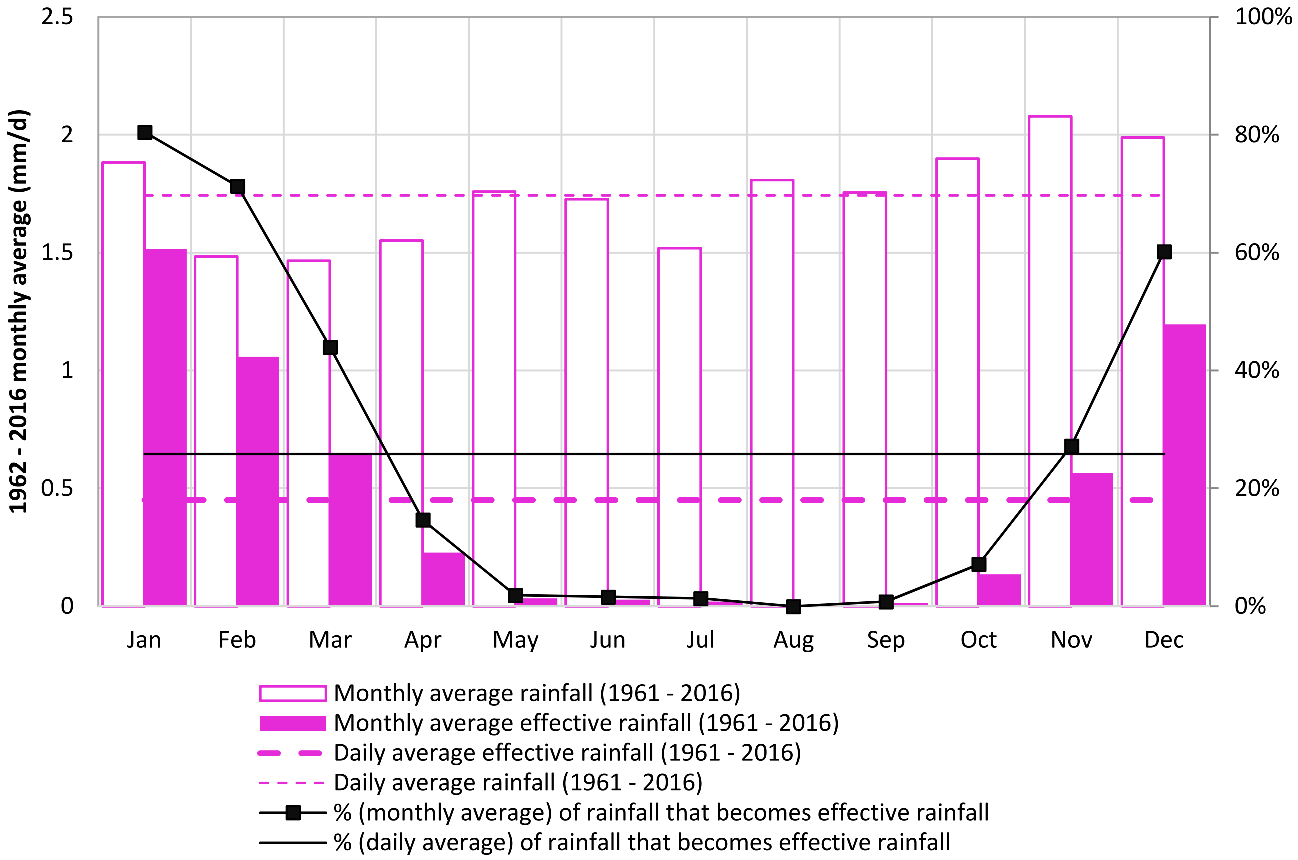

Figure 2.5
Soil Moisture Model rainfall recharge, Thame and Ock areas

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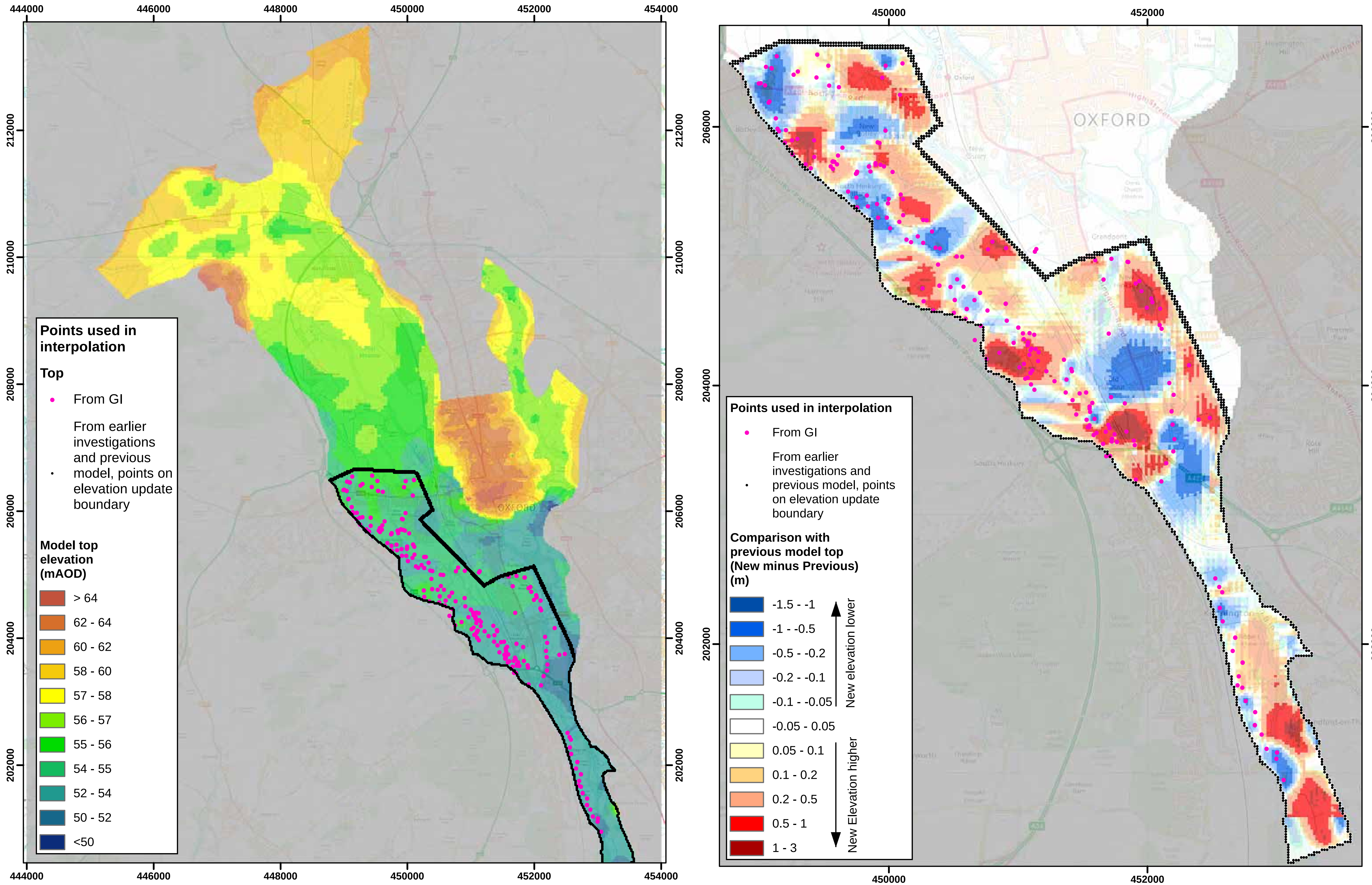

Figure 4.1
Model top elevation

N

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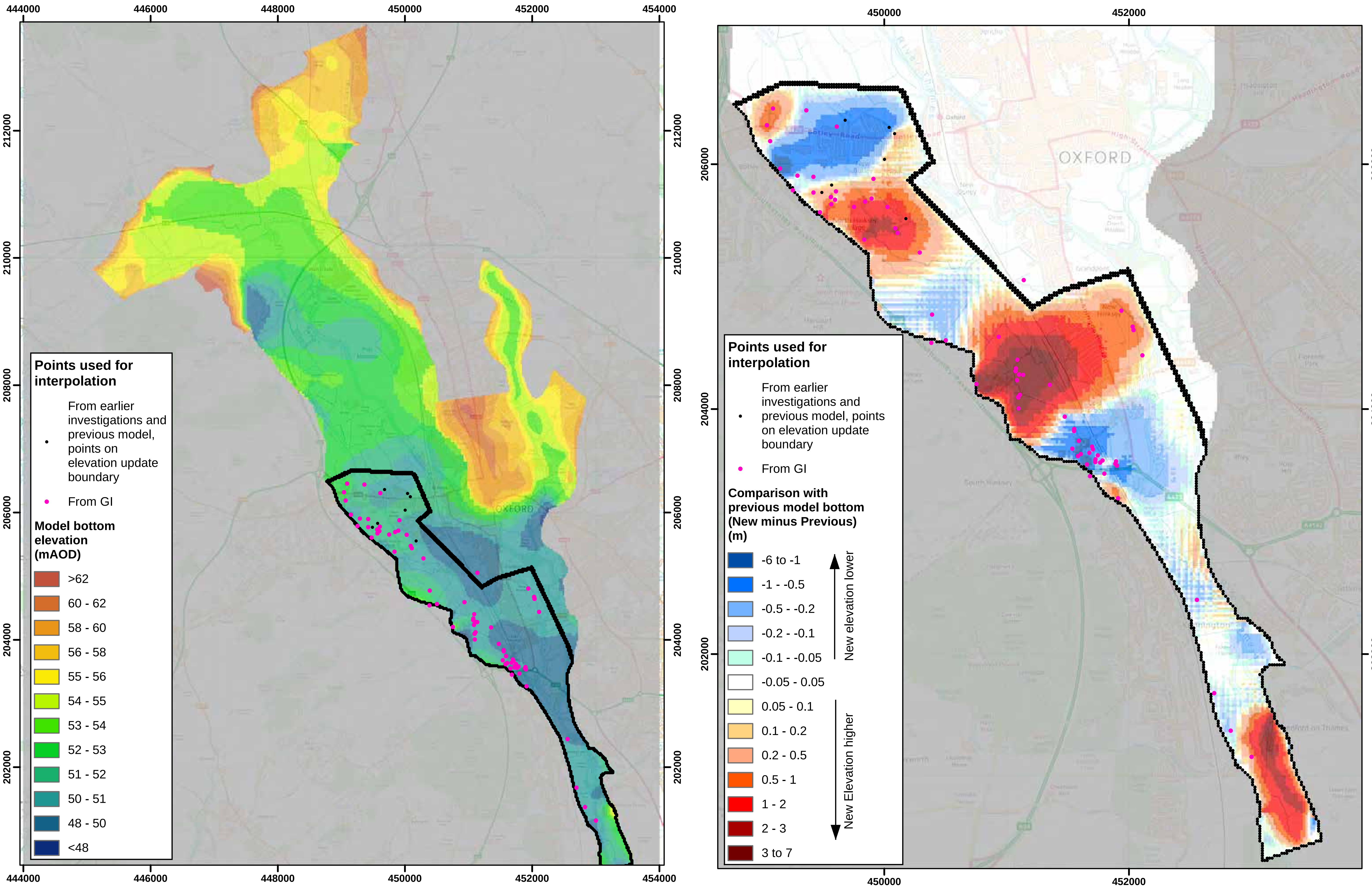

Figure 4.2
Model bottom elevation

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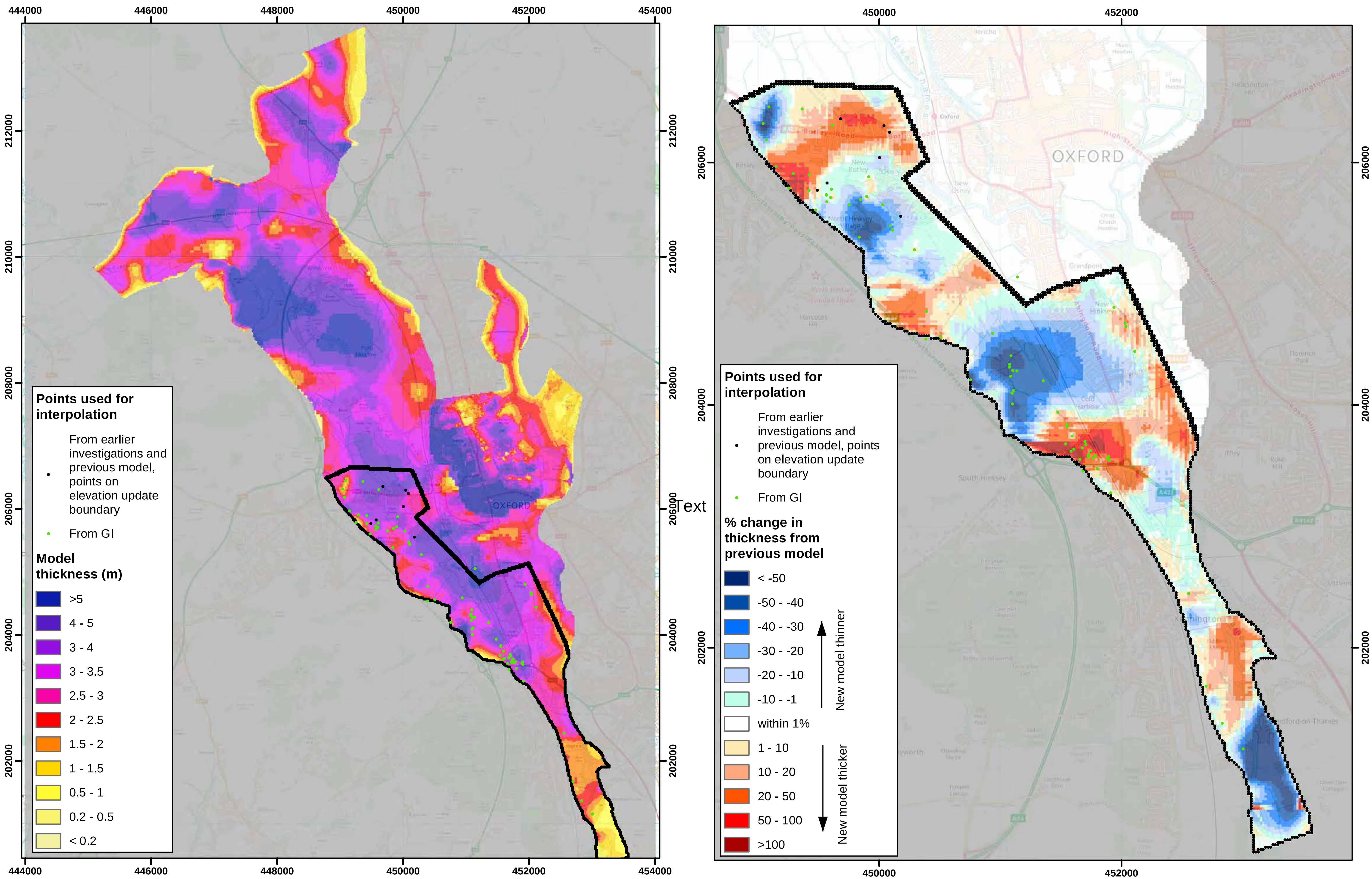

Figure 4.3
Model thickness

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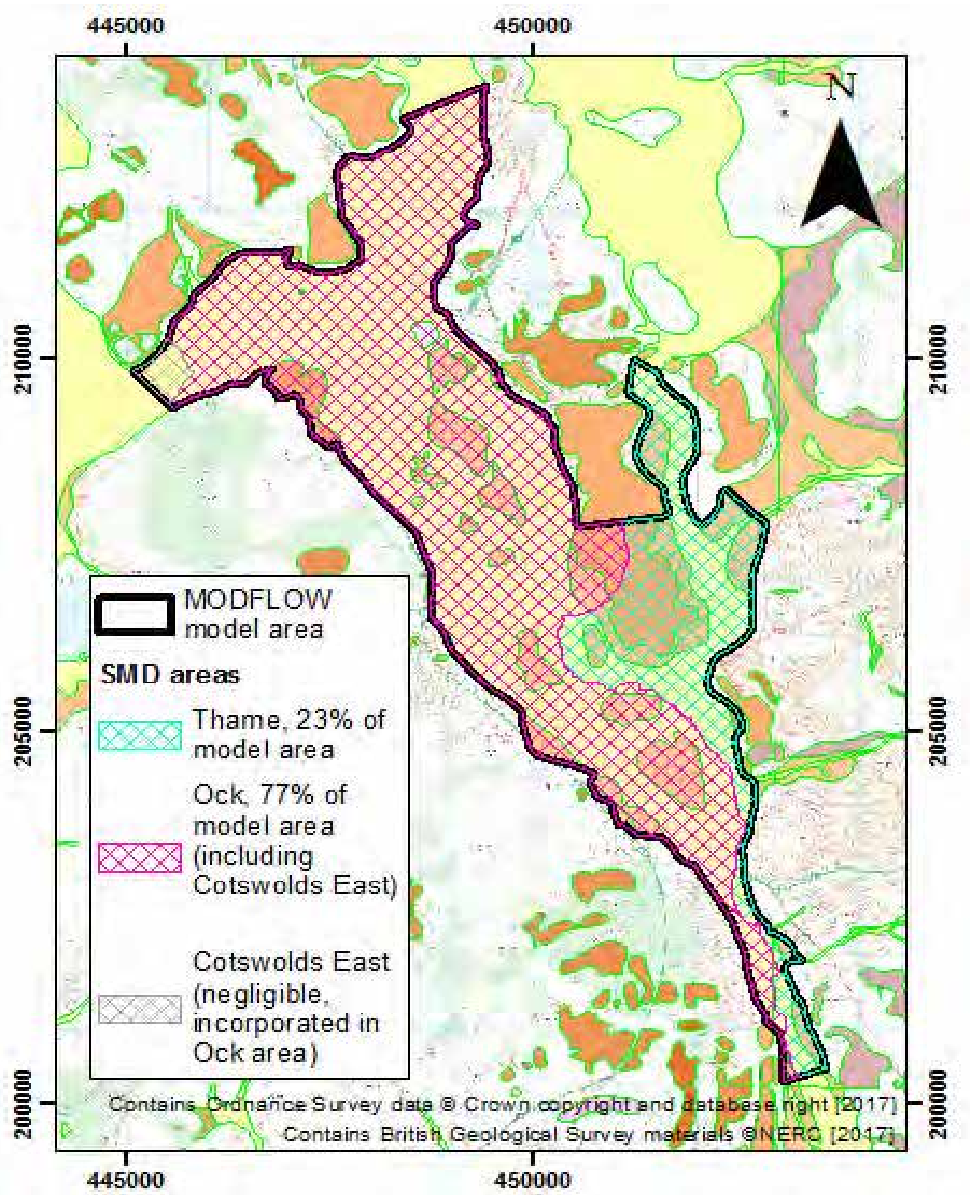
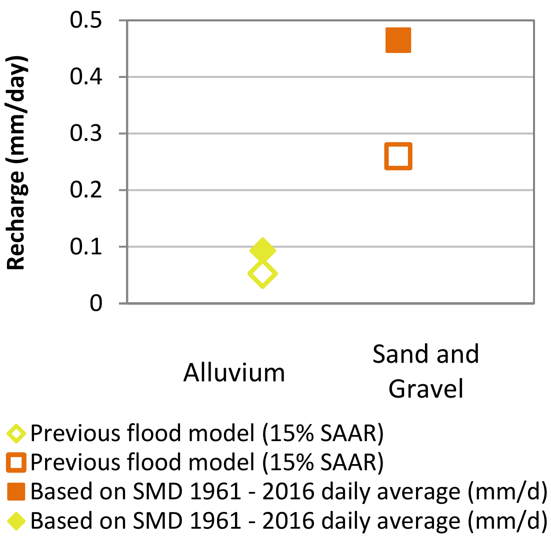


Flood model constant recharge



Dry model monthly transient recharge

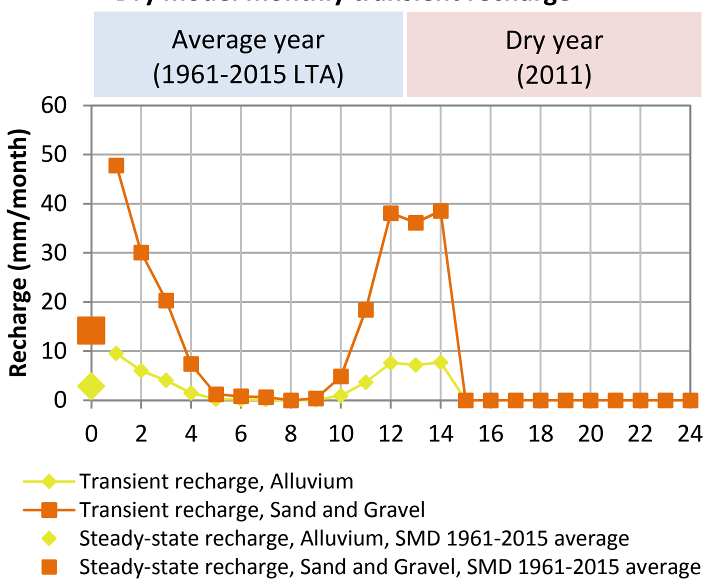


Figure 4.4

Model recharge

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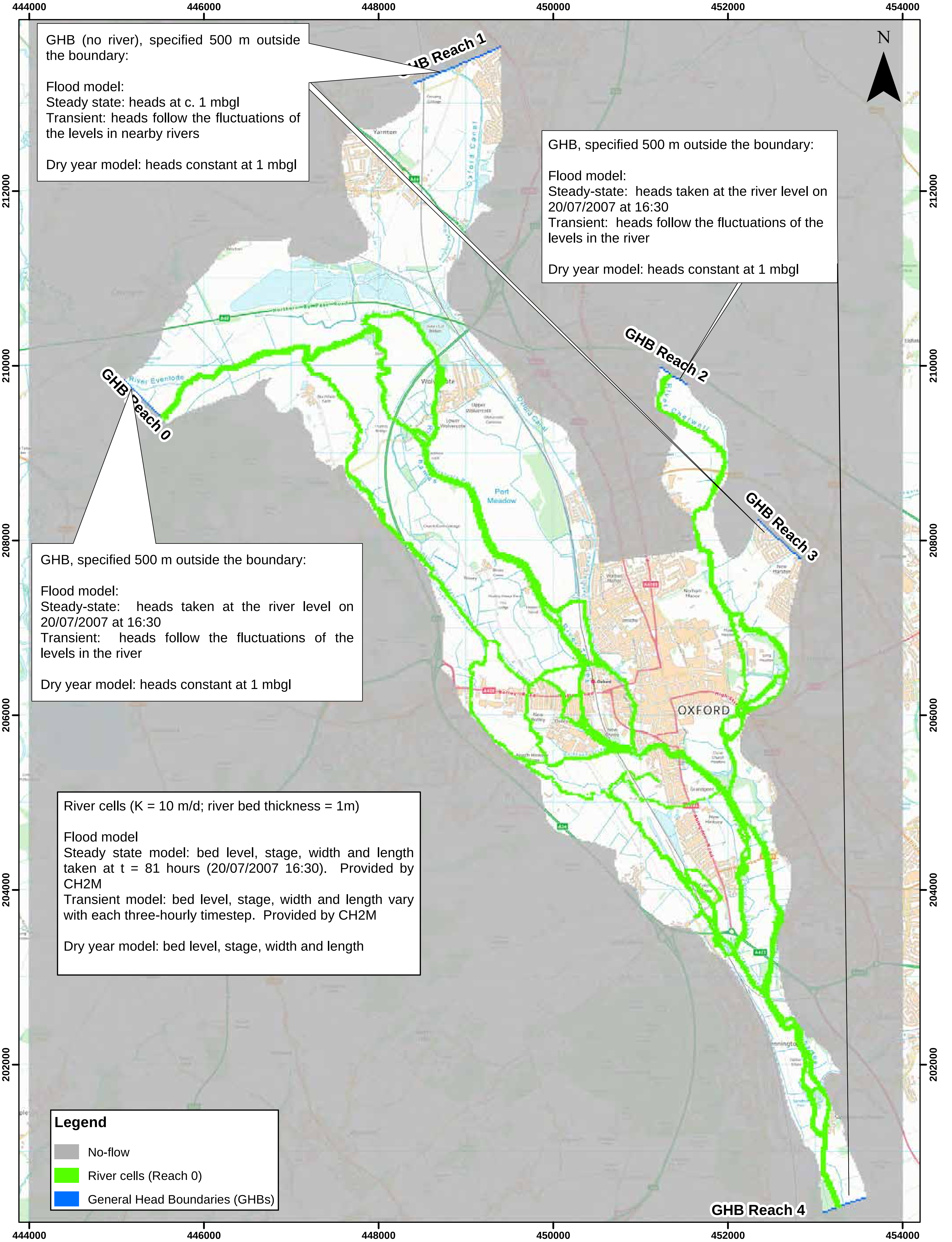

Figure 4.5
Model set up

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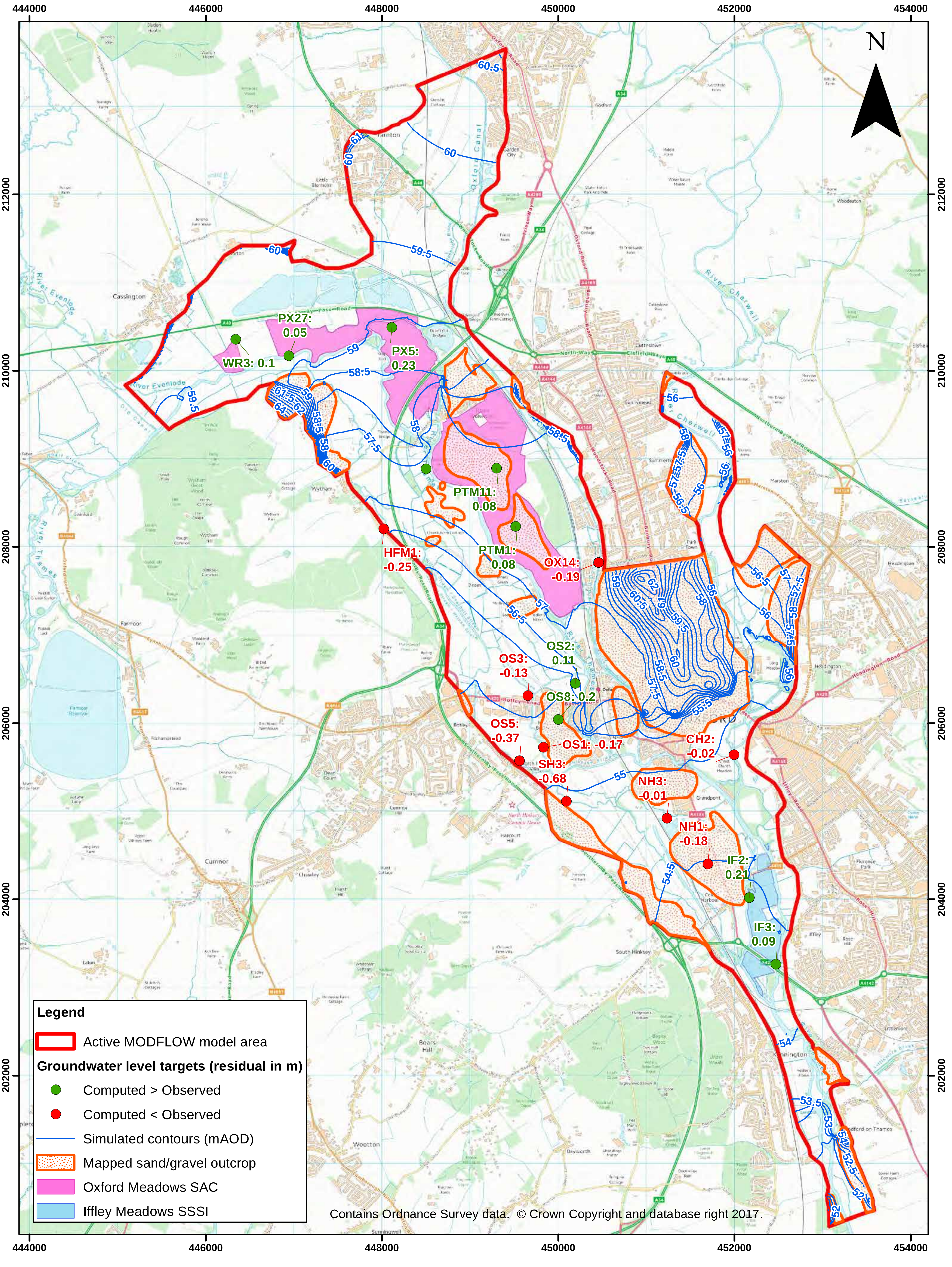

Figure 4.6 Steady-state calibration and groundwater contours	Date: Aug 2017	Drawn: IJG	esi consulting
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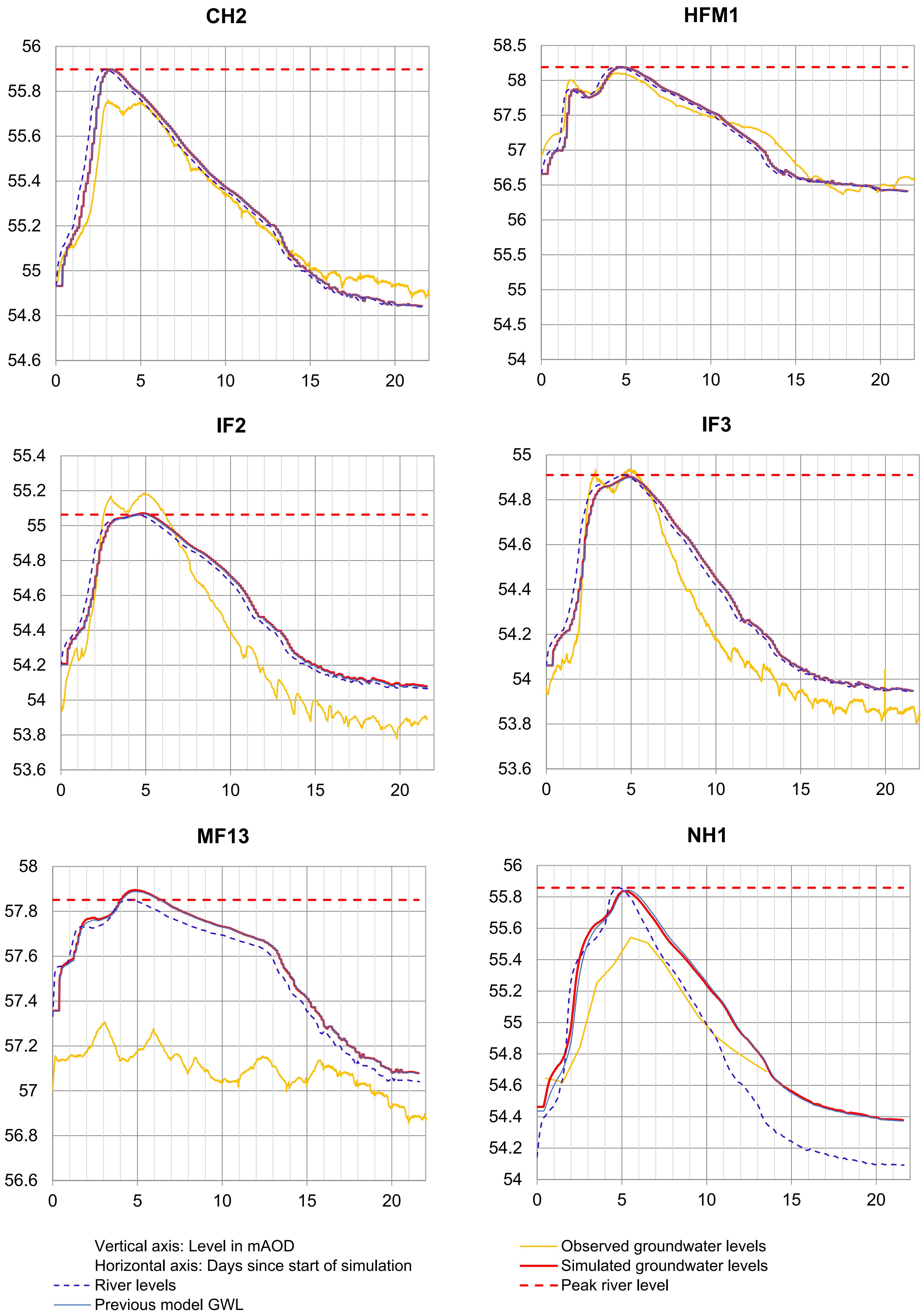

Figure 4.7a

Transient calibration: hydrographs (1)

Comparison of modelled and observed groundwater heads.
River levels (from nearest river cell) shown for reference.

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Original: A3	Revision: 1

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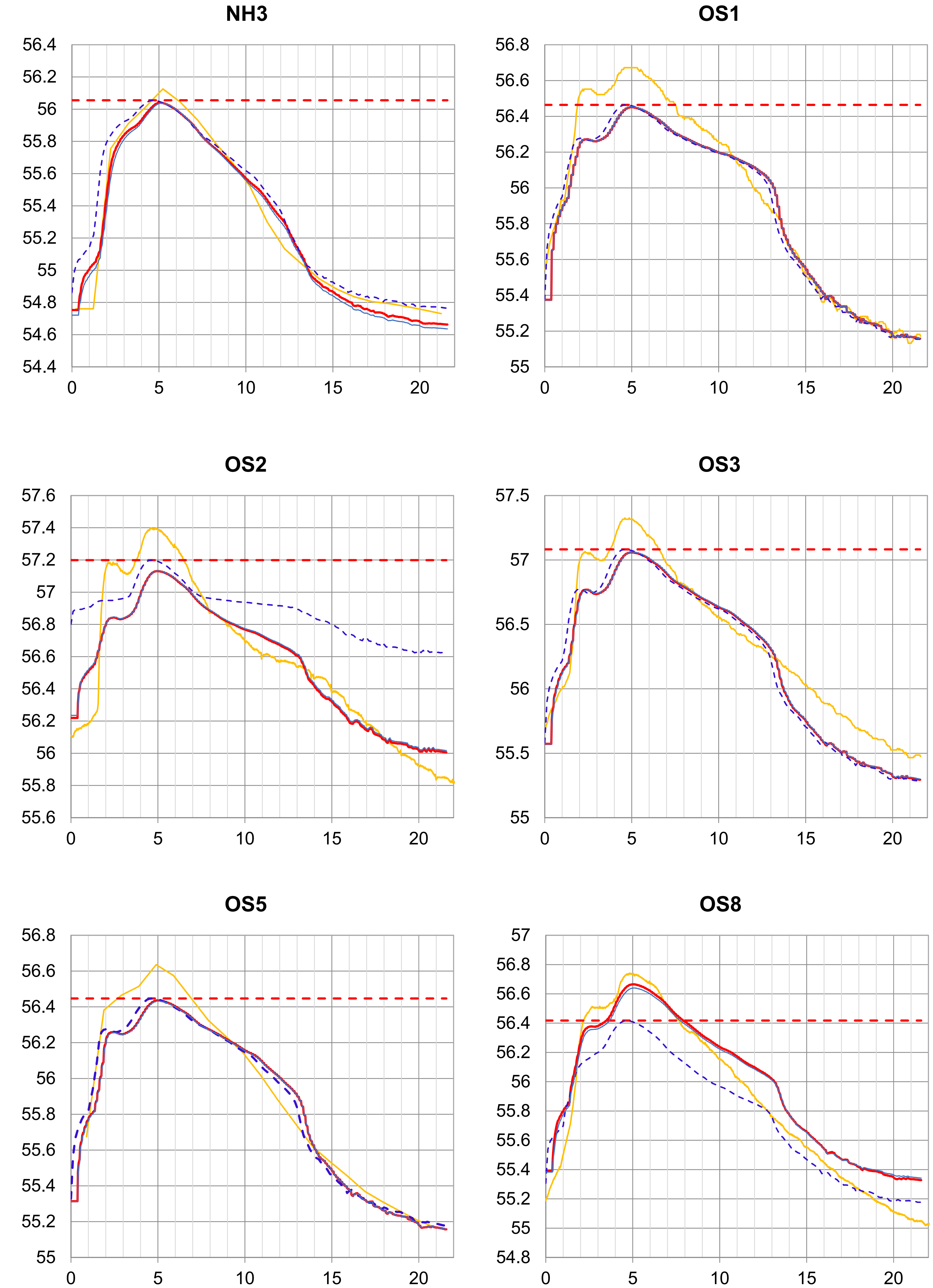

Vertical axis: Level in mAOD
Horizontal axis: Days since start of simulation
River levels
Previous model GWL
Observed groundwater levels
Simulated groundwater levels
Peak river level

Figure 4.7b

Transient calibration: hydrographs (2)

Comparison of modelled and observed groundwater heads.
River levels (from nearest river cell) shown for reference.

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Scale	Checked
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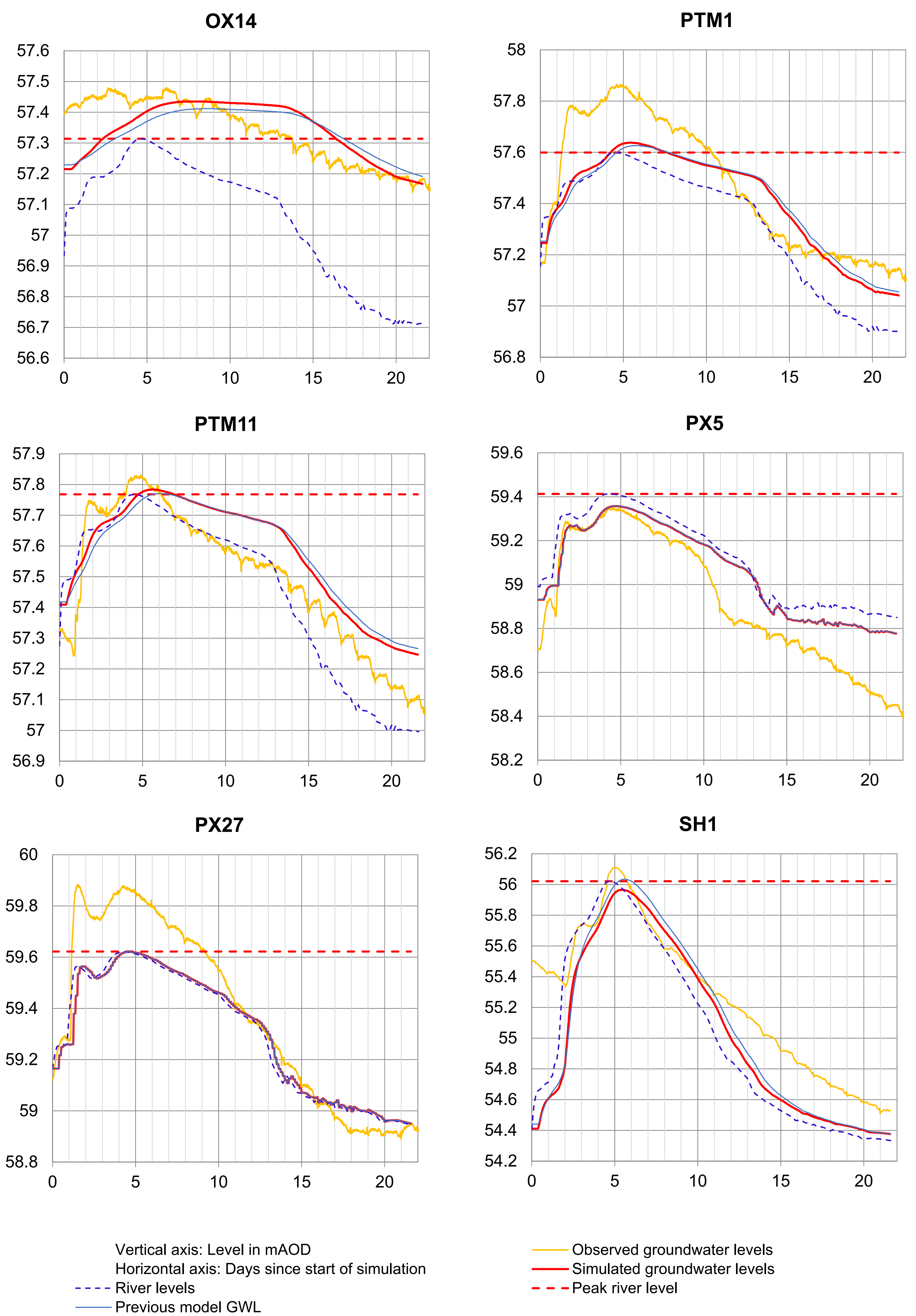

Figure 4.7c

Transient calibration: hydrographs (3)

Comparison of modelled and observed groundwater heads.
River levels (from nearest river cell) shown for reference.

Date	Drawn
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Scale: dns	Checked: SNB
Original: A3	Revision: 1

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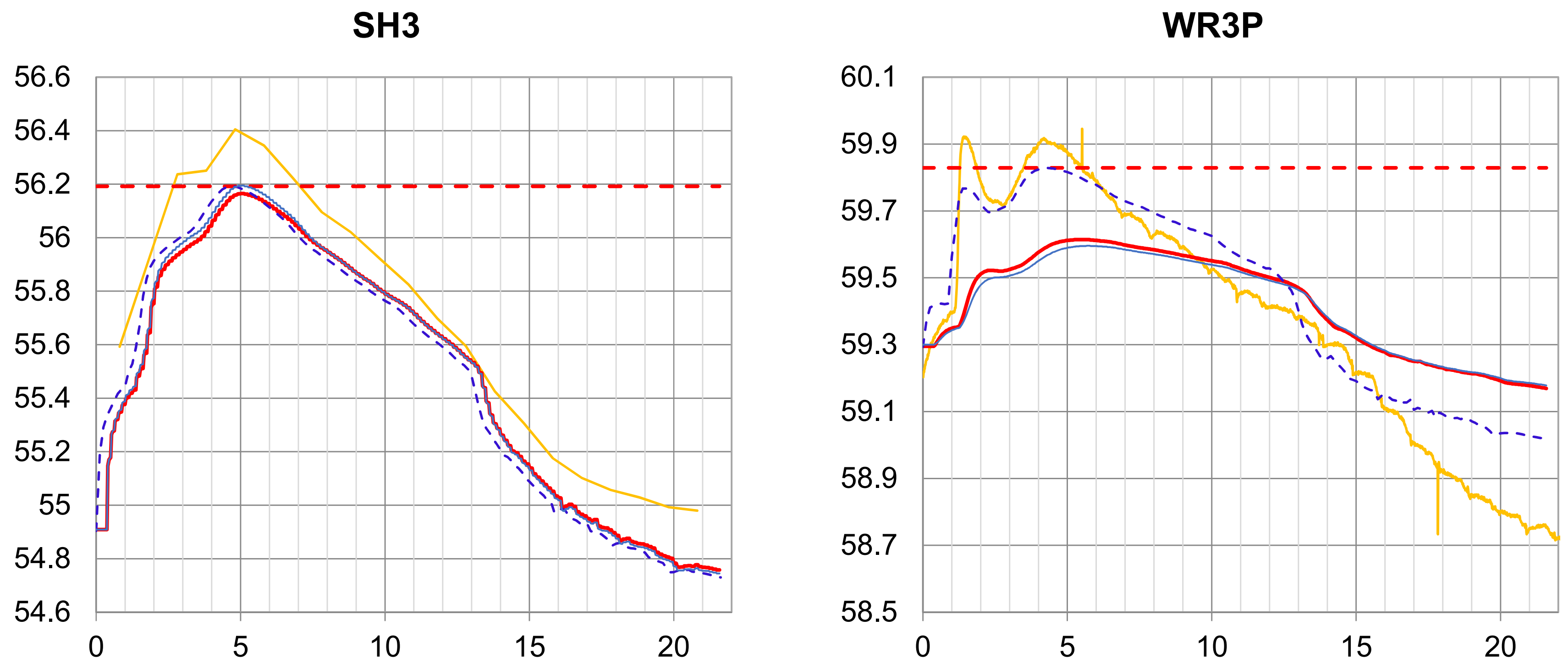

Vertical axis: Level in mAOD
Horizontal axis: Days since start of simulation
River levels
Previous model GWL
Observed groundwater levels
Simulated groundwater levels
Peak river level

Figure 4.7d

Transient calibration: hydrographs (4)

Comparison of modelled and observed groundwater heads.
River levels (from nearest river cell) shown for reference.

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Original A3	Revision 1

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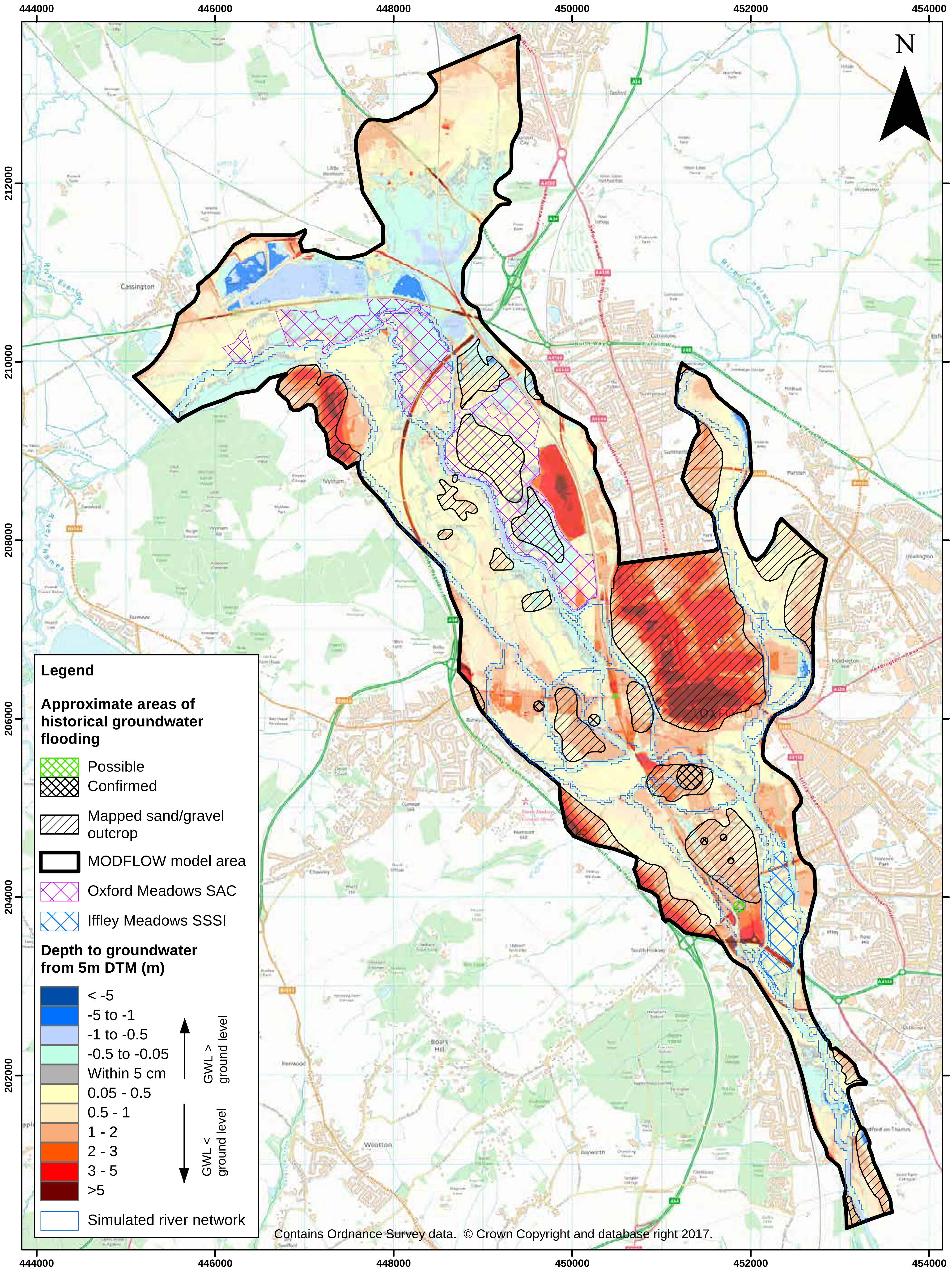

Figure 4.8
Steady-state depth to groundwater

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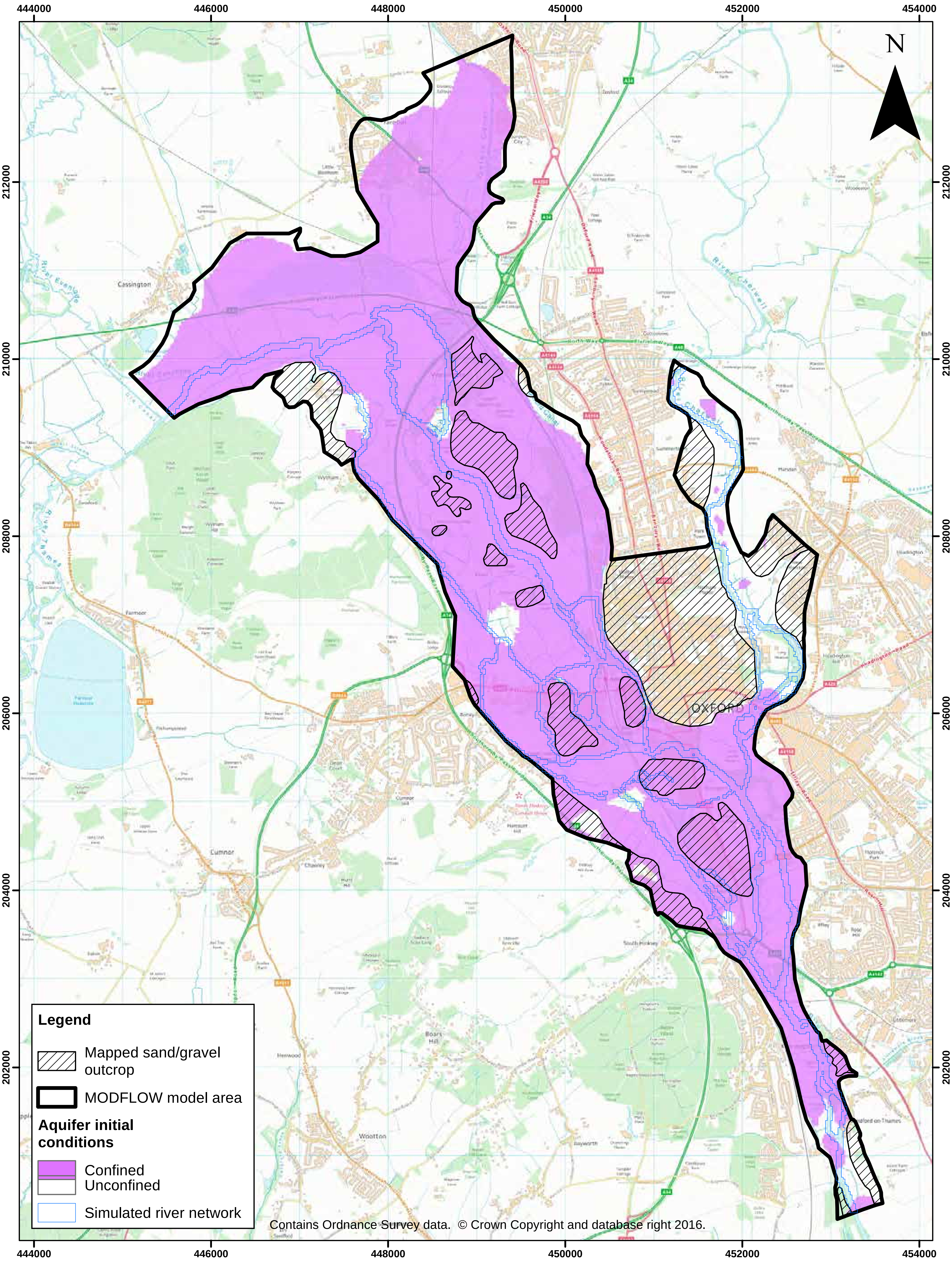

Figure 4.9
Aquifer confinement (from calibrated steady-state model)

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O:\63294 Oxford FAS\GIS\UPDATE JULY_AUGUST 2017\Map documents\Figures for report\Fig 4.9 Confined Steady state.mxd

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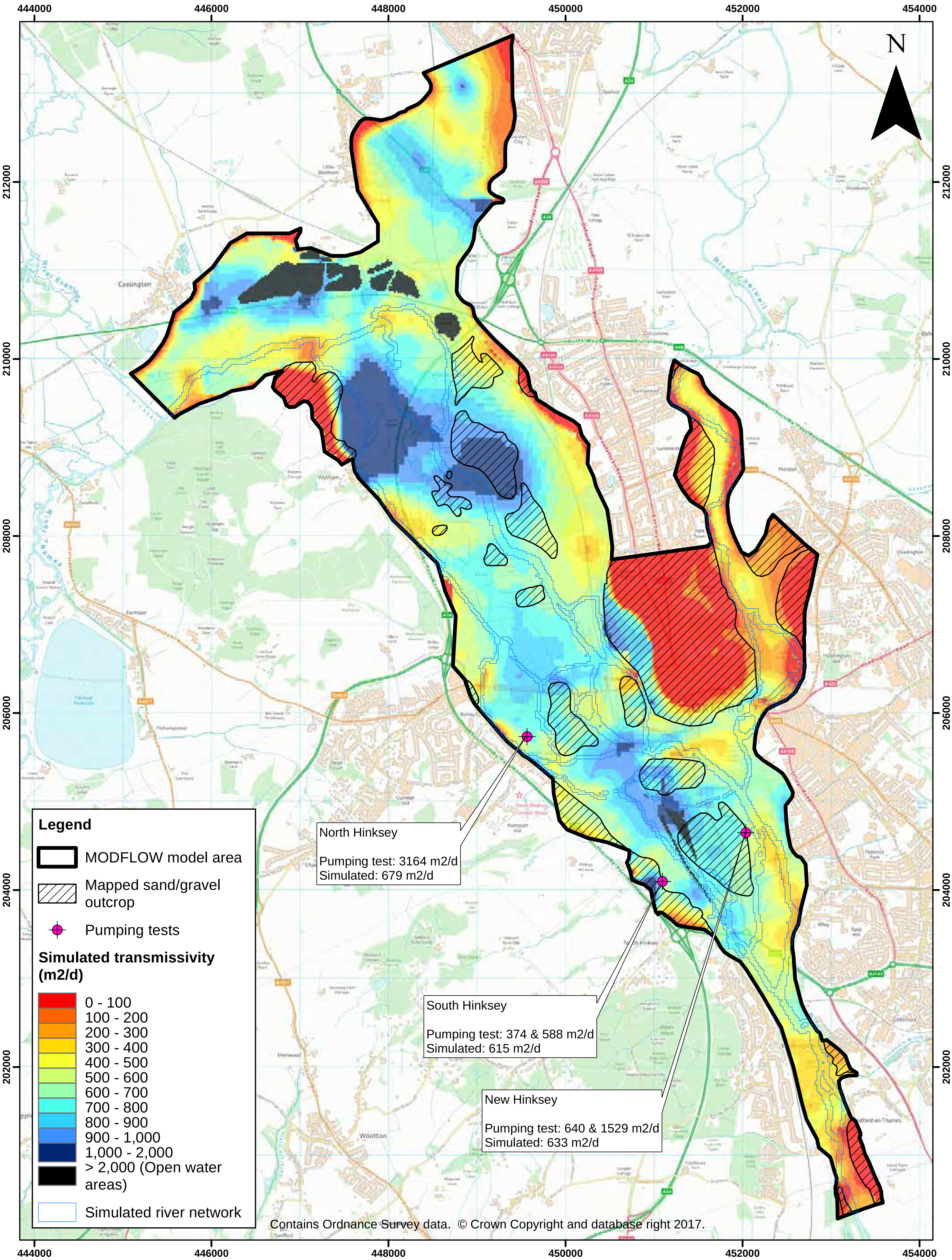

Figure 4.10
Simulated transmissivity (from calibrated steady-state model)

Date	Aug 2017	Drawn	IJG
Scale	1:40,000	Checked	SNB
Original	A3	Revision	3

File Reference
O:\63294 Oxford FAS\GIS\UPDATE JULY_AUGUST 2017\Map documents\Figures for report\Fig 4.10 Transmissivity Steady

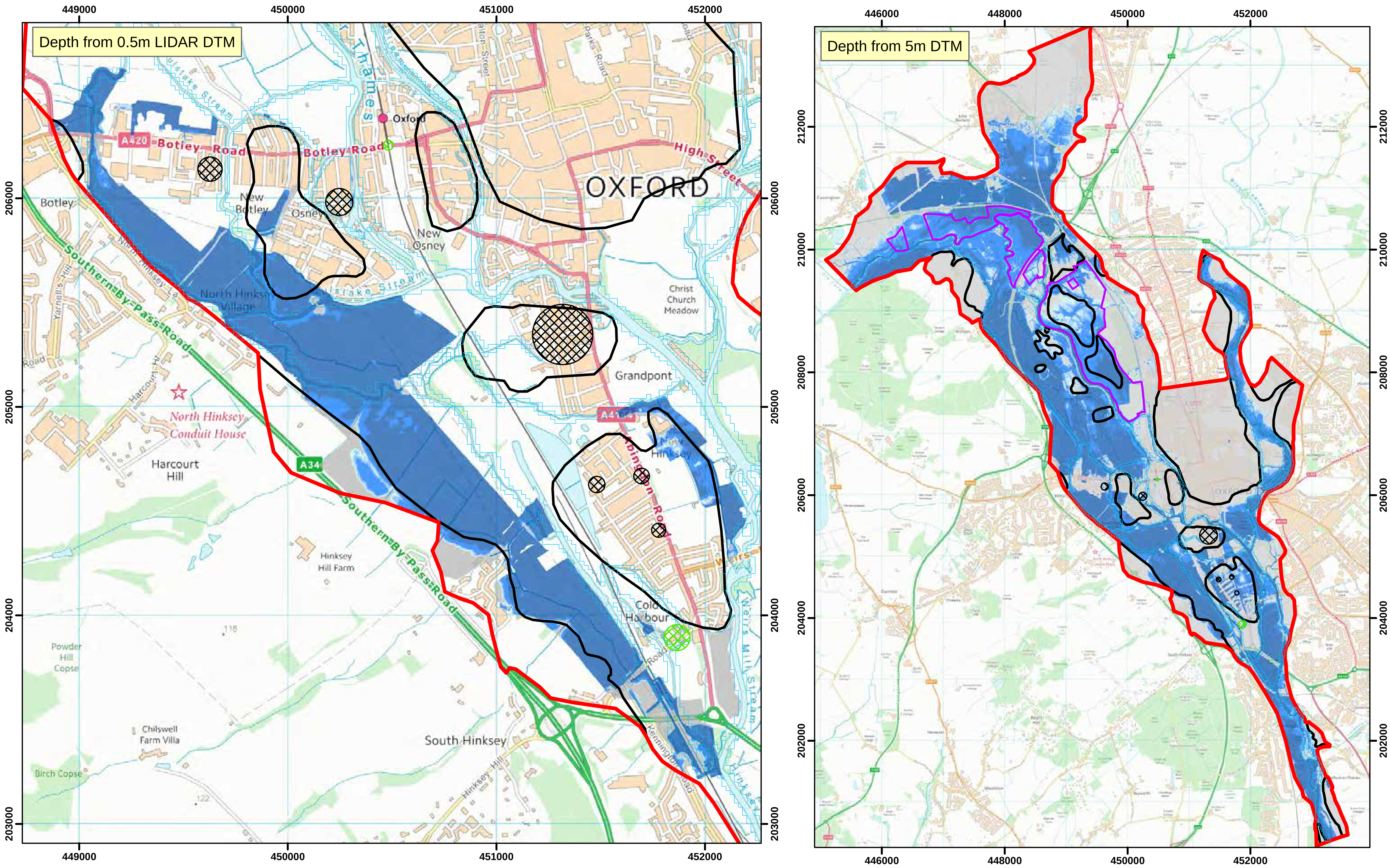

Figure 4.11
Minimum depth to groundwater
(July 2007 event).

Approximate areas of historical groundwater flooding
- Possible
- Confirmed

- Simulated river network
- MODFLOW model area
- Mapped outcrop of river terrace sand/gravel
- Oxford Meadows SAC

Minimum depth to groundwater (m)
- < -0.5
- -0.5 - -0.2
- -0.2 - -0.1
- -0.1 - -0.05
- -0.05 - 0
- Below ground

Above ground

Date	Aug 2017	Drawn	IJG
Scale		Checked	SNB
Original	A3	Revision	1

File Reference
O:\63294 Oxford FAS\GIS\UPDATE JULY_AUGUST 2017\Map documents\Figures for report\Fig 4.11 Peak depth to GW.mxd

esi consulting

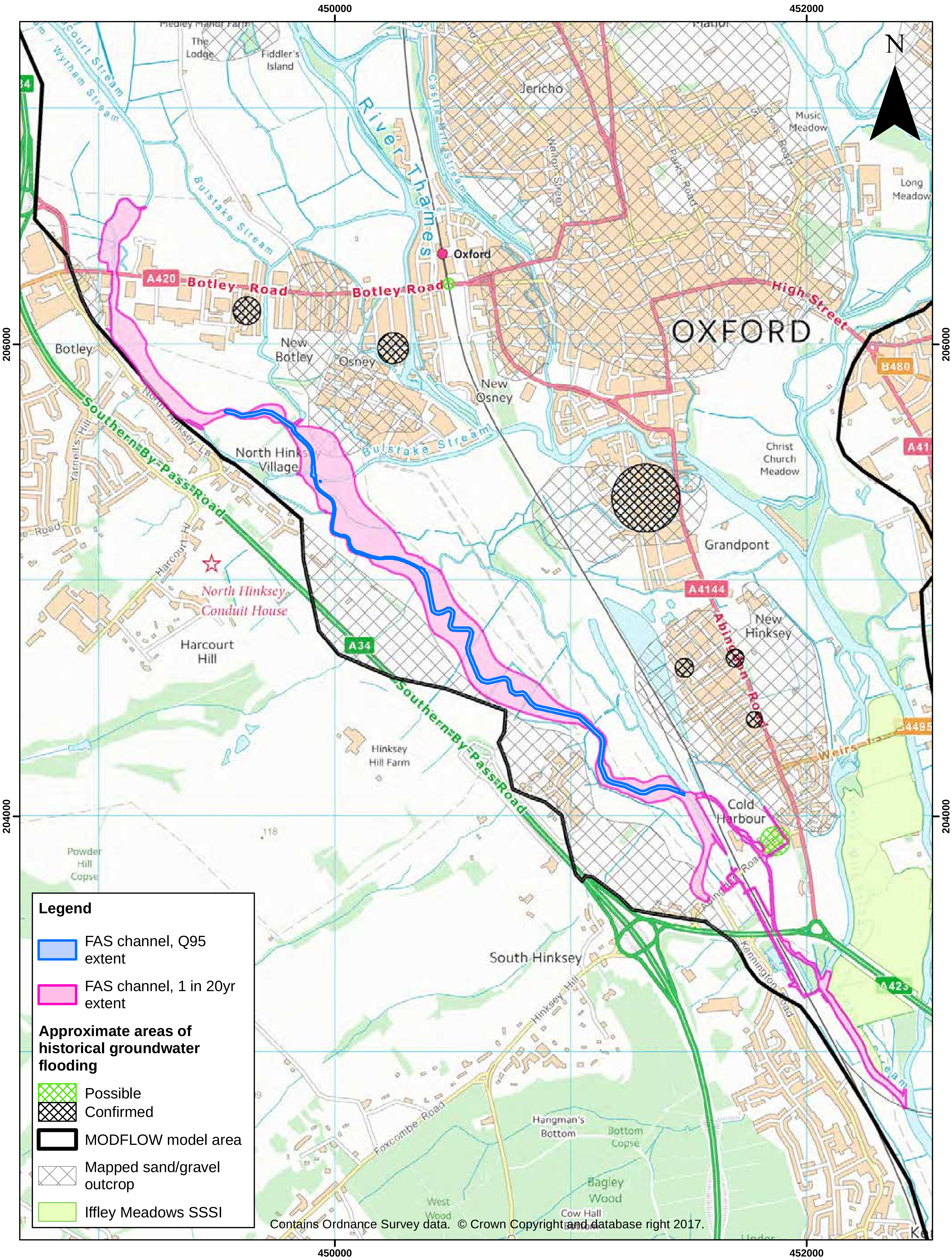

Figure 5.1
Scheme geometry

Date: Nov 2017	Drawn: IJG	
Scale: 1:15,000	Checked: SNB	
Original: A3	Revision: 1	
File Reference: O:\63294 Oxford FAS\GIS\UPDATE JULY_AUGUST 2017\Map documents\Figures for report\Fig 5.1 Scheme Geometry.mxd		

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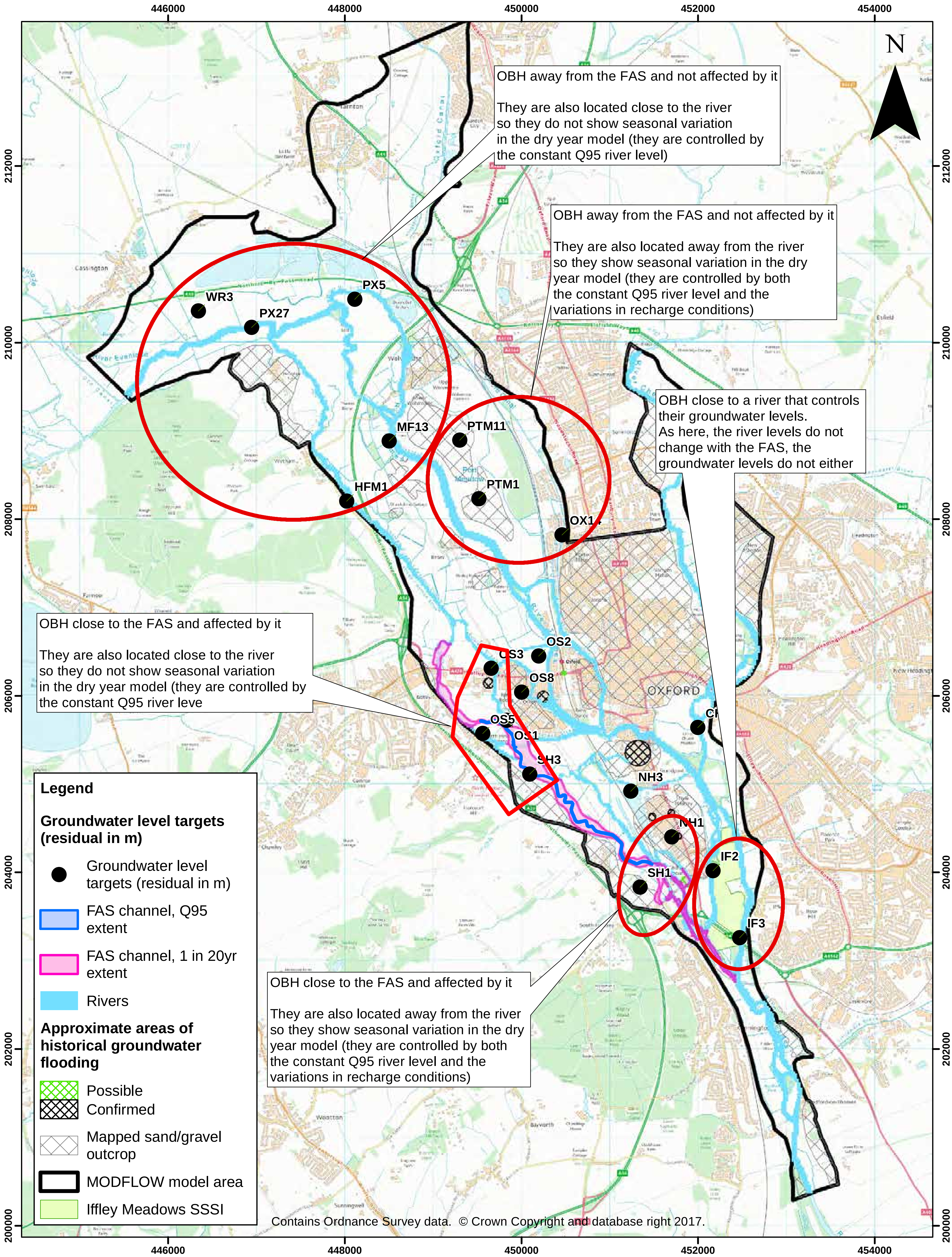

Figure 5.2
OBH time series response, summary map

Date	Jan 2018	Drawn	IJG
Scale	1:40,000	Checked	SNB
Original	A3	Revision	1
File Reference	O:\63294 Oxford FAS\GIS\UPDATE JULY_AUGUST 2017\Map documents\Figures for report\Fig 5.8 HydrographsZones.mxd		

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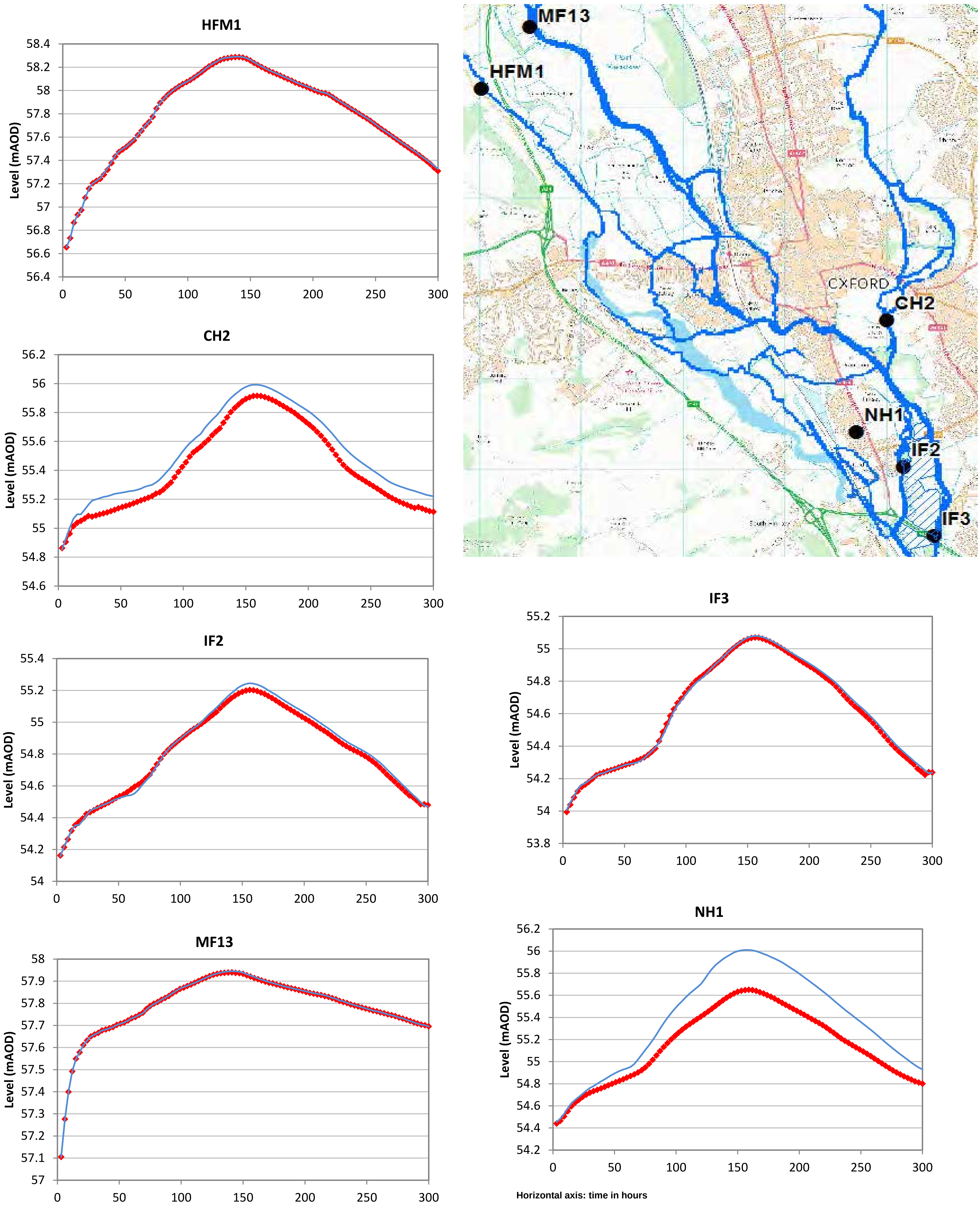

Figure 5.3a

1 in 20 year flood scenario (with and without FAS): hydrographs (1)

Simulated, with scheme

Simulated, without scheme

Date Nov 17	Drawn IJG
Scale dns	Checked SNB
Original A3	Revision 1
File Reference U:\63294 Oxford FAS\models\UPDATE JULY_AUGUST 2017\Post-processing\[Flood model_With_Without_TimeseriesGwlevels_TR28_TR29.xlsx]Figure 5.2b	

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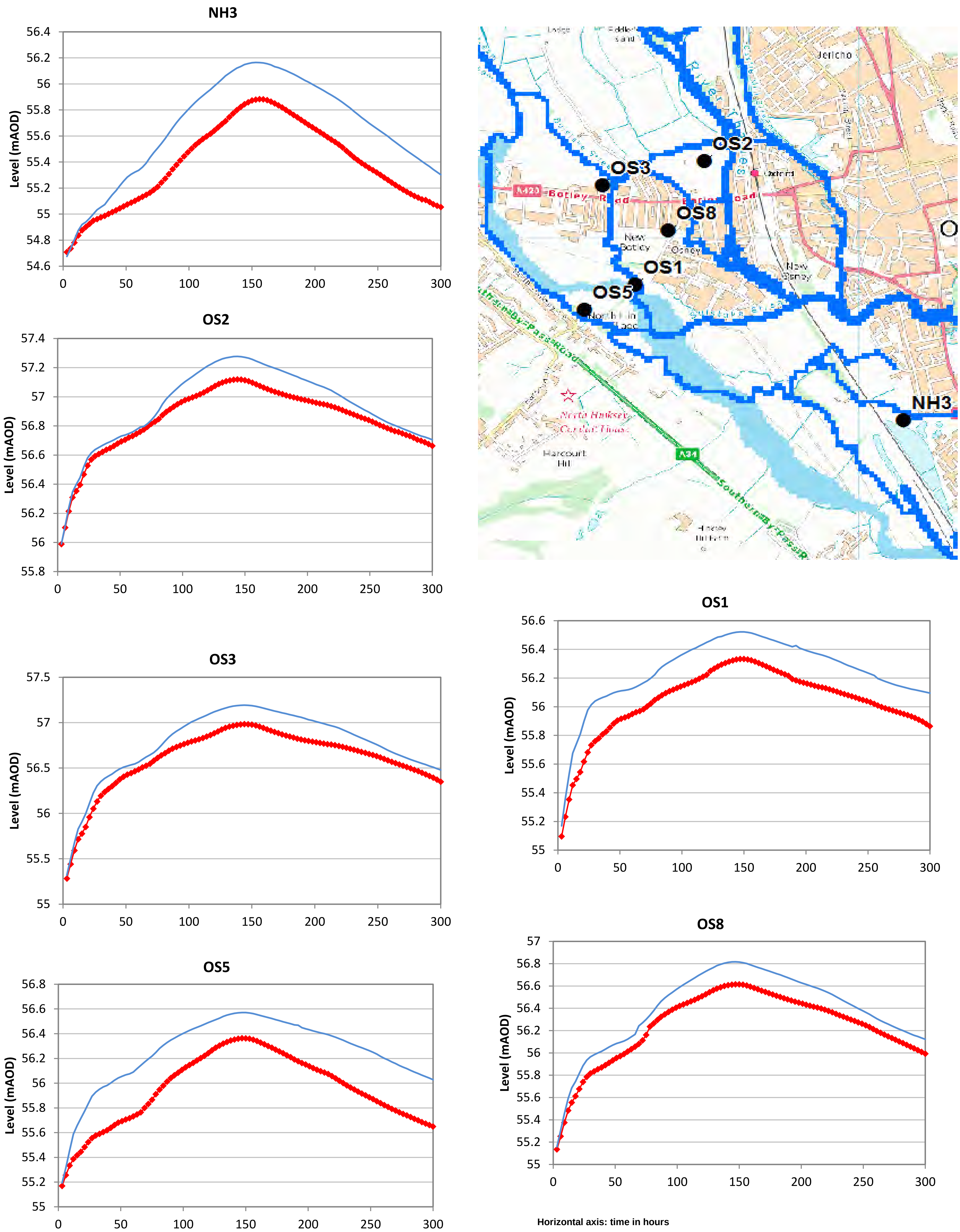


Horizontal axis: time in hours

Vertical axis: simulated groundwater levels in mAOD

Figure 5.3b

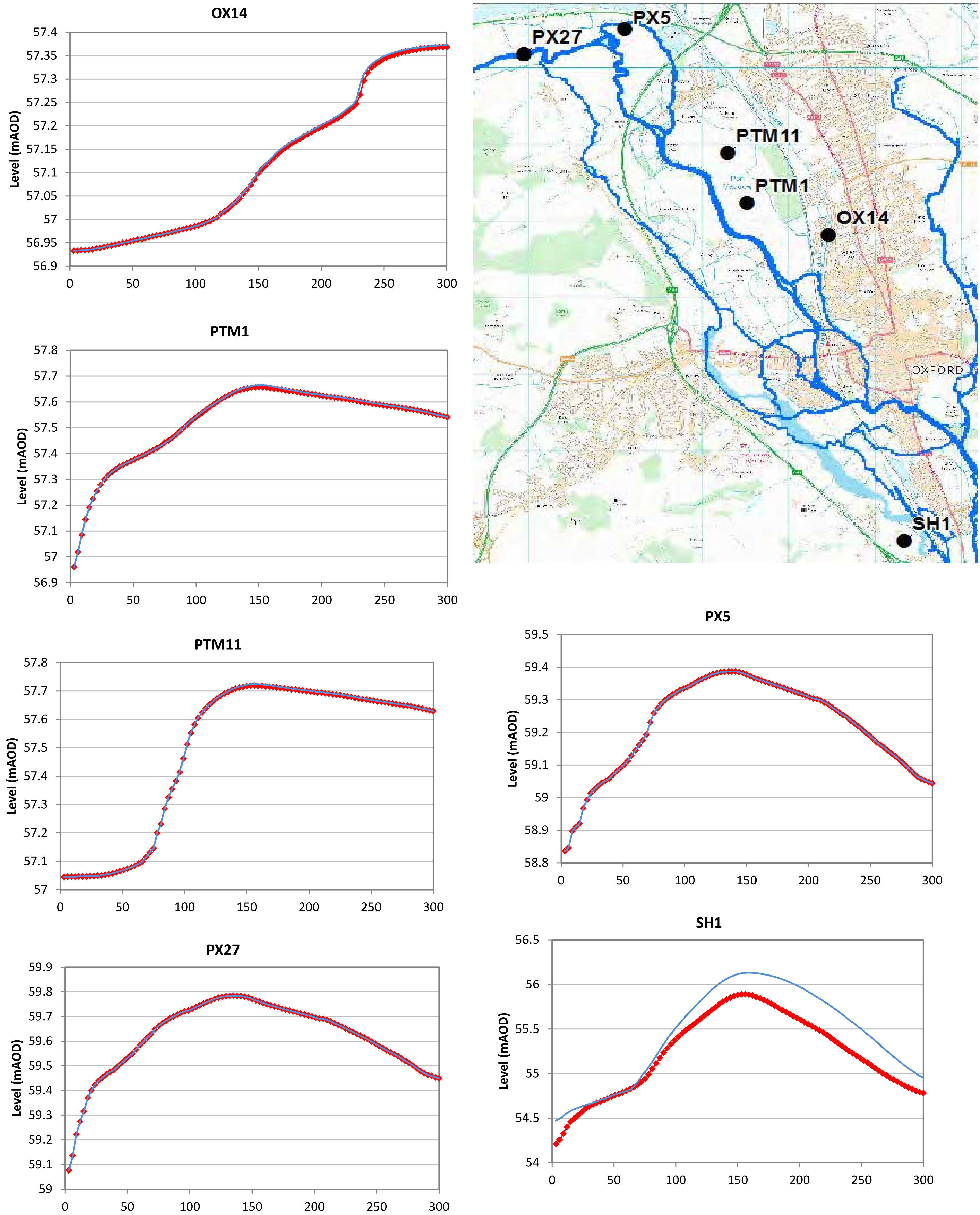
1 in 20 year flood scenario (with and without FAS): hydrographs (2)

Simulated, with scheme

Simulated, without scheme

Date: Nov 17	Drawn: IJG
Scale: dns	Checked: SNB
Original: A3	Revision: 1

File Reference: U:\63294 Oxford FAS\models\UPDATE JULY_AUGUST 2017\Post-processing\[Flood model_With_Without_TimeseriesGwlevels_TR28_TR29.xlsx]Figure 5.2b



Horizontal axis: time in hours

Vertical axis: simulated groundwater levels in mAOD

Figure 5.3c

1 in 20 year flood scenario (with and without FAS): hydrographs (3)

Simulated, with scheme

Simulated, without scheme

Date	Drawn
Nov 17	IJG
Scale	Checked
dns	SNB
Original	Revision
A3	1

File Reference
O:\63294 Oxford FAS\models\UPDATE JULY_AUGUST 2017\Post-processing\[Flood model_With_Without_TimeseriesGwlevels_TR28_TR29 xlsx]Figure 5.2b

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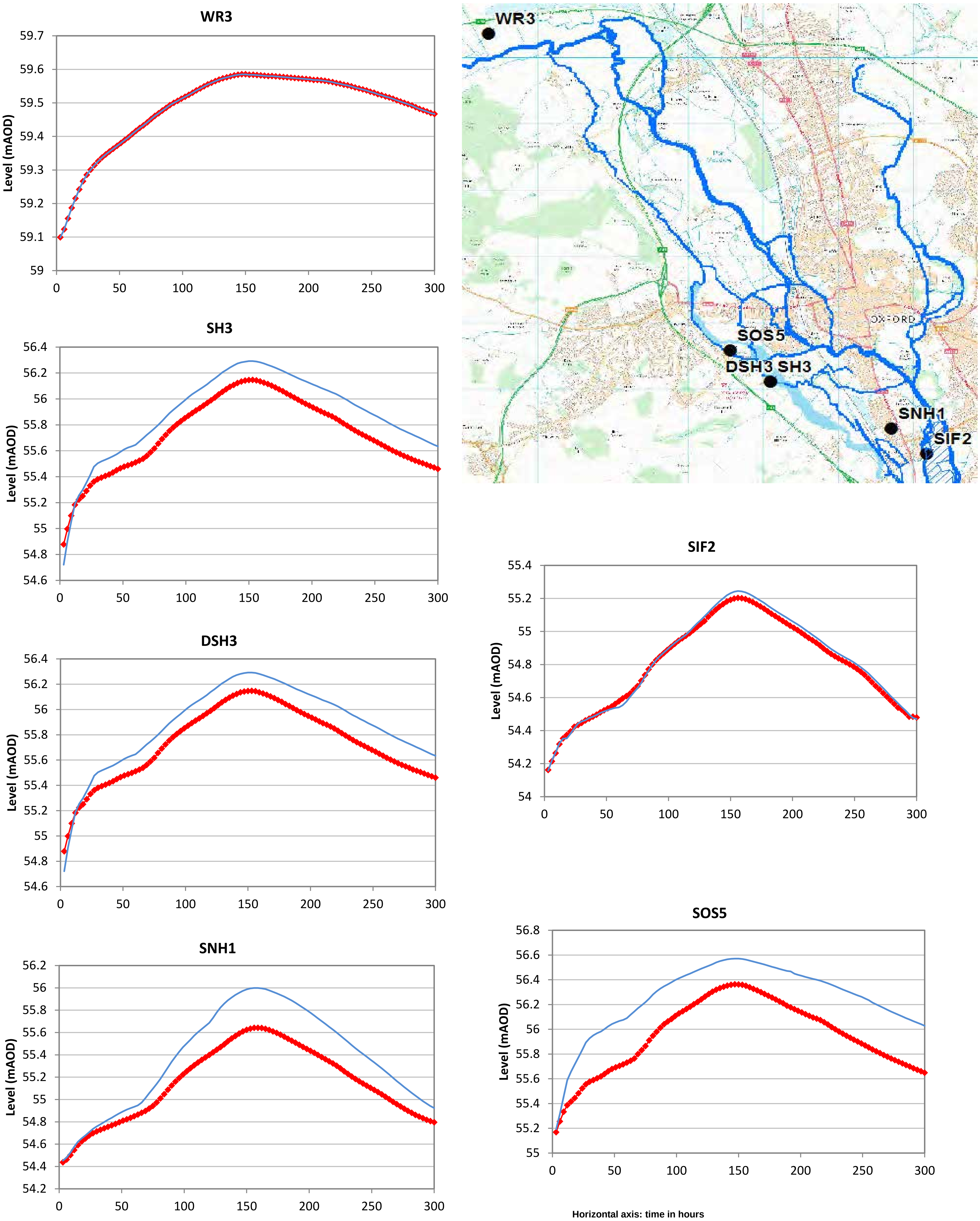

Horizontal axis: time in hours

Vertical axis: simulated groundwater levels in mAOD

Figure 5.3d

1 in 20 year flood scenario (with and without FAS): hydrographs (4)

Simulated, with scheme

Simulated, without scheme

Date Nov 17	Drawn IJG
Scale dns	Checked SNB
Original A3	Revision 1
File Reference O:\63294 Oxford FAS\models\UPDATE JULY_AUGUST 2017\Post-processing\[Flood model_With_Without_TimeseriesGwlevels_TR28_TR29 xlsx]Figure 5.2b	

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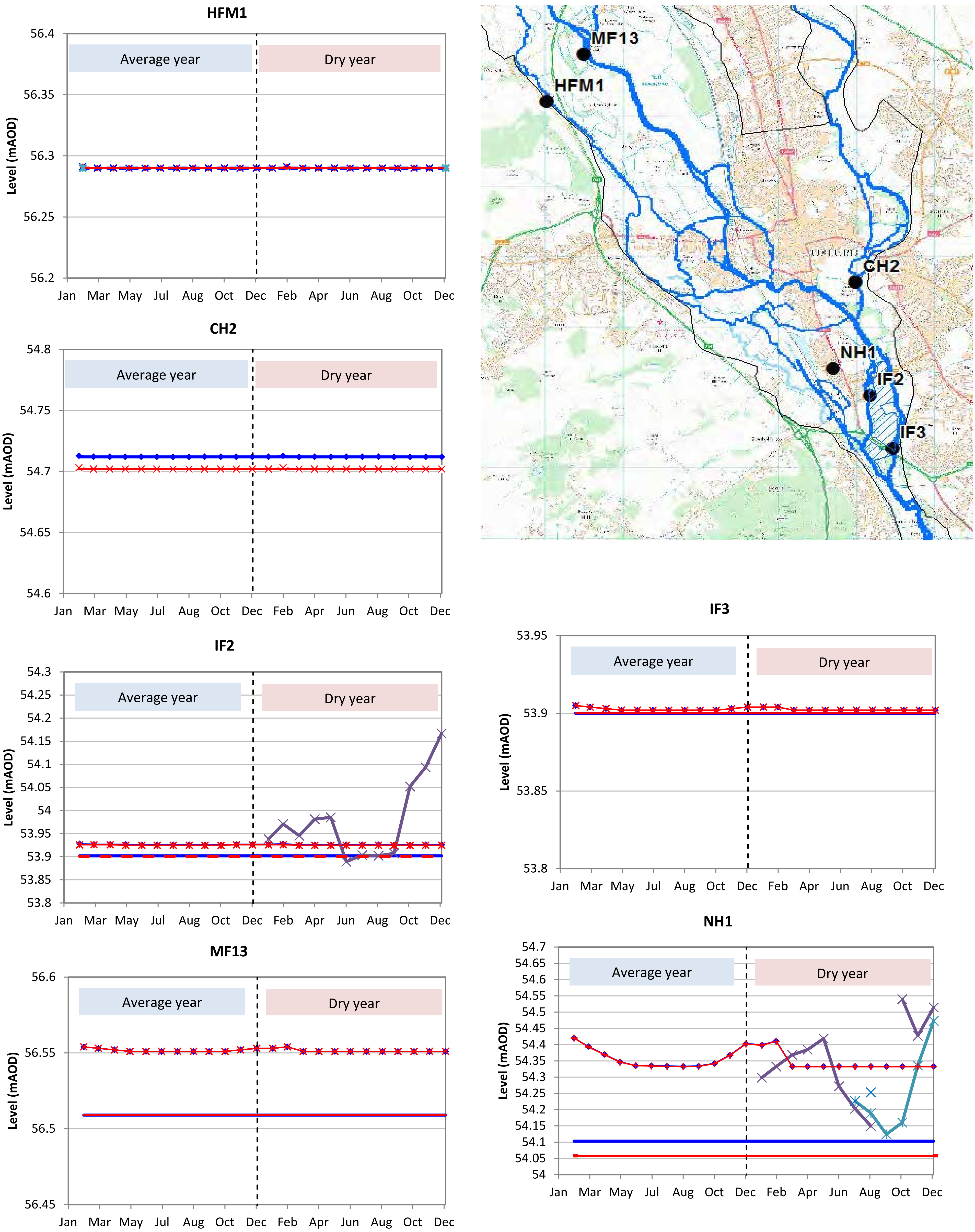

Figure 5.4a
Dry year scenario (with and without FAS):
hydrographs (1)

- Simulated groundwater level without FAS
- Q95 in nearest river cell, without FAS
- Simulated groundwater level with FAS
- Q95 in nearest river cell with FAS
- 2003 dry year data
- 2006 dry year data

Date	Drawn
Jan 18	IJG
Scale	Checked
dns	SNB
Original	Revision
A3	2

File Reference
JULY_AUGUST 2017\Post-processing\[Dry year model_With_Without_TimeseriesGwlevels_TR30_TR31

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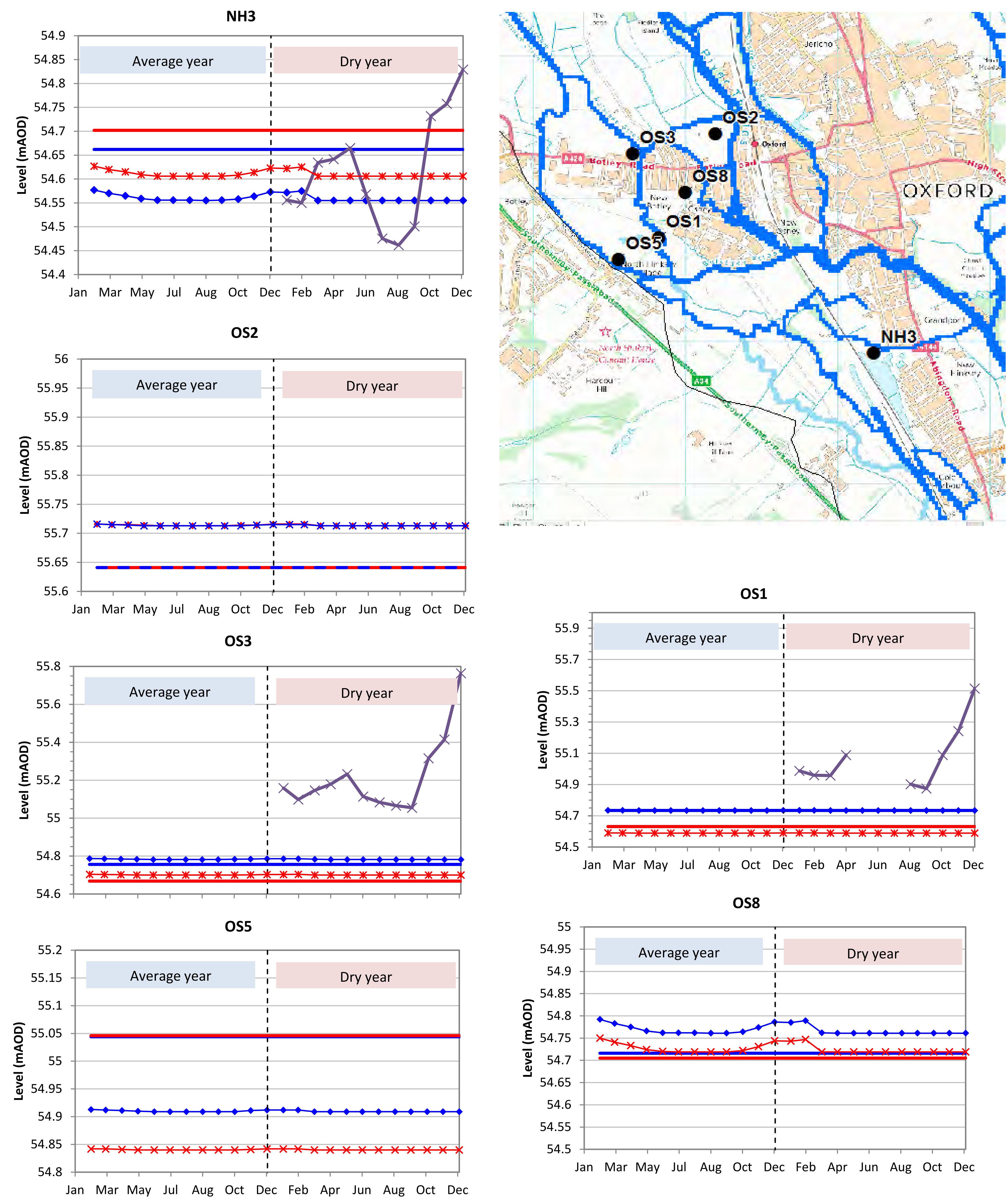

Figure 5.4b
Dry year scenario (with and without FAS): hydrographs (2)

- Simulated groundwater level without FAS
- Q95 in nearest river cell, without FAS
- Simulated groundwater level with FAS
- Q95 in nearest river cell with FAS
- 2003 dry year data
- 2006 dry year data

Date	Drawn
Jan 18	IJG
Scale	Checked
dns	SNB
Original	Revision
A3	2

File Reference
U:\63294 Oxford FAS\models\UPDATE JULY_AUGUST 2017\Post-processing\[Dry year model_With_Without_TimeseriesGwlevels_TR30_TR31.xlsm]Figure 5.xb

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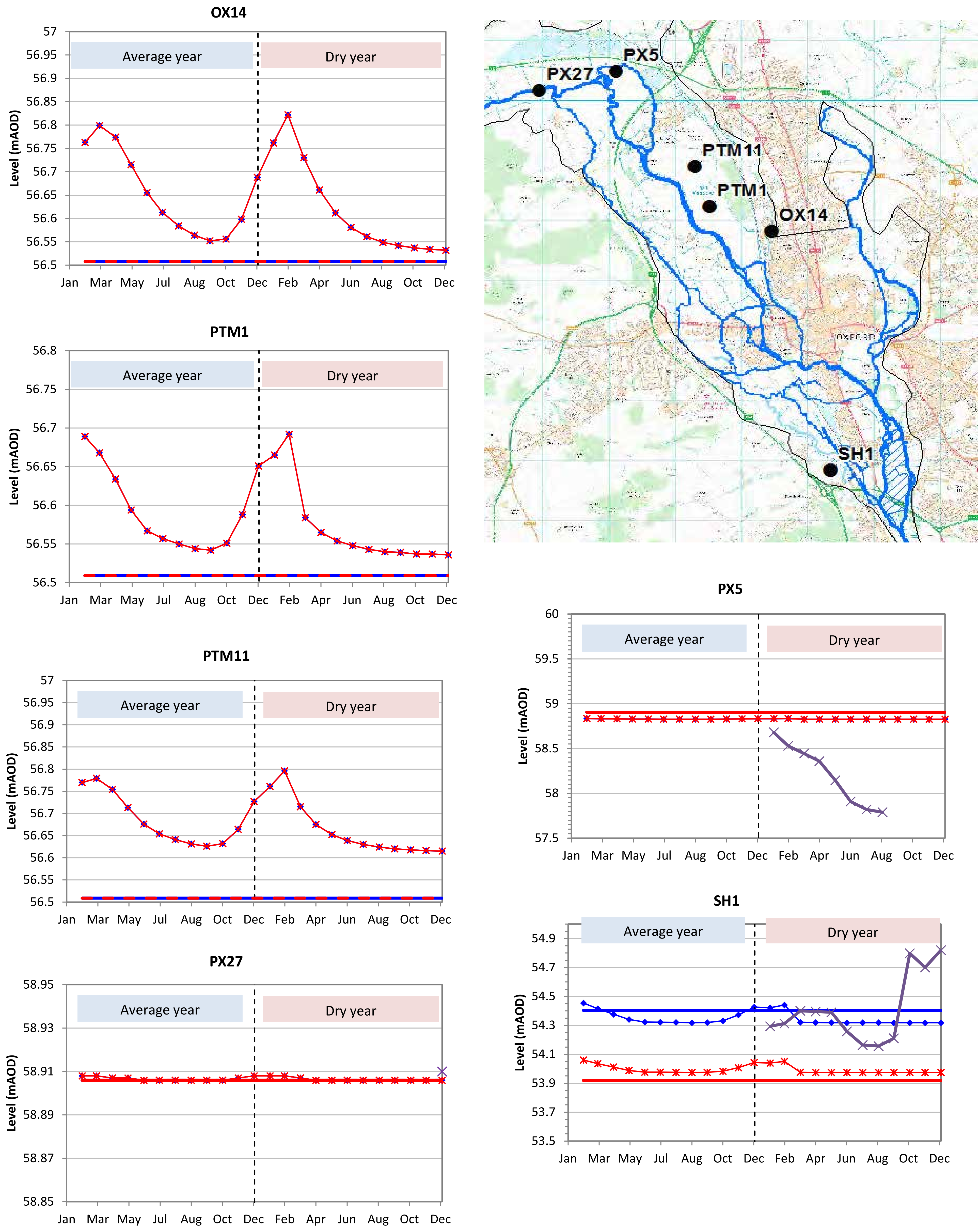

Figure 5.4c
Dry year scenario (with and without FAS): hydrographs (3)

- Simulated groundwater level without FAS
- Q95 in nearest river cell, without FAS
- Simulated groundwater level with FAS
- Q95 in nearest river cell with FAS
- 2003 dry year data
- 2006 dry year data

Date	Drawn
Jan 18	IJG
Scale	Checked
dns	SNB
Original	Revision
A3	2

File Reference
U:\63294 Oxford FAS\models\UPDATE JULY_AUGUST 2017\Post-processing\[Dry year model_With_Without_TimeseriesGwlevels_TR30_TR31.xlsm]Figure 5.xb

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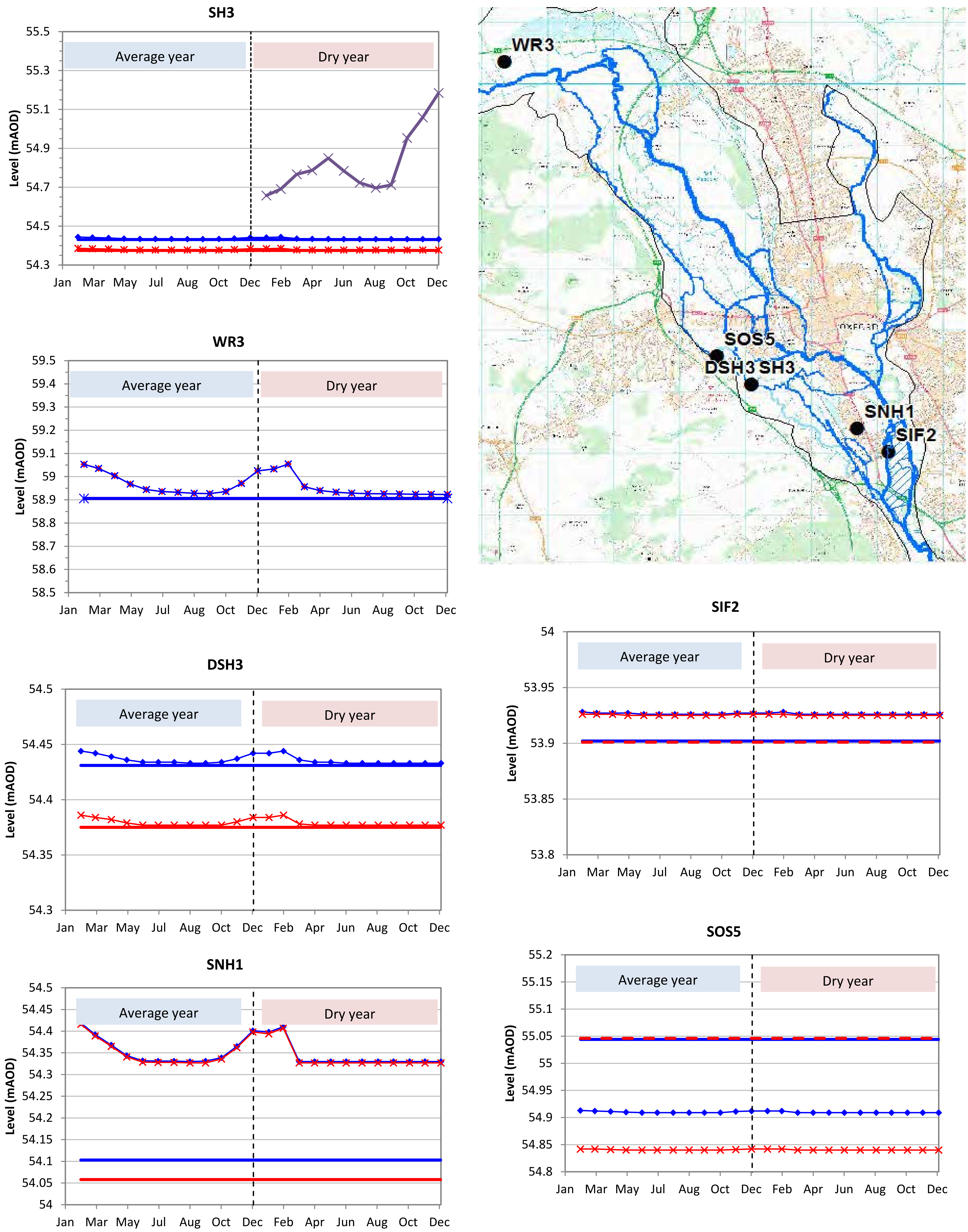

Figure 5.4d
Dry year scenario (with and without FAS): hydrographs (4)

- Simulated groundwater level without FAS
- Q95 in nearest river cell, without FAS
- Simulated groundwater level with FAS
- Q95 in nearest river cell with FAS
- 2003 dry year data
- 2006 dry year data

Date	Drawn
Jan 18	IJG
Scale: dns	Checked: SNB
Original: A3	Revision: 2
File Reference: U:\63294 Oxford FAS\models\UPDATE JULY_AUGUST 2017\Post-processing\[Dry year model_With_Without_TimeseriesGwlevels_TR30_TR31.xlsm]Figure 5.xb	

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