# GROUNDWATER MODELLING REPORT - PART 2
# FIGURES CONTINUED

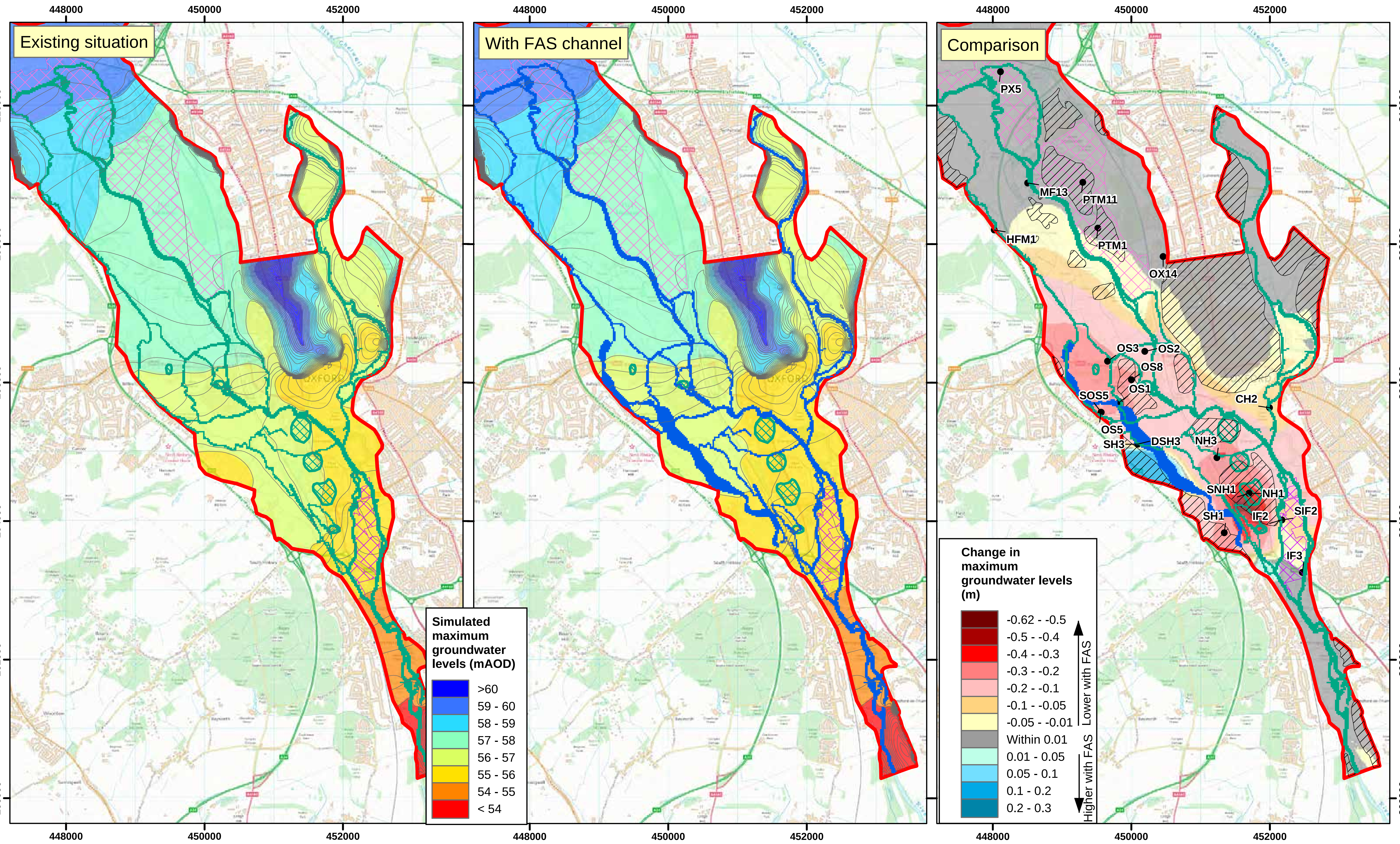



Figure 5.5
1in 20 year flood scenario: maximum groundwater levels



- Simulated groundwater contours
- Simulated rivers
- Simulated river and FAS channel
- Lined FAS channel
- MODFLOW model area
- Historical groundwater flooding
- Oxford Meadows SAC
- Iffley Meadows SSSI

| | | | |
|---|---|---|---|
| Date | Nov 2017 | Drawn | IJG |
| Scale | 1:50,000 | Checked | SNB |
| Original | A3 | Revision | 1 |
| File Reference | O:\63294 Oxford FAS\GIS\UPDATE JULY_AUGUST 2017\Map documents\Figures for report\Fig 5.3 1 in20 yr GWL difference.mxd | | |

esi consulting

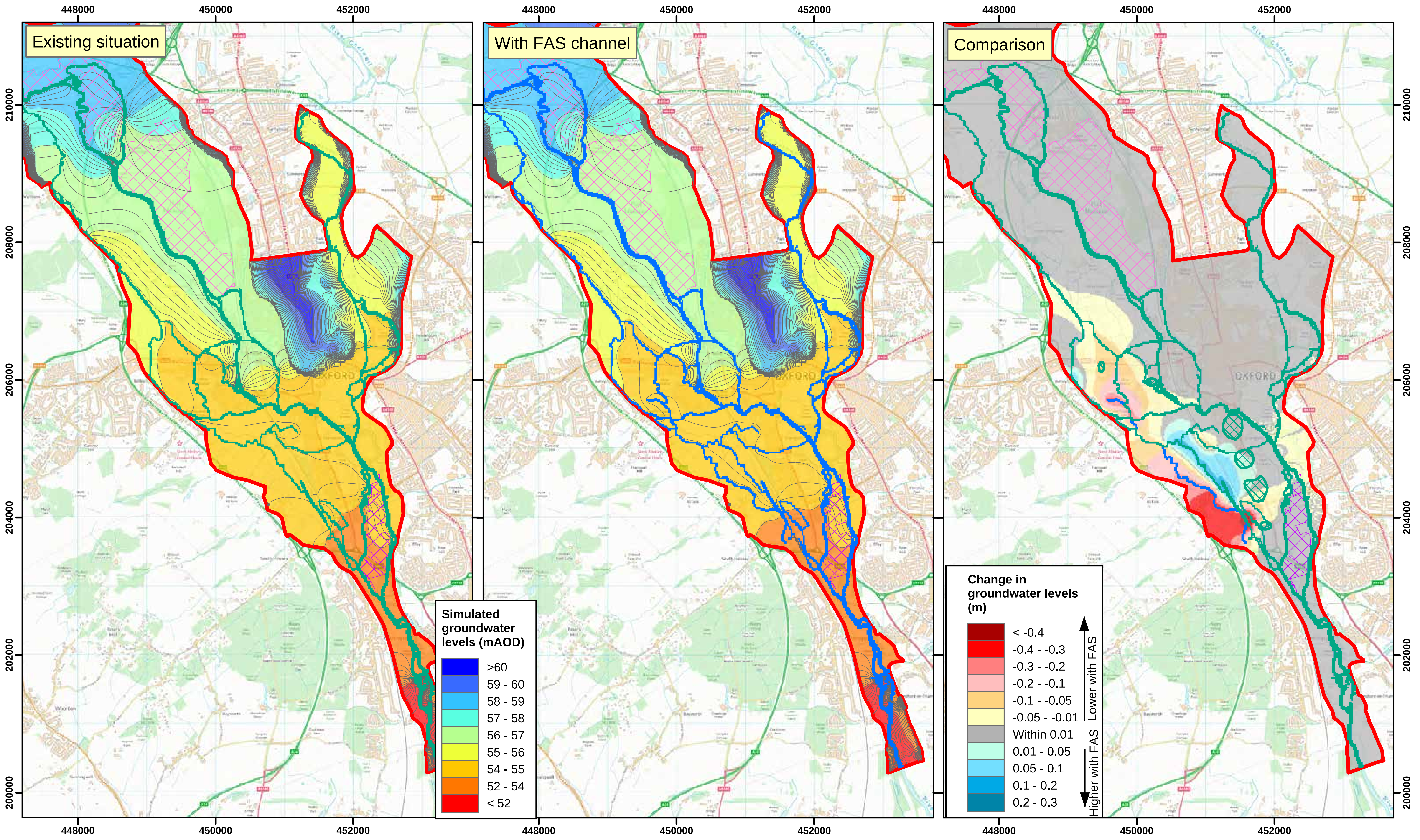



Figure 5.6
Dry year scenario: difference in groundwater levels at the end of the simulation



- Simulated rivers (existing)
- Simulated river and FAS channel
- Lined FAS channel
- Simulated groundwater contours
- MODFLOW model area
- Historical groundwater flooding
- Oxford Meadows SAC
- Iffley Meadows SSSI

| | | | |
|---|---|---|---|
| Date | Nov 2017 | Drawn | IJG |
| Scale | 1:50,000 | Checked | SNB |
| Original | A3 | Revision | 1 |

File Reference
O:\63294 Oxford FAS\GIS\UPDATE JULY_AUGUST 2017\Map documents\Figures for report\Fig 5.6 dry year GWL difference.mxd

esi consulting

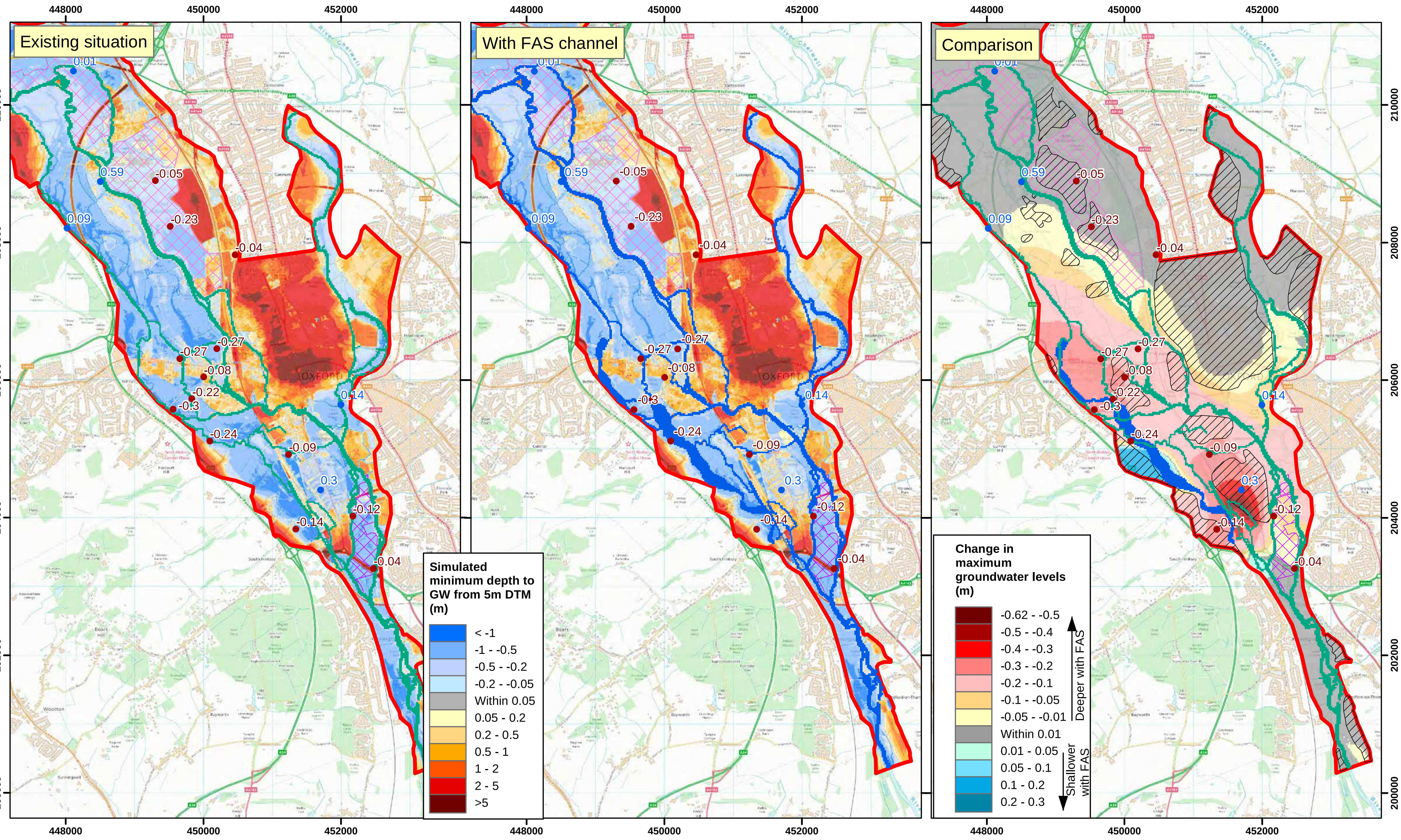



Figure 5.7a
1 in 20r year scenario: minimum depth to groundwater (from 5m DTM)



**Residual to July 2007 peak level (m)**

- Simulated < Observed
- Simulated > Observed

- Simulated rivers
- Simulated river and FAS channel
- Lined FAS channel
- MODFLOW model area
- Historical groundwater flooding
- Oxford Meadows SAC
- Iffley Meadows SSSI

| Date | Nov 2017 | Drawn | IJG |
|---|---|---|---|
| Scale | 1:50,000 | Checked | SNB |
| Original | A3 | Revision | 1 |
| File Reference | D:\63294 Oxford FAS\GIS\UPDATE JULY_AUGUST 2017\Map documents\Figures for report\Fig 5.4a 1 in 20yr Depth GW 5m | | |

esi consulting

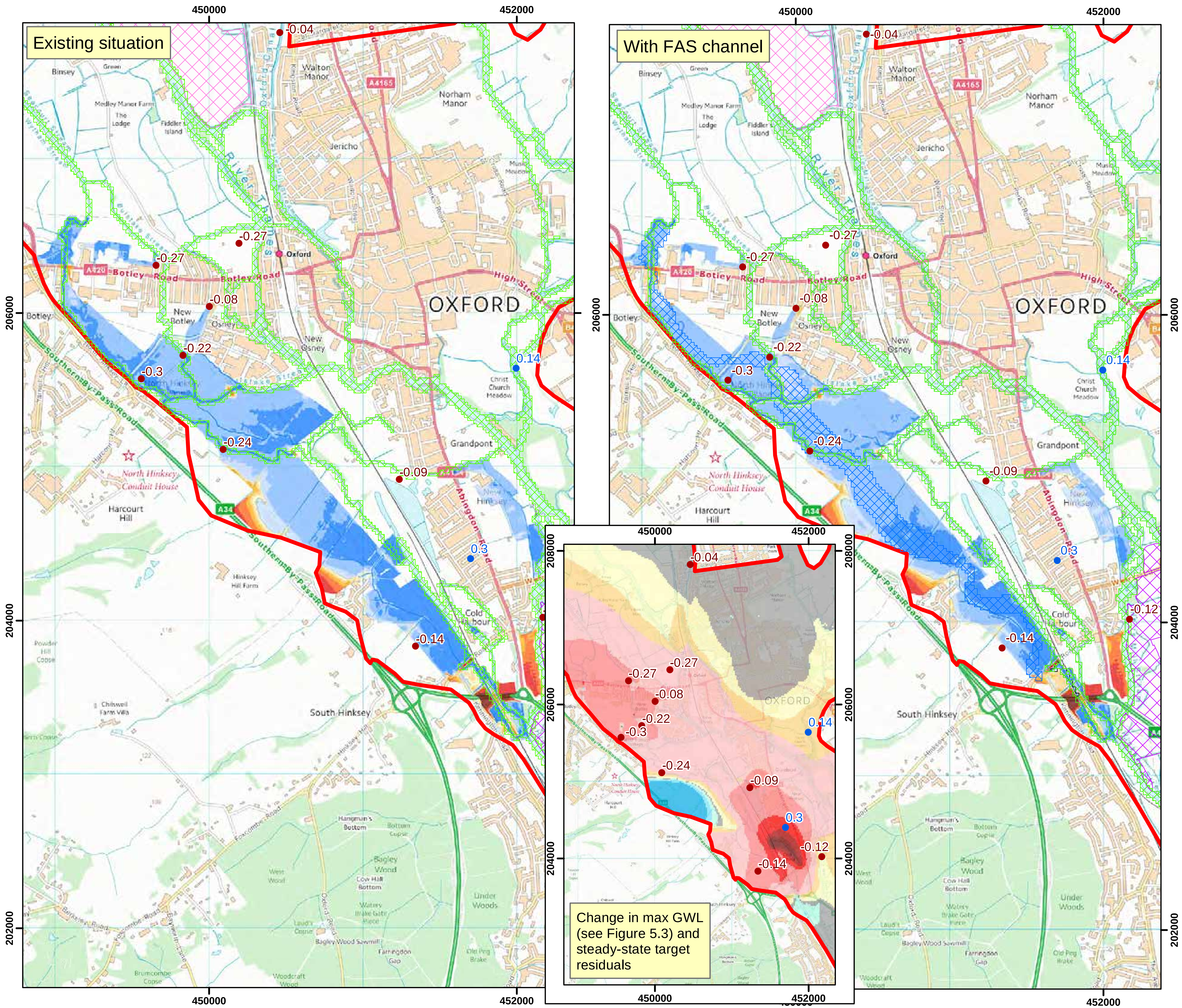



Figure 5.7b
1 in 20r year scenario: minimum depth to groundwater (from 0.5m DTM)

MODFLOW model area

**Residual to July 2007 peak level (m)**

- Simulated < Observed
- Simulated > Observed

Simulated rivers

Simulated river and FAS channel

Lined FAS channel

Historical groundwater flooding

Oxford Meadows SAC

Iffley Meadows SSSI

**Simulated minimum depth to GW from 5m DTM (m)**

- < -1
- -1 - -0.5
- -0.5 - -0.2
- -0.2 - -0.05
- Within 0.05
- 0.05 - 0.2
- 0.2 - 0.5
- 0.5 - 1
- 1 - 2
- 2 - 5
- >5

GW above ground level

GW below ground level

**Change in maximum groundwater levels (m)**

**FAS scenario minus baseline (m)**

- -0.62 - -0.5
- -0.5 - -0.4
- -0.4 - -0.3
- -0.3 - -0.2
- -0.2 - -0.1
- -0.1 - -0.05
- -0.05 - -0.01
- Within 0.01
- 0.01 - 0.05
- 0.05 - 0.1
- 0.1 - 0.2
- 0.2 - 0.3

Lower with FAS

Higher with FAS



| | |
|---|---|
| Date Nov 2017 | Drawn IJG |
| Scale 1:23,000 | Checked SNB |
| Original A3 | Revision 1 |

File Reference
O:\63294 Oxford FAS\GIS\UPDATE JULY_AUGUST 2017\Map documents\Figures for report\Fig 5.4b 1 in 20yr Depth GW 0.5m

esi consulting

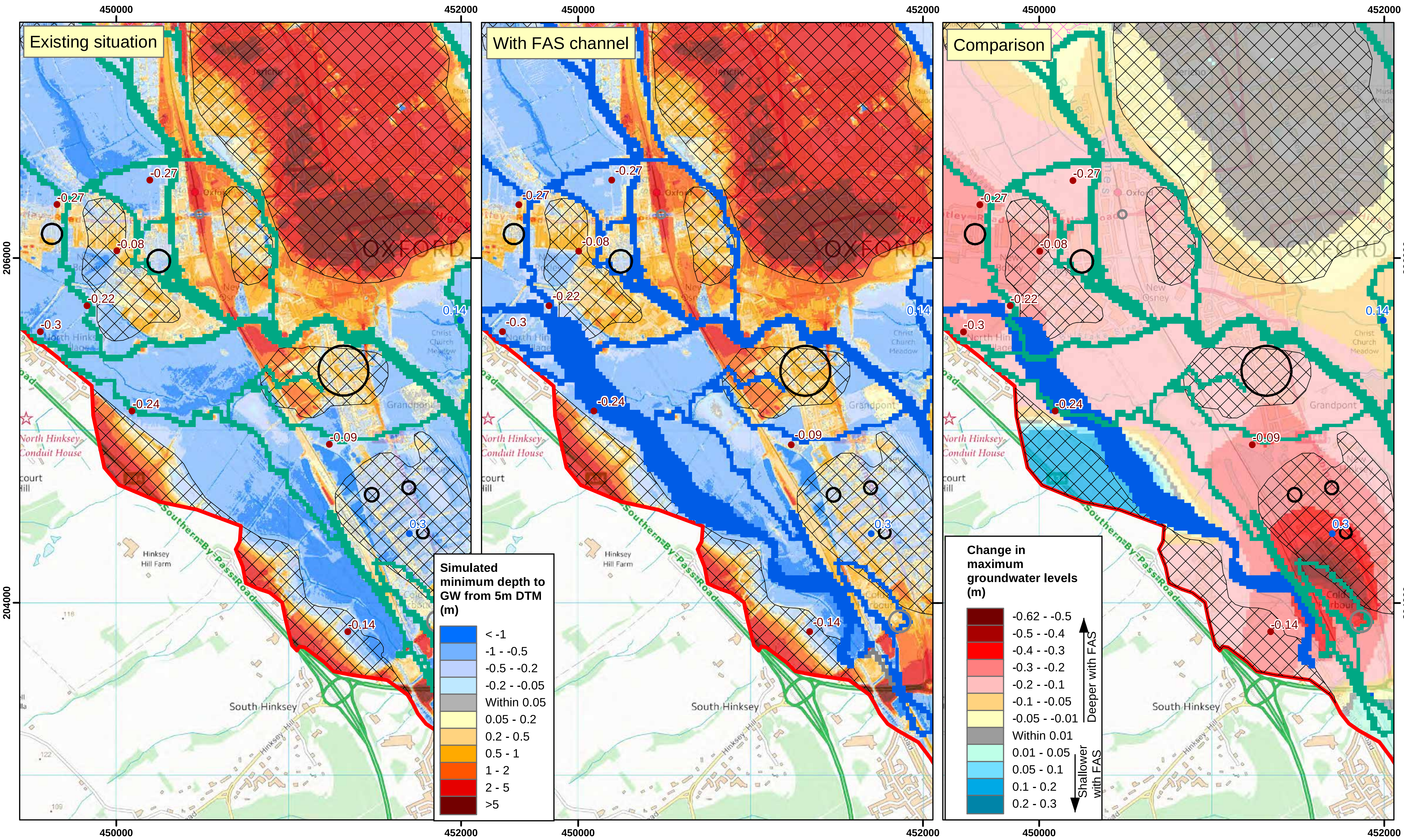



Figure 5.7c
1 in 20r year scenario: minimum depth to groundwater (from 5m DTM) in areas of groundwater flooding



**Residual to July 2007 peak level (m)**
- Simulated < Observed
- Simulated > Observed

- Simulated rivers
- Simulated river and FAS channel
- Lined FAS channel
- MODFLOW model area

- Mapped outcrop of river terrace sand/gravel
- Oxford Meadows SAC
- Iffley Meadows SSSI

**Approximate areas of historical groundwater flooding**
- Possible
- Confirmed

| | | | |
|---|---|---|---|
| Date | Nov 2017 | Drawn | IJG |
| Scale | 1:20,000 | Checked | SNB |
| Original | A3 | Revision | 1 |

File Reference
D:\63294 Oxford FAS\GIS\UPDATE JULY_AUGUST 2017\Map documents\Figures for report\Fig 5.4c 1 in 20yr Depth GW 5m

esi consulting

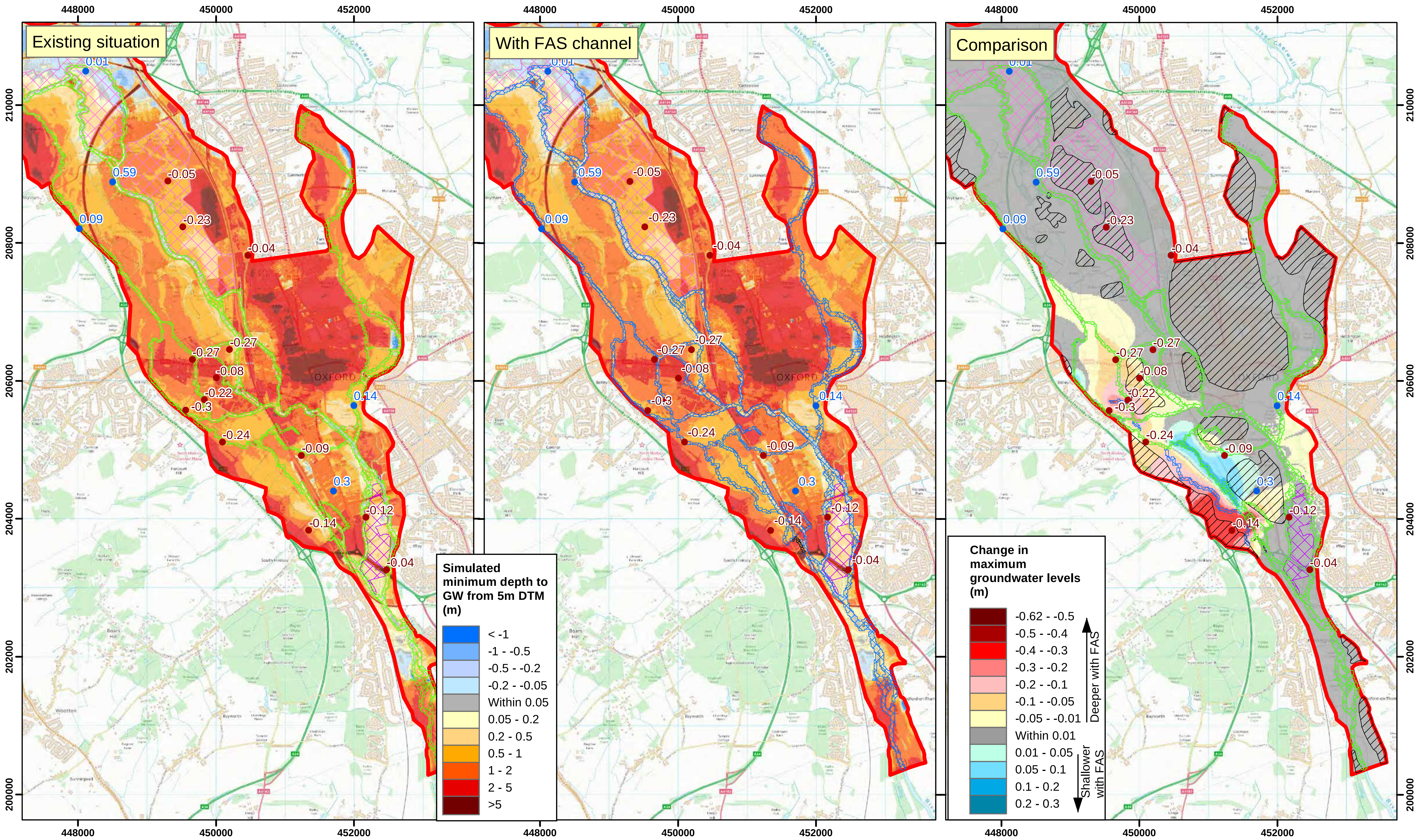



Figure 5.8a
Dry year scenario: depth to groundwater at the end of the simulation (from 5m DTM)



**Residual to July 2007 peak level (m)**

- Simulated < Observed
- Simulated > Observed

- Simulated rivers
- Simulated river and FAS channel
- Lined FAS channel
- MODFLOW model area
- Oxford Meadows SAC
- Iffley Meadows SSSI

| Date | Nov 2017 | Drawn | IJG |
|---|---|---|---|
| Scale | 1:50,000 | Checked | SNB |
| Original | A3 | Revision | 1 |

File Reference
D:\63294 Oxford FAS\GIS\UPDATE JULY_AUGUST 2017\Map documents\Figures for report\Fig 5.7a dry year Depth GW 5m

esi consulting

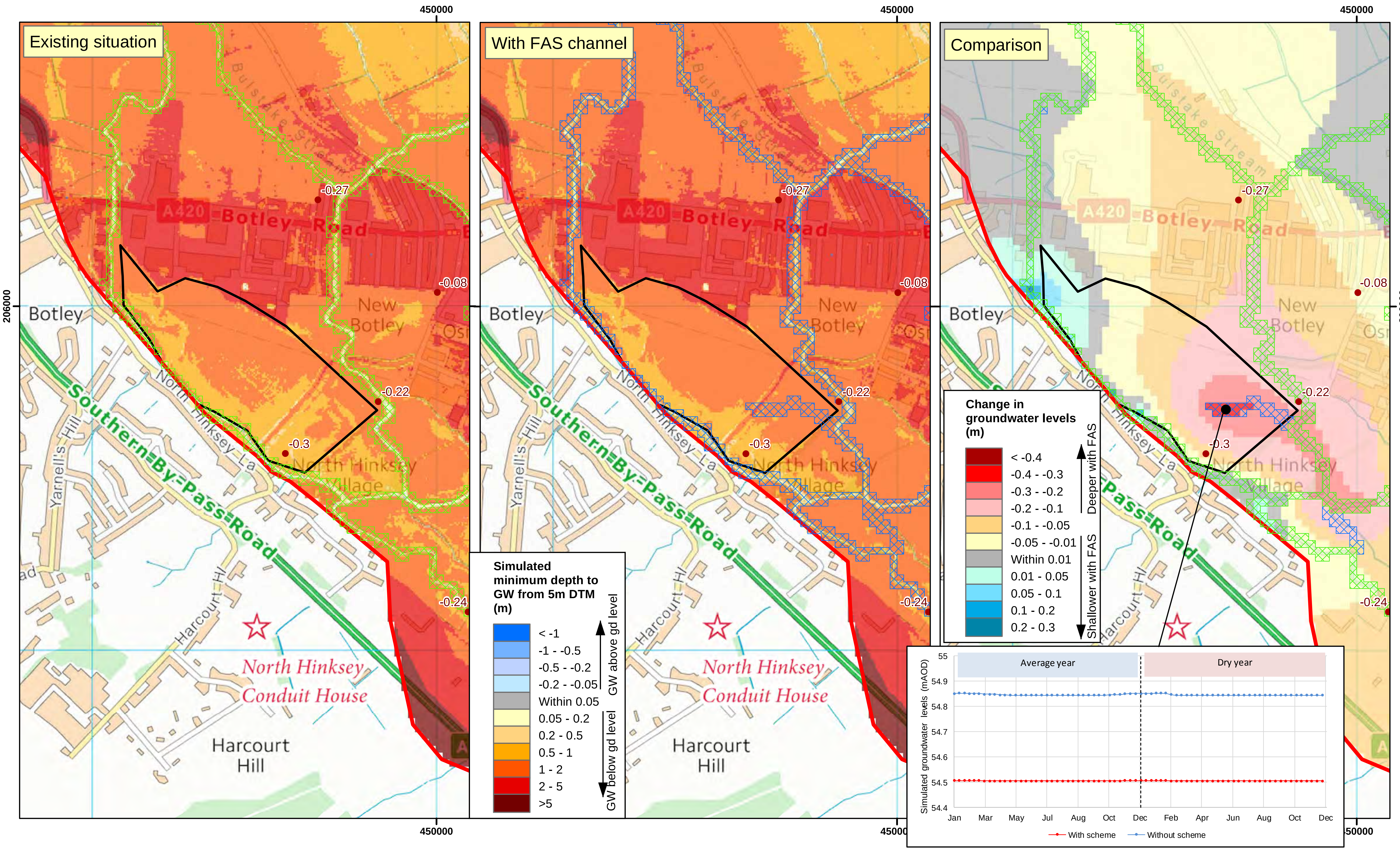



Figure 5.8b
Dry year scenario: depth to groundwater at the end of the simulation.
Hinksey Meadow MG4 grassland



MODFLOW model area
Simulated rivers
Simulated river and FAS channel
Lined FAS channel
Hinksey Meadow

**Residual to July 2007 peak level (m)**
Simulated < Observed
Simulated > Observed

| | | | |
|---|---|---|---|
| Date | Nov 2017 | Drawn | IJG |
| Scale | 1:10,000 | Checked | SNB |
| Original | A3 | Revision | 1 |

File Reference
O:\63294 Oxford FAS\GIS\UPDATE JULY_AUGUST 2017\Map documents\Figures for report\Fig 5.7b M4Grassland dry year Depth

esi consulting

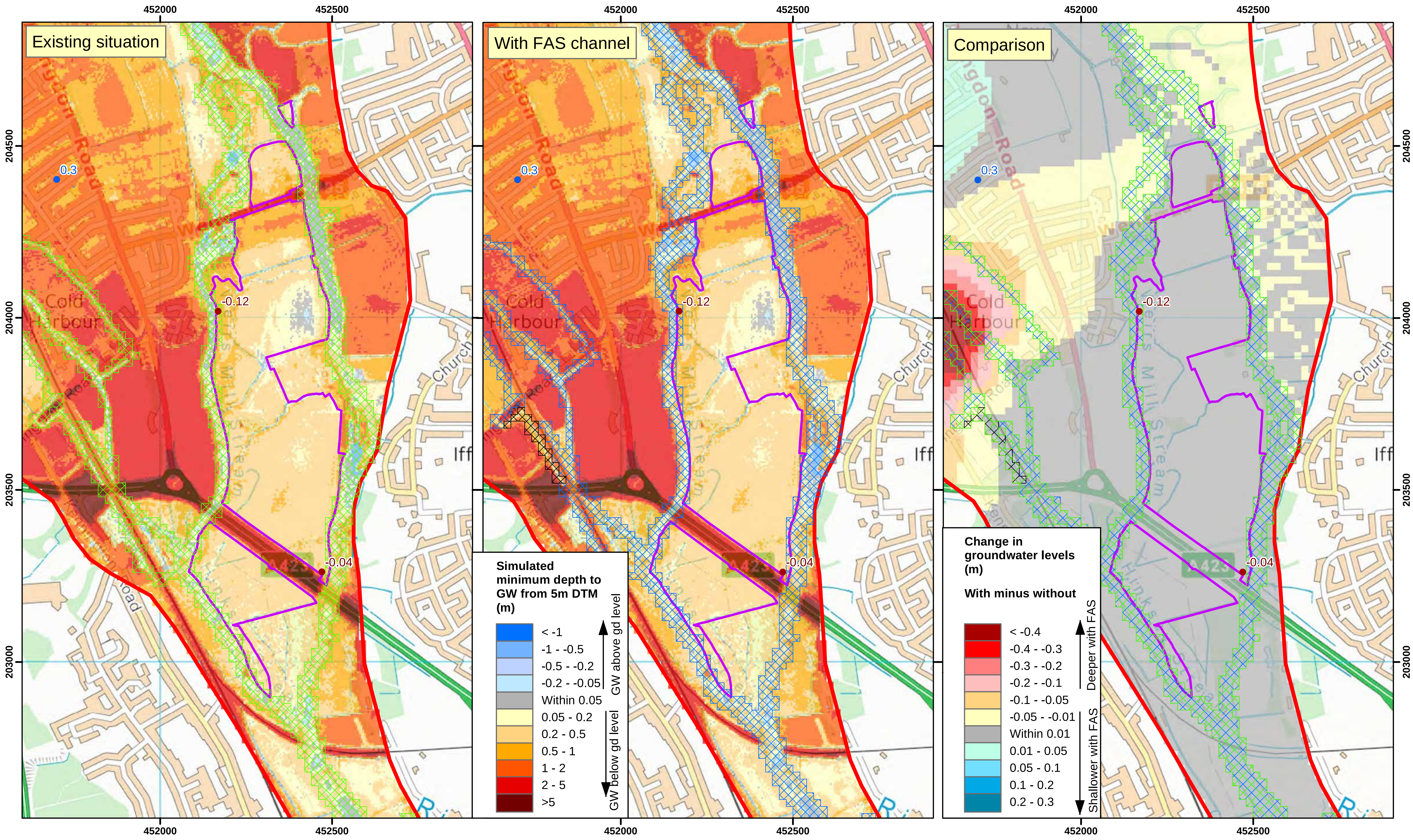



Figure 5.8c
Dry year scenario: difference in depth to groundwater at the end of the simulation (from 5m DTM)
Iffley Meadows



MODFLOW model area
Simulated river and FAS channel
Lined FAS channel
Historical groundwater flooding
Oxford Meadows SAC
Iffley Meadows SSSI

**Residual to July 2007 peak level (m)**
- Simulated < Observed
- Simulated > Observed

| | | | |
|---|---|---|---|
| Date | Nov 2017 | Drawn | IJG |
| Scale | 1:10,000 | Checked | SNB |
| Original | A3 | Revision | 1 |

File Reference
O:\63294 Oxford FAS\GIS\UPDATE JULY_AUGUST 2017\Map documents\Figures for report\Fig 5.7c Iffley Meadows dry year

esi consulting

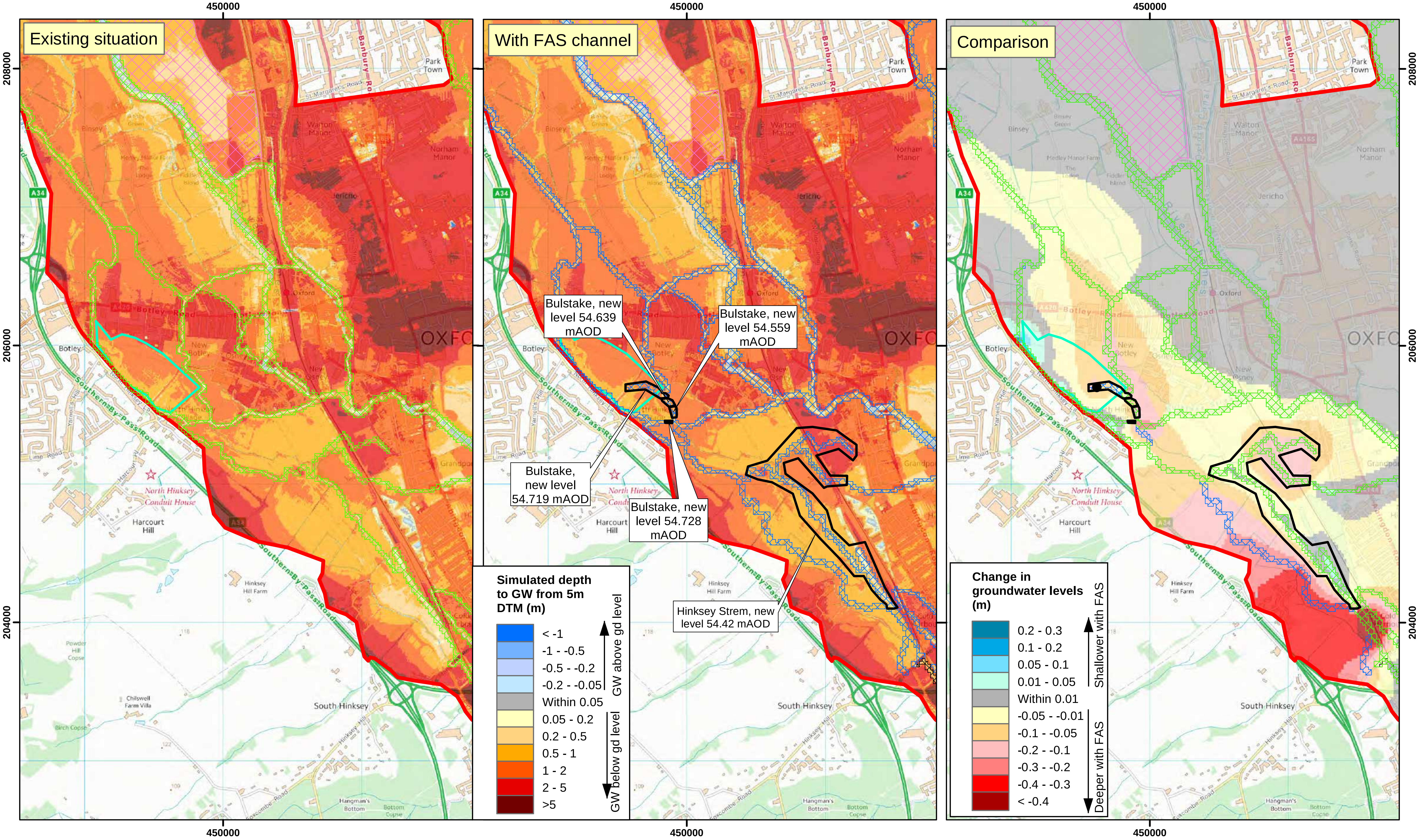



Figure 5.9
Dry year scenario: depth to groundwater at the end of the simulation.
around Hinksey Meadow MG4 grassland
Scenario A: River water level adjusted for weir levels



- MODFLOW model area
- Simulated rivers
- Simulated river and FAS channel
- Lined FAS channel
- Hinksey Meadow
- Areas of corrected river levels (correction from report R2D1)

| | | | |
|---|---|---|---|
| Date | Dec 2017 | Drawn | IJG |
| Scale | 1:25,000 | Checked | SNB |
| Original | A3 | Revision | 1 |
| File Reference | O:\63294 Oxford FAS\GIS\UPDATE JULY_AUGUST 2017\Map documents\Figures for report\Fig_PostR2D1 HinkseyBulstake | | |

esi consulting

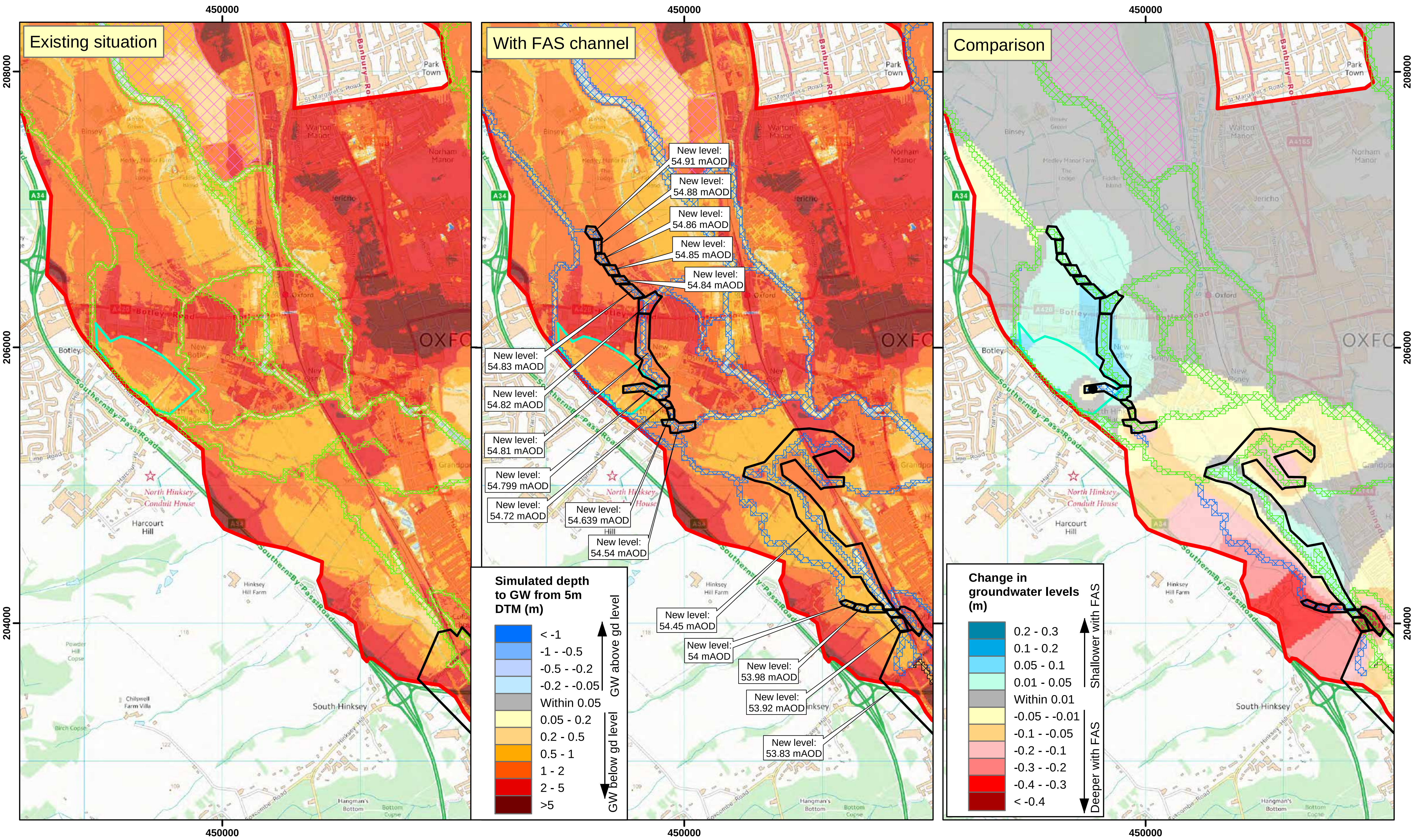



Figure 5.10
Dry year scenario: depth to groundwater at the end of the simulation around Hinksey Meadow MG4 grassland
Scenario B: River water level adjusted for weir levels



- MODFLOW model area
- Simulated rivers
- Simulated river and FAS channel
- Lined FAS channel
- Hinksey Meadow
- Areas of corrected river levels (correction from report R2D1)

| | | | |
|---|---|---|---|
| Date | Feb 2018 | Drawn | IJG |
| Scale | 1:25,000 | Checked | SNB |
| Original | A3 | Revision | 1 |
| File Reference | O:\63294 Oxford FAS\GIS\UPDATE JULY_AUGUST 2017\Map documents\Figures for report\Fig_PostR2D1 Feb2018 revised | | |

esi consulting

# APPENDICES

# APPENDIX A

## Model Run Log

| GWV file name | Outputs Zippe | Root file | Working directory | Steady or transient | Date | Modified by | Key parameters changed | Comments |
|---|---|---|---|---|---|---|---|---|
| Oxford_FAS_BLINE_TR14 | N | Oxford_F | O:\63294 Oxford FAS\models\MODFLOW | Transient | 02/12/2015 | SNB | [From TR12a] With corrected top and base. Initial heads from SS8. | |
| Oxford_FAS_BLINE_SS8a | N | Oxford_F | O:\63294 Oxford FAS\models\MODFLOW | Steady-state | 15/12/2015 | SNB | [From SS8] With 12 additional targets! | |
| Oxford_FAS_EXISTING10yr_TR19 | Y | Oxford_F | O:\63294 Oxford FAS\models\PREFERRED OPTION EXISTING | Transient | 17/08/2016 | SNB | Model copied from [TR16]<br>River cells deleted<br>New river cells imported (after selected cells removed using delete_cells.py)<br>Model base checked against river stage (no change needed) | |
| Oxford_FAS_EXISTING20yr_TR20 | Y | Oxford_F | O:\63294 Oxford FAS\models\PREFERRED OPTION EXISTING | Transient | 17/08/2016 | SNB | Model copied from [TR17]<br>River cells deleted<br>New river cells imported (after selected cells removed using delete_cells.py)<br>Model base checked against river stage (no change needed) | |
| Oxford_FAS_EXISTING100yr_TR21 | Y | Oxford_F | O:\63294 Oxford FAS\models\PREFERRED OPTION EXISTING | Transient | 18/08/2016 | SNB | Model copied from [TR18]<br>River cells deleted<br>New river cells imported (after selected cells removed using delete_cells.py)<br>Model base checked against river stage (no change needed) | |
| Oxford_FAS_FLOODCHANNEL_DROUGHT_SS13 | N | Oxford_F | O:\63294 Oxford FAS\models\PREFERRED OPTION DRY\MODFLOW | Steady state | 05/10/2016 | IJG | Copied from Oxford_FAS_FLOODCHANNEL_DROUGHT_SS11<br>Correction to the rivers. All river cells deleted and reimported from "O:\63294 Oxford FAS\models\PREFERRED OPTION | Calculation Sheet: "O:\63294 Oxford FAS\calculations\Calc record and QA\636294_Oxford_DRY_FASandBASE_October2016Update.docx" |
| Oxford_FAS_FLOODCHANNEL_DROUGHT_TR24 | N | Oxford_F | O:\63294 Oxford FAS\models\PREFERRED OPTION DRY\MODFLOW | Transient | 05/10/2016 | IJG | Copied from Oxford_FAS_FLOODCHANNEL_DROUGHT_TR22<br>Correction to the rivers. All river cells deleted and reimported from "O:\63294 Oxford FAS\models\PREFERRED OPTION DRY\Preprocessing\River_levels\Correction_October2016\RiverCells_InputForGV_CellsDeleted.csv"<br>initial heads from [SS13] | |
| Oxford_FAS_BLINE_DROUGHT_SS14 | N | Oxford_F | O:\63294 Oxford FAS\models\DROUGHT MODEL\GVfiles | Steady State | 05/10/2016 | IJG | Model copied from Oxford_FAS_BLINE_DROUGHT_SS12.gwv<br>River cells deleted and reimported from:<br>"O:\63294 Oxford FAS\models\DROUGHT MODEL\Preprocessing\River_levels\Correction_October2016\RiverCells_InputForGV_CellsDeleted.csv"<br>initial heads from [SS13] | |
| Oxford_FAS_BLINE_DROUGHT_TR25 | N | Oxford_F | O:\63294 Oxford FAS\models\DROUGHT MODEL\GVfiles | Transient | 05/10/2016 | IJG | Model copied from Oxford_FAS_BLINE_DROUGHT_TR23.gwv<br>River cells deleted and reimported from:<br>"O:\63294 Oxford FAS\models\DROUGHT MODEL\Preprocessing\River_levels\Correction_October2016\RiverCells_InputForGV_CellsDeleted.csv"<br>initial heads from [SS14] | |
| Oxford_FAS_BLINE_TR14_ForProcessingTR26 | | | Model for preprocessing, not for running | | 18/08/2017 | ijg | Copied from Oxford_FAS_BLINE_TR14. Importing updated layer elevations. Model used to check the updated Model Base against the River Bed Levels from TR14 (i.e. importing model base from O:\63294 Oxford FAS\GIS\UPDATE JULY_AUGUST 2017\Layers\Geology\Surfacing\Version2\UpdatedModelBottom.tif and exporting the RiversBC as .txt for the base_dropper.py utility) | |
| Oxford_FAS_BLINE_SS15 | | same as ( | O:\63294 Oxford FAS\models\UPDATE JULY_AUGUST 2017\GVfiles | SS | 21/08/2017 | ijg | Same as Oxford_FAS_BLINE_SS15 but with model top from O:\63294 Oxford FAS\GIS\UPDATE JULY_AUGUST 2017\Layers\Geology\Surfacing\Version2\UpdatedModelTop_Points.shp and bottom from O:\63294 Oxford FAS\calculations\UPDATE JULY_AUGUST 2017\Base_drop_transient_calibration_model\Superseded\NewBottom.csv - bottom is wrong (adjusted for reiver bed rather than river head - csv moved to superseded)<br><br>Recharge from SMD 1961-2016 (i.e ~ x2 than in SS8aBLINE). increase recharge makes GWL a bit higher (aresiduals worse) at targets that are away from rivers (WR3, PTM11, PTM1). justifies increasin K. excpet for NH1 which goes a bit lower (better calibration) | |
| Oxford_FAS_BLINE_SS16 | | same as ( | O:\63294 Oxford FAS\models\UPDATE JULY_AUGUST 2017\GVfiles | SS | 23/08/2017 | ijg | From Oxford_FAS_BLINE_SS15 with K x2 (Kx Ky=200 & Kz=20).<br>bottom (adjusted for river head) from O:\63294 Oxford FAS\calculations\UPDATE JULY_AUGUST 2017\Base_drop_transient_calibration_model\Superseded_Version2\NewBottom.csv<br>Calibration is practically identical to SS8a | |
| Oxford_FAS_BLINE_TR26 | | same as ( | O:\63294 Oxford FAS\models\UPDATE JULY_AUGUST 2017\GVfiles | transient | 23/08/2017 | ijg | Same as Oxford_FAS_BLINE_TR14 but with model top from O:\63294 Oxford FAS\GIS\UPDATE JULY_AUGUST 2017\Layers\Geology\Surfacing\Version2\UpdatedModelTop_Points.shp and bottom from O:\63294 Oxford FAS\calculations\UPDATE JULY_AUGUST 2017\Base_drop_transient_calibration_model\Superseded_Version2\NewBottom.csv<br><br>Recharge: Converted from matrix to Database in Properties > Options... unticked 'Use Matrices' for recharge. So I could change the recharge with the Db button and then copy recharge from SP1 to all the other SPs. | |
| Oxford_FAS_BLINE_TR14_ForProcessingSS17TR27 | | | Model for preprocessing, not for running | | 23/08/2017 | ijg | Copied from Oxford_FAS_BLINE_TR14_ForProcessingTR26. Importing updated layer elevations. Model used to check the updated Model Base against the River Bed Levels from TR14 (i.e. importing model base from O:\63294 Oxford FAS\GIS\UPDATE JULY_AUGUST 2017\Layers\Geology\Surfacing\Version3\UpdatedModelBottom.tif and exporting the RiversBC as .txt for the base_dropper.py utility) | |
| **Oxford_FAS_BLINE_SS17** | | **same as (** | **O:\63294 Oxford FAS\models\UPDATE JULY_AUGUST 2017\GVfiles** | **SS** | **23/08/2017** | **ijg** | **From Oxford_FAS_BLINE_SS16 with corrected layer elevations<br>bottom (adjusted for river head) from O:\63294 Oxford FAS\calculations\UPDATE JULY_AUGUST 2017\Base_drop_transient_calibration_model\NewBottom.csv<br>Top from O:\63294 Oxford FAS\GIS\UPDATE JULY_AUGUST 2017\Layers\Geology\Surfacing\Version3\UpdatedModelTop_Points.shp** | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Oxford_FAS_BLINE_TR27** | **same as (** | **O:\63294 Oxford FAS\models\UPDATE JULY_AUGUST 2017\GVfiles** | **transient** | **24/08/2017** | **ijg** | **From Oxford_FAS_BLINE_TR26 with corrected layer elevations**<br>**bottom (adjusted for river head) from O:\63294 Oxford FAS\calculations\UPDATE JULY_AUGUST 2017\Base_drop_transient_calibration_model\NewBottom.csv**<br>**Top from O:\63294 Oxford FAS\GIS\UPDATE JULY_AUGUST 2017\Layers\Geology\Surfacing\Version3\UpdatedModelTop_Points.shp**<br><br>**intial heads from SS17** | |
| Oxford_FAS_EXISTING20yr_TR28 | same as ( | O:\63294 Oxford FAS\models\UPDATE JULY_AUGUST 2017\GVfiles | transient (1st SP stead | 01/11/2017 | ijg | 1 in 20yr without FAS channel - copied from Oxford_FAS_EXISTING20yr_TR20.gwv<br><br>Edits to:<br>model top and bottom (same as SS17/TR27 + bott adjustments for river WL)<br>recharge and K S&G (same as SS17/TR27)<br>river levels | |
| Oxford_FAS_FLOODCHANNEL20yr_TR29 | same as ( | O:\63294 Oxford FAS\models\UPDATE JULY_AUGUST 2017\GVfiles | transient (1st SP stead | 01/11/2017 | ijg | 2 in 20yr with FAS channel - copied from Oxford_FAS_FLOODCHANNEL20yr_TR17.gwv<br><br>Edits to:<br>model top and bottom (same as SS17/TR27 + bott adjustments for river WL)<br>recharge and K S&G (same as SS17/TR27)<br>river levels<br>K under lined river cells | |
| Oxford_FAS_EXISTING_DRY_TR30 | same as ( | O:\63294 Oxford FAS\models\UPDATE JULY_AUGUST 2017\GVfiles | transient (1st SP stead | 01/11/2017 | ijg | Q95 dry year without FAS channel - copied from Oxford_FAS_BLINE_DROUGHT_TR25.gwv<br><br>Edits to:<br>SP (added one as steady state at beginning)<br>model top and bottom (same as SS17/TR27 + bott adjustments for river WL)<br>recharge and K S&G (same as SS17/TR27)<br>river levels | QA sheets:<br><br>"O:\63294 Oxford FAS\calculations\Calc record and QA\63294_Oxford_OCT2017_BLINE FAS MODEL_V2.docx"<br><br>"O:\63294 Oxford FAS\calculations\Calc record and QA\63294_Oxford_JULY 2017_NUMERICAL MODEL.docx" |
| Oxford_FAS_FLOODCHANNEL_DRY_TR31 | same as ( | O:\63294 Oxford FAS\models\UPDATE JULY_AUGUST 2017\GVfiles | transient (1st SP stead | 01/11/2017 | ijg | Q95 dry yearwith FAS channel - copied from Oxford_FAS_FLOOCCHANNEL_DROUGHT_TR24.gwv<br><br>Edits to:<br>SP (added one as steady state at beginning)<br>model top (same as SS17/TR27) and bottom (same as SS17/TR27 + adjustments for river WL)<br>recharge and K S&G (same as SS17/TR27)<br>river levels<br>K under lined river cells | |
| Oxford_FAS_FLOODCHANNEL_DRY__BulstakeHinksey_TR32 | same as ( | O:\63294 Oxford FAS\models\UPDATE JULY_AUGUST 2017\GVfiles | transient (1st SP stead | 01/12/2017 | ijg | Copied from Oxford_FAS_FLOODCHANNEL_DRY_TR31.gwv river levels in Bulstake and Hinksey adjusted manually as requested by CH2M (following issue of report R2D1) | |
| Oxford_FAS_EXISTING_DRY_CorrectionsFeb2018_TR33 | same as ( | O:\63294 Oxford FAS\models\UPDATE JULY_AUGUST 2017\GVfiles | transient (1st SP stead | 05/02/2018 | ijg | Copied from Oxford_FAS_FLOODCHANNEL_DRY_TR31.gwv river levels adjusted manually as requested by Chris Weeks on email from 30/01/2018 (following issue of report R2D1) | |
| Oxford_FAS_FLOODCHANNEL_DRY_CorrectionsFeb2018_TR34 | same as ( | O:\63294 Oxford FAS\models\UPDATE JULY_AUGUST 2017\GVfiles | transient (1st SP stead | 05/02/2018 | ijg | Copied from Oxford_FAS_EXISTING_DRY_TR30.gwv river levels adjusted manually as requested by Chris Weeks on email from 30/01/2018 (following issue of report R2D1) | |

# APPENDIX B

## Technical Note: Investigation of Apparent Groundwater Level Anomaly

# Technical Note:

## Oxford FAS Groundwater Model: Investigation of Apparent Groundwater Level Anomaly

Published by ESI Limited
February 2018

Document reference:
*63294 TN02*

Report status:
*Final*



CONFIDENTIAL

t. 01743 276 100
e. info@esi-consulting.co.uk | www.esi-consulting.co.uk
@ESI_consulting

ESI Ltd., New Zealand House, 160-162 Abbey Foregate, Shrewsbury, Shropshire SY2 6FD

**Shrewsbury** 01743 276 100
**Reading** 01189 572 915
**Cardiff** 02920 660 144

ESI Limited is registered in England and Wales with Company No. 3212832 at New Zealand House, 160 Abbey Foregate, Shrewsbury, SY2 6FD

# Prepared for CH2MHill (Jacobs)

Document reference: 63294 TN02, February 2018



| | **Name** | **Signature** |
|---|---|---|
| Author | Samuel Bishop<br>Isabelle Girardin | |
| Checked by | Barnaby Harding | |
| Reviewed by | Barnaby Harding | |

# Summary

This Technical Note relates to a numerical groundwater model built by ESI (2016, 2017) to represent the superficial sand/gravel aquifer beneath the floodplain of the River Thames near Oxford. The model was built to simulate the likely effects of the proposed Oxford Flood Alleviation Scheme (FAS) on groundwater flood risk and on several areas of ecologically-important grassland habitat.

This document addresses a query raised by a peer reviewer regarding an apparent anomaly in simulated groundwater level. It is not a standalone report and should be read in conjunction with the ESI reports that describe the model in detail (ESI 2016, 2017).

# Contents

# 1 Introduction

A Flood Alleviation Scheme (FAS) is proposed for Oxford 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 in MODFLOW 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 aquifer beneath the floodplain of the River Thames and its tributaries. River levels derived from a separate fluvial model (Flood Modeller Pro, formerly ISIS) are used as boundary conditions for the groundwater model.

The focus of the 2015/16 modelling was on predicting the likely impact of the FAS on groundwater flood risk and on dry year groundwater levels beneath areas of ecologically-important grassland habitat (Oxford Meadows and Iffley Meadows). The model was updated by ESI (2017) to reflect new ground investigation data and also changes to the FAS design. The update included consideration of effects on groundwater levels beneath an additional area of MG4 grassland (Hinksey Meadow).

ESI's (2017) predictive simulation of a 1 in 20 year flood suggested that the FAS might lead to a small (up to 0.2 m) rise in peak groundwater levels in an area between North and South Hinksey, close to the edge of the sand/gravel aquifer (Figure A.1). This result was identified by a peer reviewer (AECOM) as potentially anomalous and requiring further investigation and explanation. This Technical Note has been prepared to address the issue. It is not a stand-alone report and should be read in conjunction with ESI (2016) and ESI (2017).

# 2 Investigation of Apparent Anomaly

## 2.1 Description of the apparent anomaly

Figure A.1 is a reproduction of Figure 5.3 in ESI (2017), with the apparent groundwater level anomaly highlighted. The left-hand and middle panes of Figure A.1 show coloured contours of maximum groundwater head for the 1 in 20 year flood scenario (left = existing situation, middle = situation with FAS in place). It should be emphasised that the contours do not relate to a single instant in time but take the maximum value observed throughout the model run period at each particular location. The right-hand panel of Figure A.1 shows the difference in maximum groundwater head between the existing, and “with FAS”, scenarios.

In the existing situation, the area of the apparent anomaly is a local minimum within the surface defined by the groundwater head maxima (left-hand panel in Figure A.1). When the FAS channel is added to the model this local minimum disappears (middle panel in Figure A.1). The apparent anomaly is also seen in the difference between the existing and “with FAS” scenarios (right-hand panel in Figure A.1): as the difference is plotted as “with minus without” the apparent anomaly is positive, representing a slightly higher maximum groundwater head with the FAS in place. In a sense, the local minimum present in the existing situation is “infilled” when the scheme is in place.

## 2.2 Approach

Within the sand/gravel aquifer represented by the model there is a strong connection between river levels and groundwater (ESI, 2016). During a flood event, river levels rise and this causes a rise in groundwater heads within the connected aquifer. It was suspected that the apparent anomaly might be related to the transient (time-varying) propagation of a head increase away from the nearby river channel. To test this hypothesis the 1 in 20 year flood model outputs were interrogated to produce the following:

- Groundwater contour plots for a series of time slices before, during and following the fluvial flood peak.
- Groundwater level hydrographs for selected model cells within the area of the apparent anomaly and also within a similar area to the south east (selected for the purposes of comparison).

In each case the results were extracted for the existing (baseline) and “with scheme” (FAS) scenarios.

The rate of propagation of a head change through an aquifer is determined by the hydraulic diffusivity, D (Freeze and Cherry, 1979):

$$D = \frac{T}{S} = \frac{K.b}{S_s.b}$$ **Equation 1**

where:

T = transmissivity [$m^2/d$];

S = storativity or storage coefficient [dimensionless];

K = hydraulic conductivity [m/d];

$S_s$ = specific storage [1/m]; and

b = saturated thickness [m].

With lengths in metres and time in days, D has units of $m^2/d$.

The larger the value of D, the more rapidly a head change will propagate through the aquifer. Although K, S and $S_s$ do not vary across the model (except in lakes – see ESI, 2016), the saturated thickness b does vary; this means that T varies, potentially giving rise to differences in the propagation rate of head changes. For this reason, spatial variations in T were examined to see if they might explain the apparent anomaly.

The bed conductance, C, of the MODFLOW River cells determines the degree of hydraulic connectivity between the rivers and the aquifer and is given by (McDonald and Harbaugh, 1988):

$$C = \frac{K_v.W.L}{b'}$$ **Equation 2**

where:

$K_v$ = vertical hydraulic conductivity of river bed sediment [m/d];

b′ = thickness of river bed sediment [m];

W = width of channel [m]; and

L = length of channel crossing model cell [m].

With lengths in metres and time in days, C has units of $m^2/d$.

The greater the value of C, the greater the connectivity between the river and the aquifer. Within the model, all the rivers have the same values for $K_v$ and b′. Nevertheless, C varies because of variation in the contact area (W x L) between the rivers and aquifer. However, for a given river reach (such as that closest to the area of the anomaly) the channel dimensions vary little; for this reason variations in C are unlikely to give rise to significant differences in the rate of propagation of a head change away from such a reach. C was therefore not examined in detail as part of this assessment.

## 2.3 Results

Graphical model outputs are provided in Appendix A. Figure A.2 shows groundwater head contours for five time slices. Figure A.3 shows groundwater level (head) hydrographs for selected model cells, both within the area of the anomaly and within an area immediately to the south east. Note that the river flood peak (as approximated by the cells immediately adjacent to rivers) is about 150 hours into the simulation ("location A" in Figure A.3 is in a river cell). Figures A.3a and A.3b make a clearer comparison between groundwater level hydrographs for model cells at different distances from rivers.

## 2.4 Discussion

The time slices presented in Figure A.2 show that in the area of the apparent anomaly a local minimum (in head) exists at certain times, and is not merely (as "apparently" portrayed in Figure A.1) a composite phenomenon created as a result of plotting asynchronous cell-by-cell maxima together. The minimum is absent at the start of the simulation period, only appearing as groundwater heads rise towards the flood peak (it has appeared by time = 57 hours and is still present at the fluvial flood peak, time = 150 hours). By the time 237 hours have elapsed (by which time the river has been in recession for around 87 hours), the local minimum has disappeared. The time slices show a lag in head propagation from the river toward the centre of the anomaly with the levels in this area finally catching up and equalising with receding levels nearer the river. A similar pattern occurs under both existing (baseline) and "with scheme" conditions. It is notable that there is a second local minimum immediately to the south east of the apparent anomaly under investigation.

Comparison of the the red (with scheme) and blue (without scheme) lines on the hydrographs on Figure A.3 shows that the effect of the FAS is to lower peak groundwater levels immediately adjacent to the existing Hinksey Stream (locations A and I). In the area of the apparent anomaly, comparison of the with and without scheme scenarios shows that the presence of the scheme has the effect of slightly increasing peak groundwater heads and reducing the lag time (by about 70 hours) between peak river level (i.e. at 150 hours into the simulation) and peak groundwater head. In the area of the second local minimum to the south east there is a similar effect but the reduction in lag time is less pronounced.

In Figures A.3a and A.3b the hydrographs of Figure A.3 are plotted together in such a way as to make it easy to compare the changes in head at different distances from the rivers. At the start of the existing/baseline simulation, the monitoring locations in the area of the anomaly (upper plot in Figure A.3a) all have similar heads. As the fluvial flood progresses, the groundwater hydrographs diverge. In general, those model cells closest to rivers respond (rise) quickest, and those farther away lag behind, giving a concave-upward curve. Location E is unusual in that it responds more quickly than C and D. At about time = 237 hours the hydrographs converge on a head of 55.9 mAOD. From this time onwards (which is some 87 hours after the fluvial flood peak) there is a recession of groundwater heads, and all the monitoring points track together.

The presence of strong lag effects during the period of rising groundwater heads reflects the gradual filling of unconfined storage in response to a sudden increase in river level. Once the unconfined storage has been filled (as it has by time = 237 hours), further rises in head lead to confined conditions under which the aquifer responds more rapidly, and more uniformly, to changes in river level. After the flood peak, river levels fall gradually, and heads in the confined aquifer track them fairly closely. In other words, the marked asymmetry in the rising and falling limbs of the groundwater hydrographs reflects the difference in the volume of storage that must be filled (or emptied) in order to transmit the head change imposed by the river boundary. In the unconfined case, S is replaced in Equation 1 by the specific yield, $S_y$, which is several orders of magnitude greater than the confined storage coefficient; D is therefore reduced and the flood pulse progresses more slowly through the aquifer.

In the FAS scenario (lower plot in Figure A.3a) the overall pattern is similar to the baseline, but the hydrographs converge on a slightly higher head (about 56.0 mAOD), and the lag is less, happening at time = 174 hours. Also, location F now tracks river level changes much more closely, reflecting its location on the edge of the new flood channel.

Figure A.3b shows that in the area to the south east of the apparent anomaly the groundwater heads at locations close to the river respond more rapidly to the fluvial flood than those at more distant locations. As distance from the river decreases, the groundwater peak is later in time and has lower amplitude. Here the effect of the FAS is to lower peak groundwater levels and to make the peak occur earlier in time.

In the existing/baseline scenario, groundwater heads in the area of the apparent anomaly lag behind the fluvial flood peak to a greater degree than do the groundwater heads in the area to the south east. The result is that peak heads in the area to the south east are closer to the river peak than those in the area of the apparent anomaly are. This is consistent with Figure A.1.

The effect of the FAS is to slightly change peak groundwater heads - raising them in the area of the apparent anomaly and lowering them in the area to the south east - and to bring the peak forward in time, reducing the lag between fluvial flood peak and peak groundwater level. The increase in maximum groundwater levels in the area of the apparent anomaly, and the decrease in maximum groundwater levels in the south eastern area, are apparent in Figure A.1 (right-hand panel).

Location E behaves unusually in that it responds more rapidly to rising river levels than parts of the aquifer that are closer to the river. Such behaviour could potentially reflect aquifer heterogeneity, with a relatively transmissive pathway providing a link between location E and the river. However, a map of model transmissivity (Figure A.4) suggests that this is not the case. It may be that the unusual behaviour of E relates to its proximity to the no-flow boundary and to "focussing" of the fluvial flood pulse. To the north west of location E the river diverges away from the no-flow boundary, and it may be that this geometry is somehow influencing the pattern of propagation of the flood pulse through the aquifer.

One question that the observations above raise is why the response lag in the area of the apparent anomaly is greater than that seen in the south eastern area. This may potentially reflect one or more of the following:

- A greater distance for the flood pulse to propagate in the case of the apparent anomaly.
- A lower transmissivity (T) in the area of the apparent anomaly, reducing the rate of propagation of the fluvial flood pulse through the aquifer.
- A greater volume of storage to fill in the area of the apparent anomaly.

These are discussed in turn below.

Figure A.2 shows that two transient groundwater level minima develop along the western edge of the aquifer: one within the area of the apparent anomaly and a smaller one further to the south east (although this latter "low" is less evident in Figure A.1). These minima represent parts of the aquifer in which heads are not rising, or not rising as quickly, as those in adjacent areas. In each case the minimum occurs in an area where there is a local increase in distance from the river to the aquifer edge. The increase in distance associated with the area of the apparent anomaly is greater than that associated with the area further to the south east.

Figure A.4 shows that the river channel immediately north of the anomaly is associated with relatively low aquifer T values (approximately 440 to 530 $m^2$/d, compared to values in the range of 790 to 940 $m^2$/d further downstream). This may help explain why the area of the apparent anomaly lags behind the area to the south east in terms of its response to the fluvial flood pulse.

Another explanation for the greater lag in response time in the area of the anomaly is that there may be a greater volume of (unconfined) storage to fill in order to transmit the rise in head from the river through the aquifer (Figure A.5). It is notable that the anomaly corresponds to an area of mapped sand/gravel outcrop in which the aquifer is likely to be unconfined (in the calibrated steady-state model of ESI, 2017, simulated heads are such that a portion of this area is represented as unconfined).

When considering the significance of the apparent anomaly, it is important to bear in mind both the small magnitude of groundwater level rise at the apparent anomaly location (an increase in maximum head of about 0.2 m) and the spatial distribution of depth to groundwater (Figure A.6). The overall pattern of potential groundwater emergence (areas with groundwater head above ground level, shown in blue in the left and middle panels of Figure A.6) does not change significantly between existing/baseline and FAS scenarios (Figure A.6). In those parts of the apparent anomaly area that might be considered most vulnerable to flooding, i.e. the A34 road and nearby buildings, the simulated peak groundwater head is below ground level, even with the FAS in place. In the south western part of the apparent anomaly area, along the A34, the depth to peak groundwater is three to five metres. Along the edge of the floodplain the depth to groundwater is lower and there is potential for local groundwater emergence; this is true both with and without the FAS, although the area of potential emergence is slightly larger with the scheme in place.

# 3 Conclusions

The analysis presented in this Technical Note suggests that the apparently anomalously low peak groundwater head simulated between North Hinksey and South Hinksey for a 1 in 20 year flood with the Oxford FAS in place is related to the difference in the speed of propagation of the flood pulse through the aquifer when comparing the with and without scheme scenarios.

Under existing/baseline conditions, the area of the apparent anomaly lags behind adjacent parts of the aquifer in terms of its response to the fluvial flood event. This creates a local minimum in peak groundwater heads. With the FAS scheme in place a new flood relief channel passes through the area of the apparent anomaly and raises maximum groundwater heads (as well as shortening the lag time between peak river level and peak groundwater level). In this way, what was originally a local minimum becomes an apparently anomalous rise in peak groundwater level. This rise is of a small magnitude (up to 0.2 m) and has only a small impact on the area of potential groundwater emergence simulated by the model.

In conclusion, the apparent anomaly can be explained as a realistic response in the aquifer to flood levels within the South Hinksey Stream and FAS channel.

# GLOSSARY

| | |
|---|---|
| DTM | Digital Elevation Model |
| FAS | Flood Alleviation Scheme |
| mAOD | Metres above Ordnance Datum |
| MODFLOW | MODular three-dimensional groundwater FLOW model |
| PAR | Project Appraisal Report |

# REFERENCES

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

**ESI, 2017.** Oxford Flood Alleviation Scheme: Groundwater Model Update. Draft report prepared for CH2M, ref. 63294 R2D1, November 2017.

**Freeze, R. A. and Cherry, J. A., 1979.** Groundwater. Prentice-Hall, Englewood Cliffs, NJ, 604pp.

**Fugro Engineering Services, 2014.** Oxford Relief Channel: Route Geology Volume Assessment. Desk Study Report. Report prepared for the Environment Agency, 7th July, 2014. Contract No. G140027U.

**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.

# APPENDICES

# Appendix A
## Figures

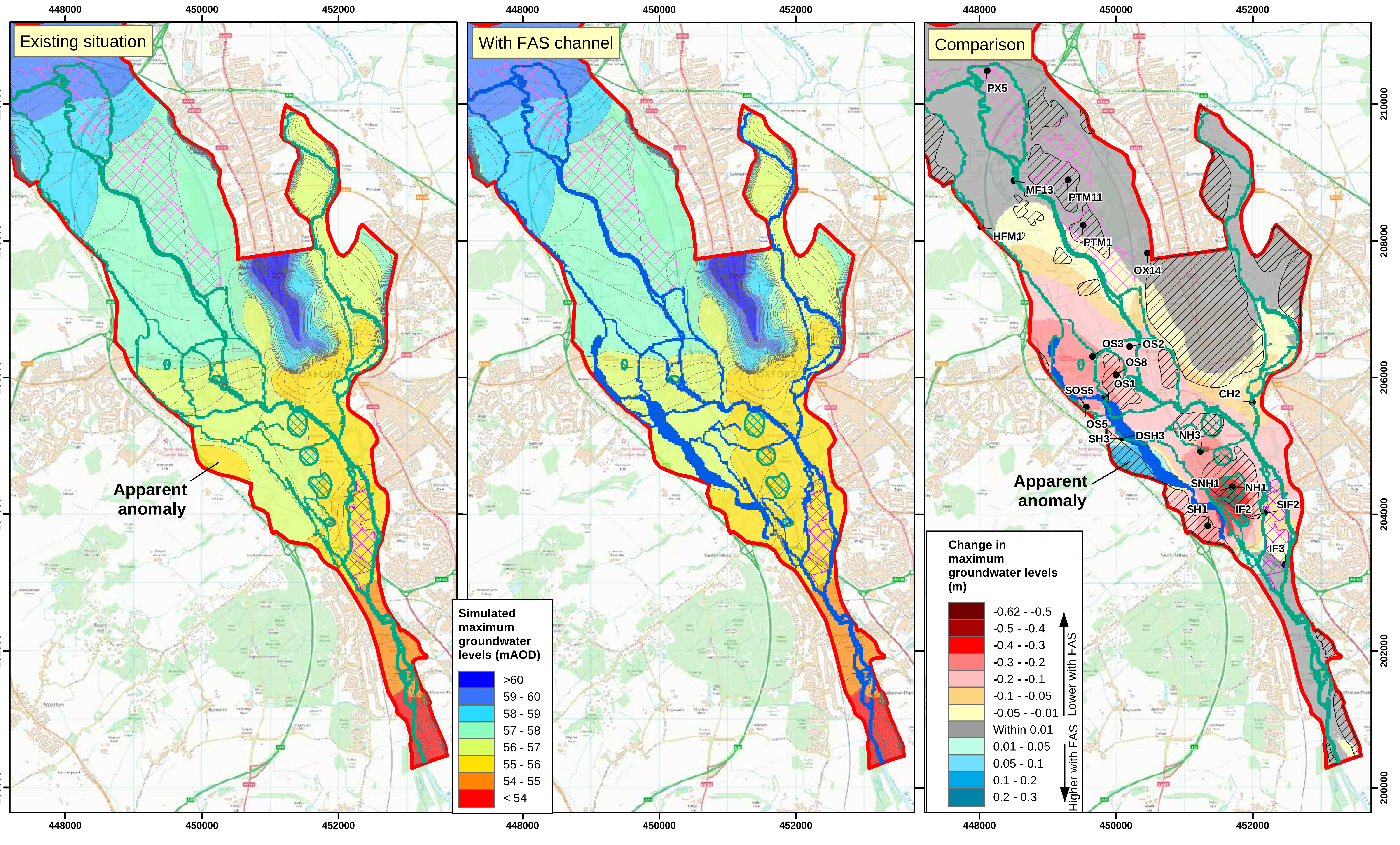



Figure A.1
1in 20 year flood scenario: maximum groundwater levels

Simulated groundwater contours
Simulated rivers
Simulated river and FAS channel
Lined FAS channel
MODFLOW model area
Historical groundwater flooding
Oxford Meadows SAC
Iffley Meadows SSSI

| | | | |
|---|---|---|---|
| Date | Jan 2018 | Drawn | IJG/SNB |
| Scale | 1:50,000 | Checked | SNB |
| Original | A3 | Revision | 1 |
| File Reference | O:\63294 Oxford FAS\GIS\UPDATE JULY_AUGUST 2017\Map documents\Figures for report\Fig A1_for Technical Note TN02 on | | |

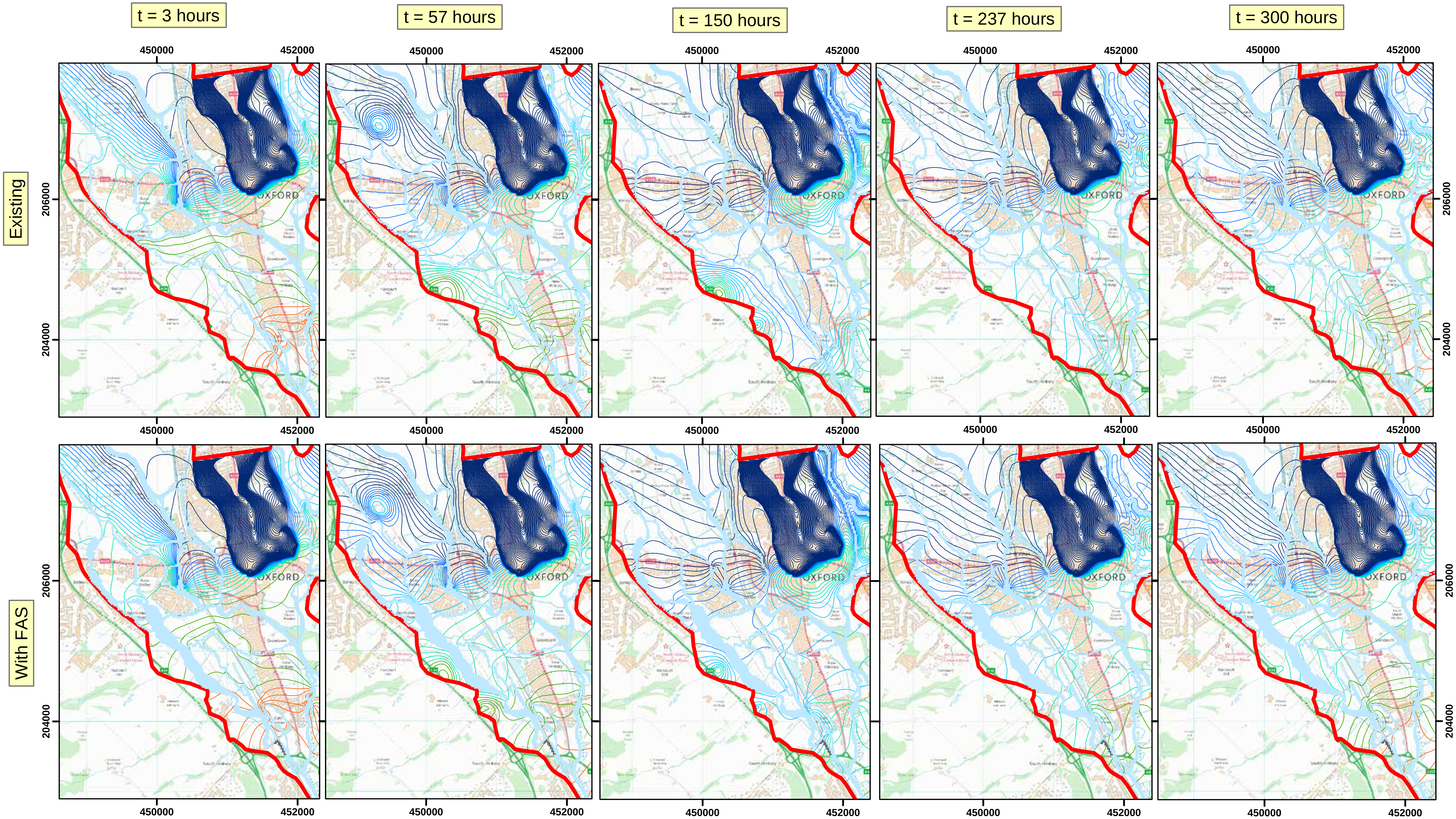



Figure A.2
1in 20 year flood scenario: simulated groundwater levels



MODFLOW model area
Simulated rivers

**Simulated GW contours (mAOD)**

- <53.5
- 53.5 - 54
- 54 - 54.5
- 54.5 - 55
- 55 - 55.5
- 55.5 - 56
- 56 - 56.5
- > 56.5

| | | | |
|---|---|---|---|
| Date | Jan 2018 | Drawn | IJG |
| Scale | 1:50,000 | Checked | SNB |
| Original | A3 | Revision | 1 |

File Reference
O:\63294 Oxford FAS\GIS\UPDATE JULY_AUGUST 2017\Map documents\Figures for report\Fig TN 1 in20 yr GWL contours.mxd

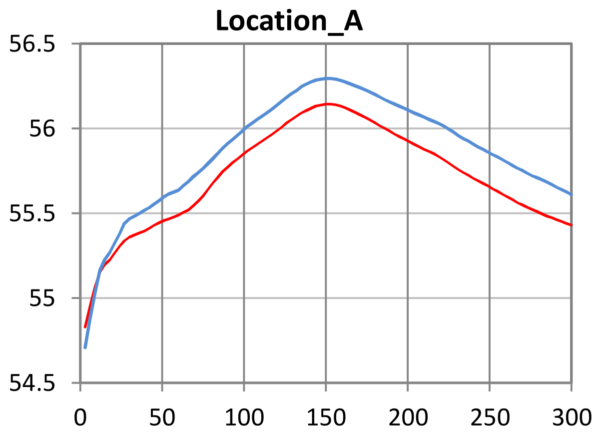
esi consulting

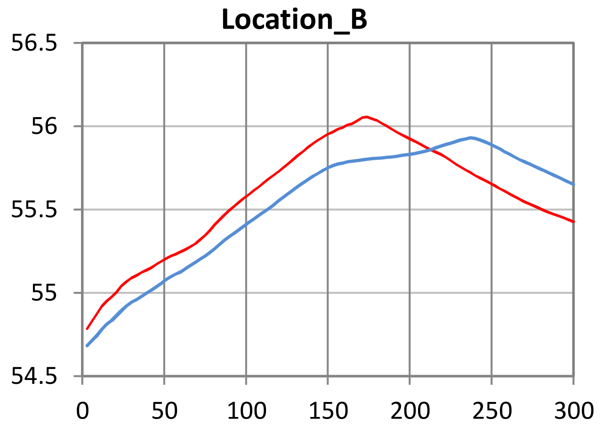
## Main area of interest, south of Bulstake Stream

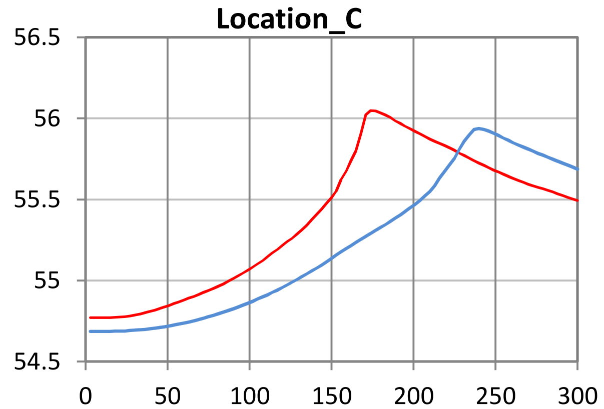
In the area of the anomaly (blue area on the location map), the model predicts that the FAS will generally increase the spatial <u>maximum</u> groundwater heads (note these are <u>not representative of a specific time</u> but give the maximum simulated head for each model cell).

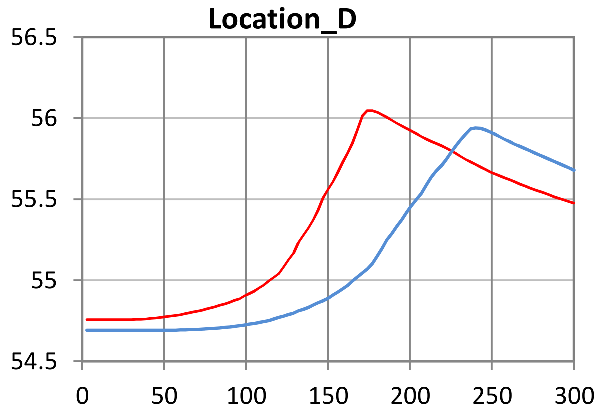
The time series show that in the model representing the baseline /existing situation (no FAS, blue lines on graphs), the peak groundwater heads are controlled by the propagation, from the rivers (dark brown on map), of the rise in head associated with the fluvial flood event.

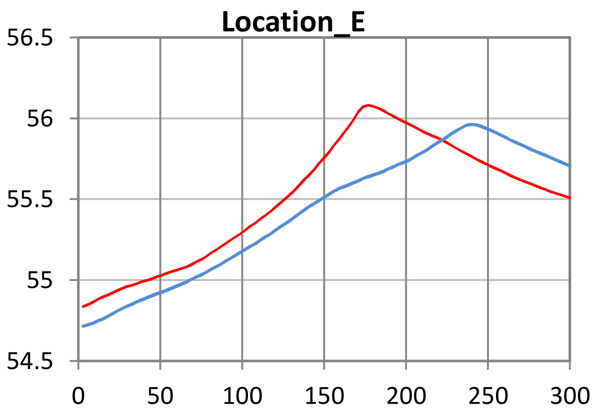
With the FAS in place (channels shown in light brown on map, groundwater levels plotted as red lines on graphs), the river levels at location A reduce and so do the groundwater heads. However, the FAS now flows from north west to south east through the "blue" area. Here the river levels of the FAS are higher than the baseline groundwater heads (location F) and their effect is to cause a rise in maximum groundwater head.

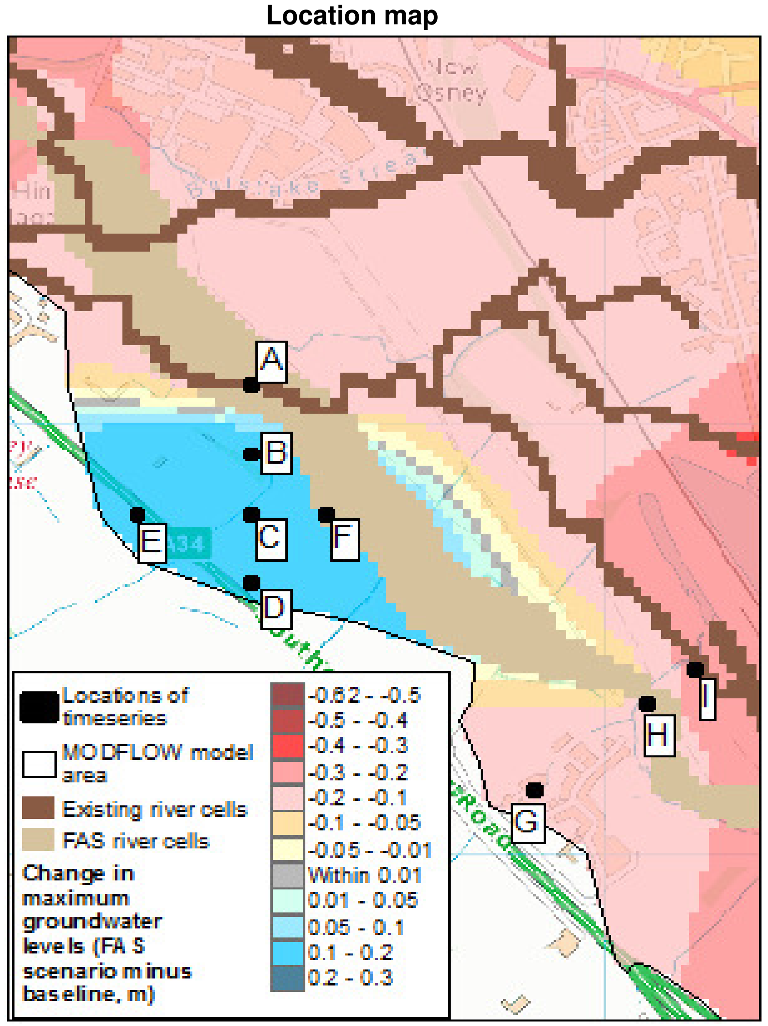


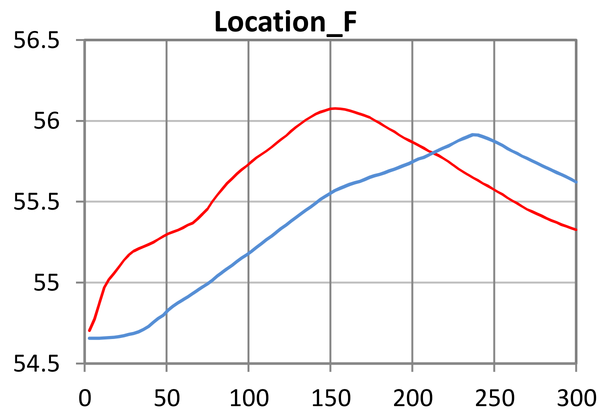



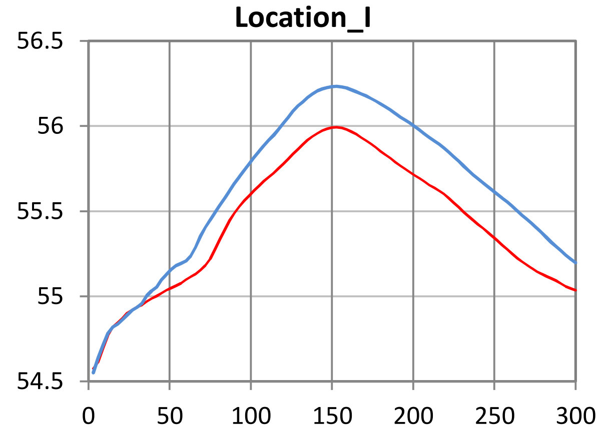



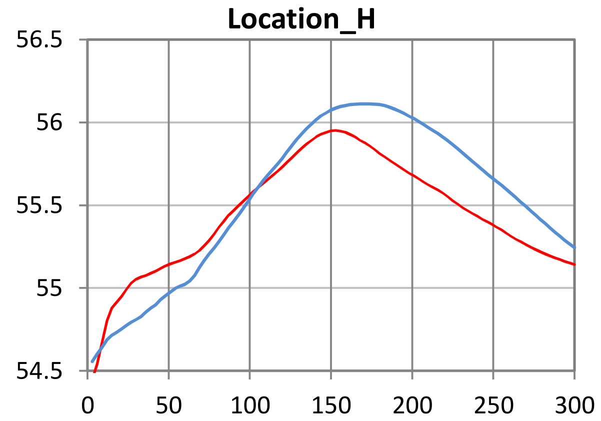


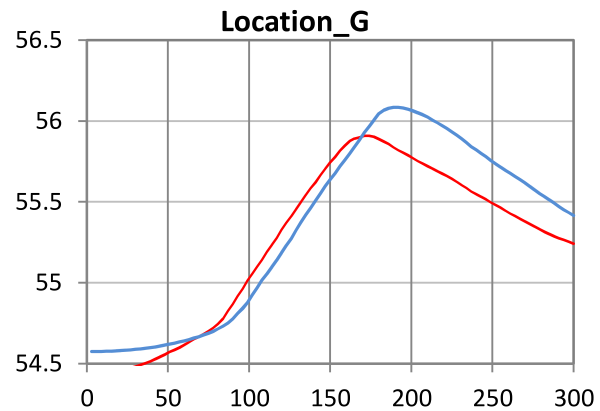




**Horizontal axis: time in hours**
**Vertical axis: simulated groundwater level in mAOD**

## Area north west of Cold Harbour



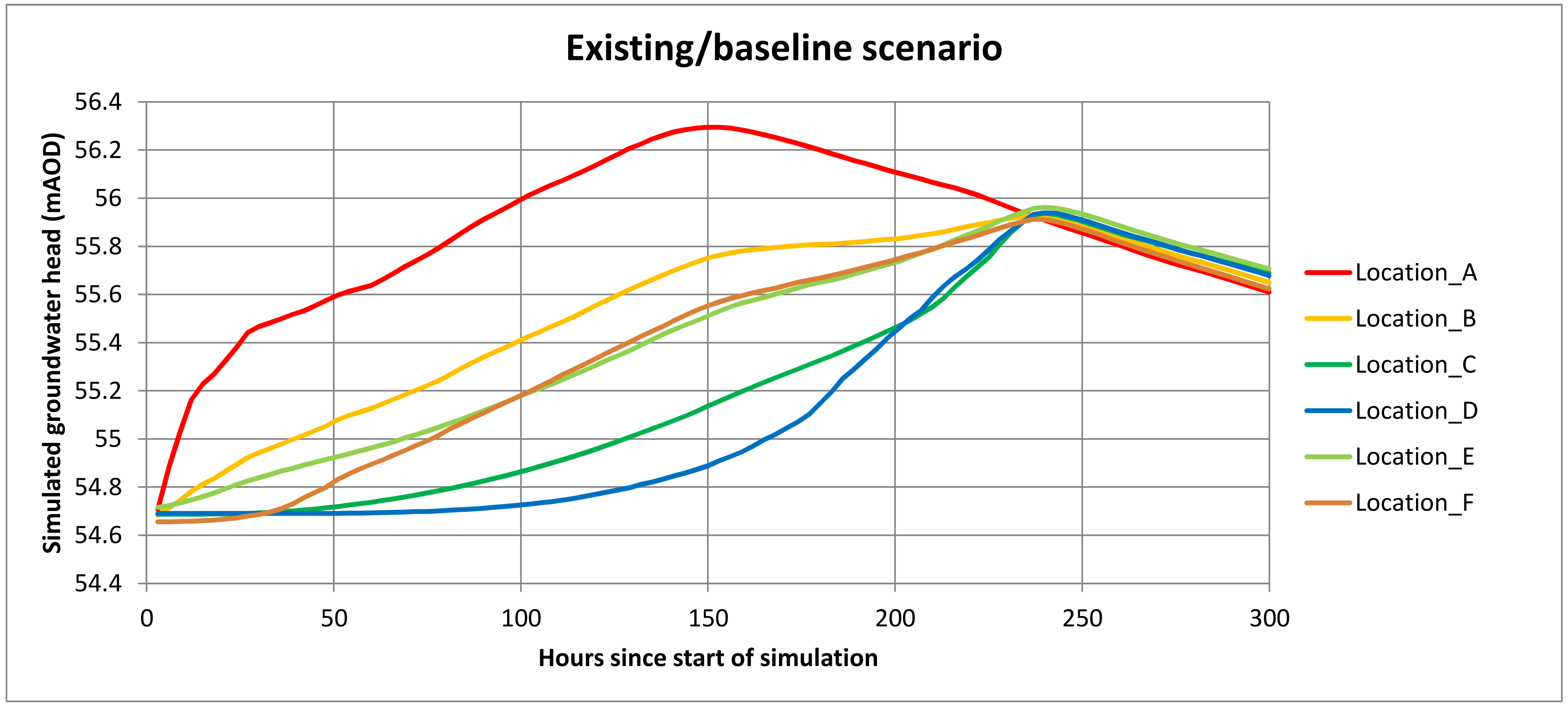

At location G, the FAS leads to a reduction in groundwater heads. This is propagated from the north east (e.g. location H) where the river levels of the FAS are lower than the existing groundwater heads, which are themselves controlled by the river levels at location I.

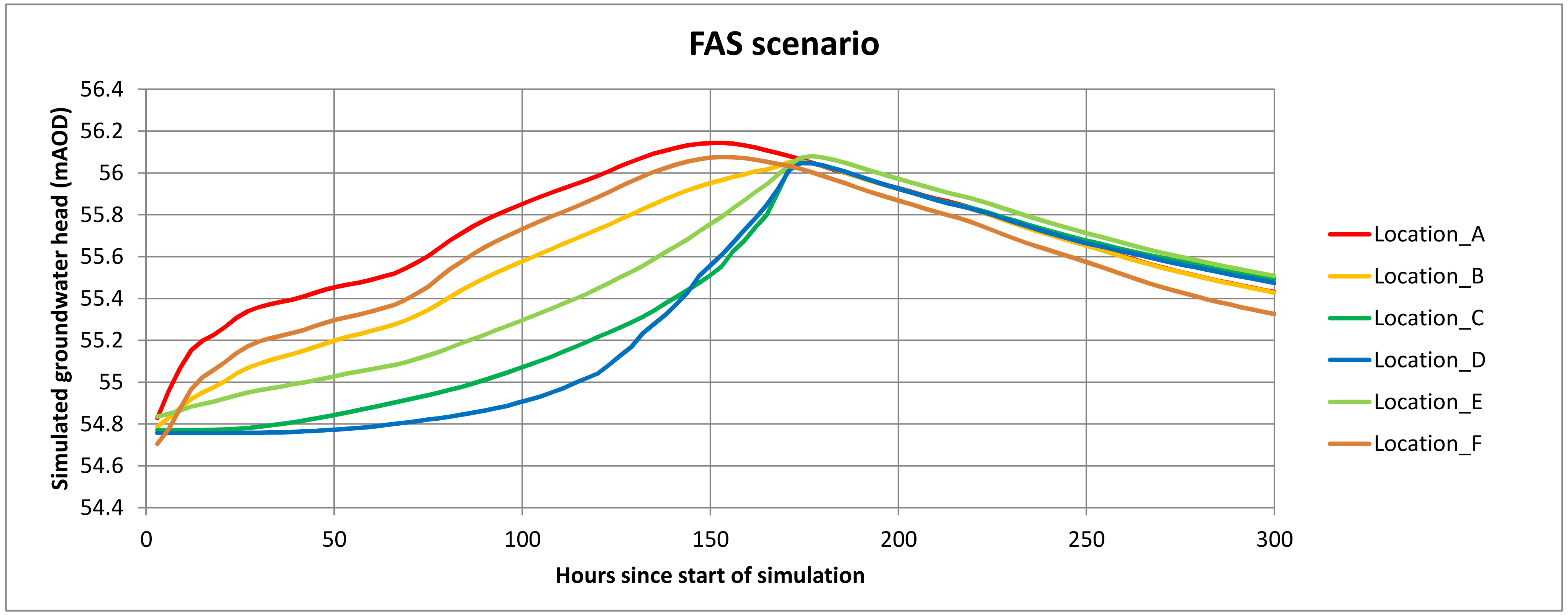
Figure A.3
Simulated groundwater level time series for 1 in 20 year flood event

Simulated, with scheme
Simulated, without scheme

| | |
|---|---|
| Date: Jan 18 | Drawn: IJG |
| Scale: dns | Checked: SNB |
| Original: A3 | Revision: 1 |
| File Reference: O:\63294 Oxford FAS\models\UPDATE JULY_AUGUST 2017\Post-processing\[Flood | |

Environment Specialists



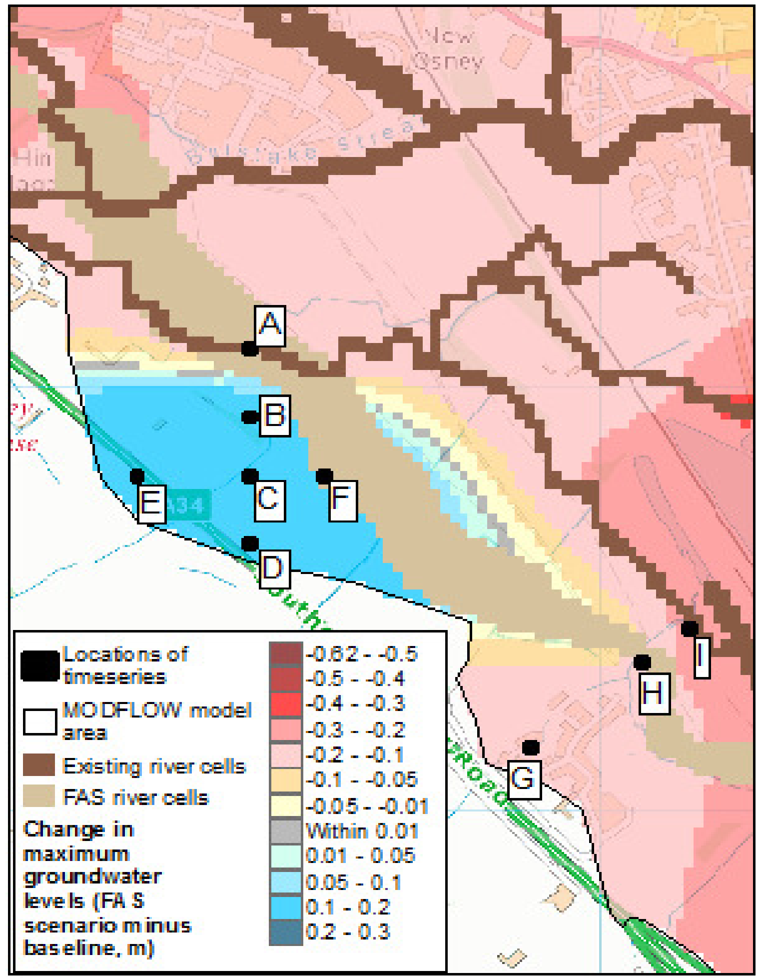
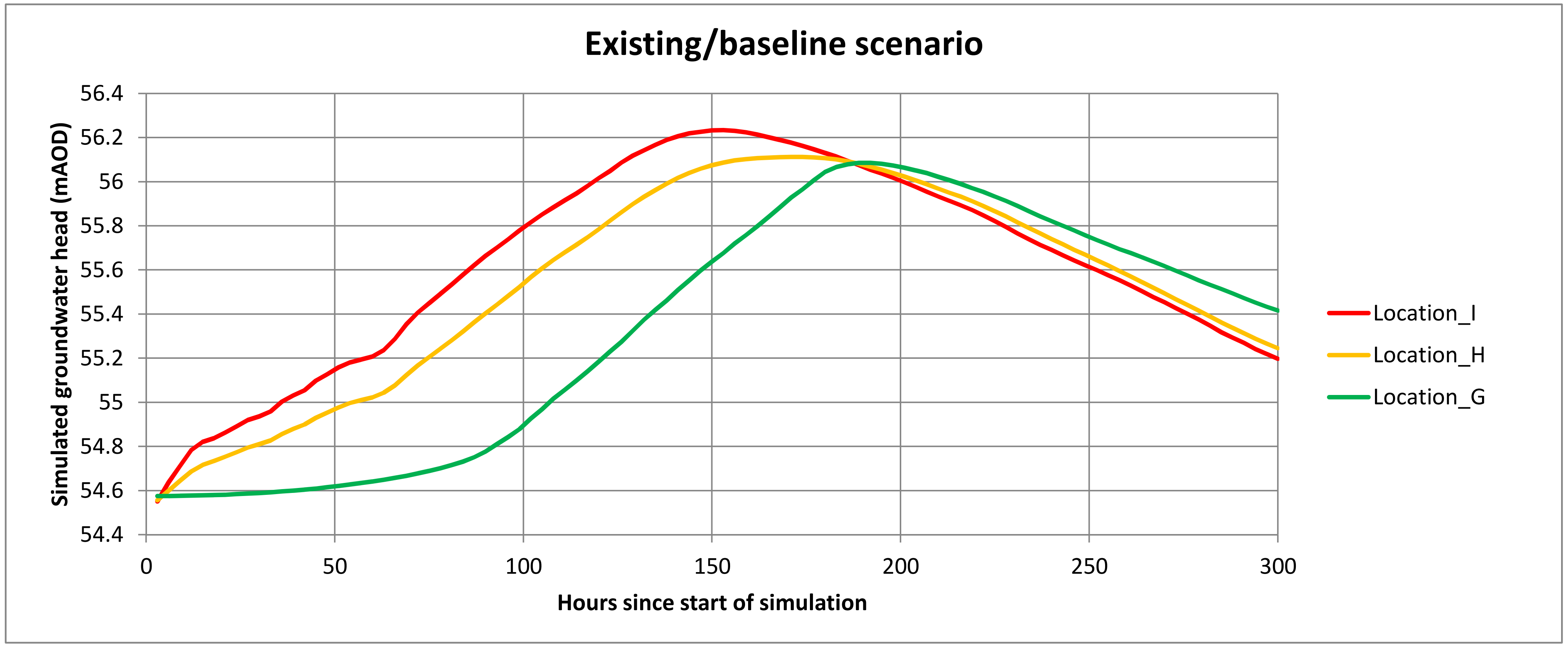



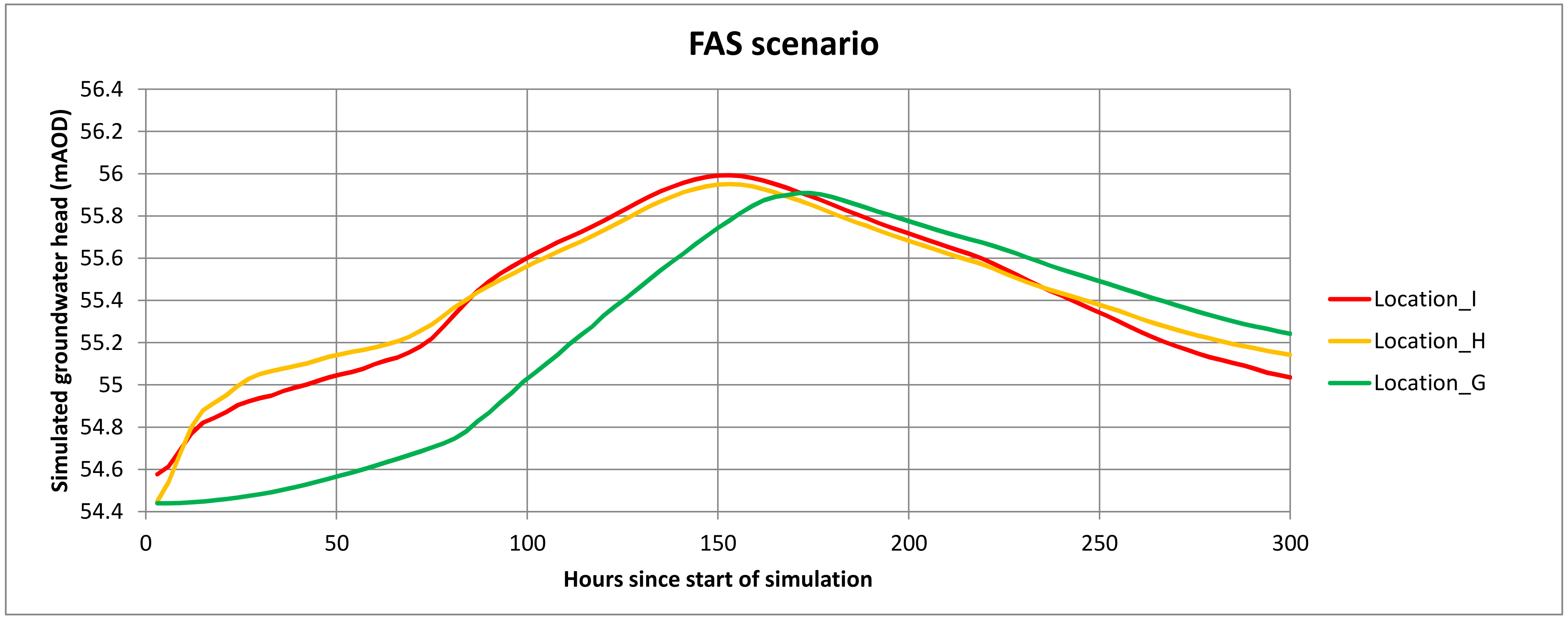



Figure A.3a
Simulated groundwater level time series for 1 in 20 year flood event: area of anomaly

| Date Jan 18 | Drawn SNB |
| --- | --- |
| Scale dns | Checked BCH |
| Original A3 | Revision 1 |
| File Reference O:\63294 Oxford FAS\models\UPDATE JULY_AUGUST 2017\Post-processing\(Flood | |

Environment Specialists



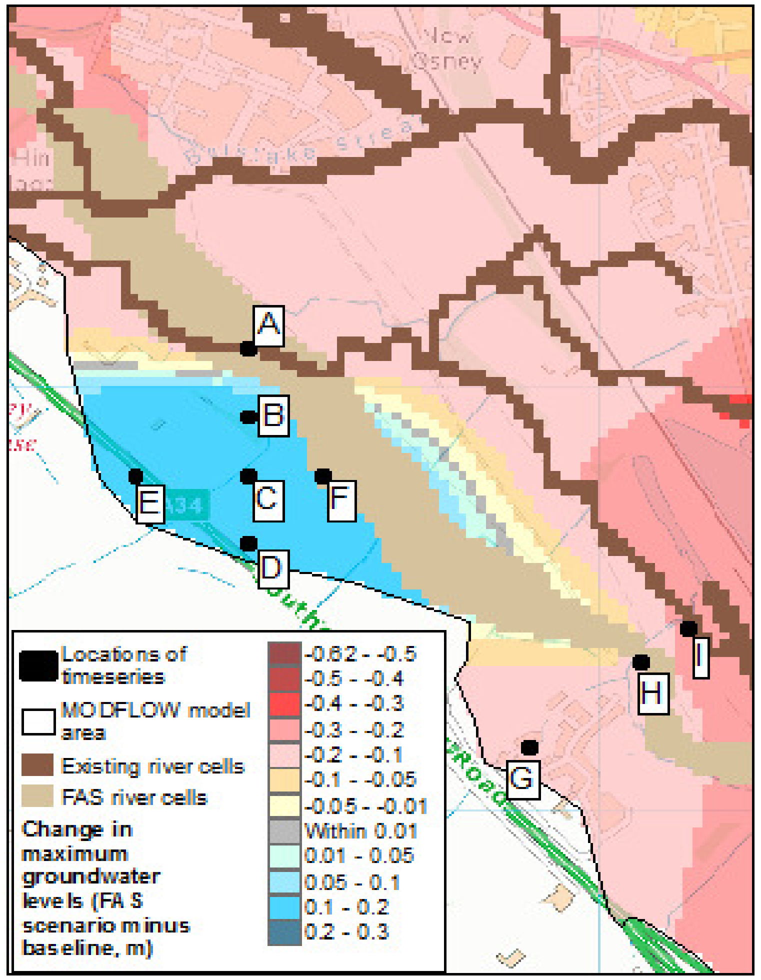






Figure A.3b

Simulated groundwater level time series for 1 in 20 year flood event: south eastern area

| | |
|---|---|
| Date: Jan 18 | Drawn: SNB |
| Scale: dns | Checked: BCH |
| Original: A3 | Revision: 1 |
| File Reference: O:\63294 Oxford FAS\models\UPDATE JULY_AUGUST 2017\Post-processing\(Flood | |

ESI Environment Specialists

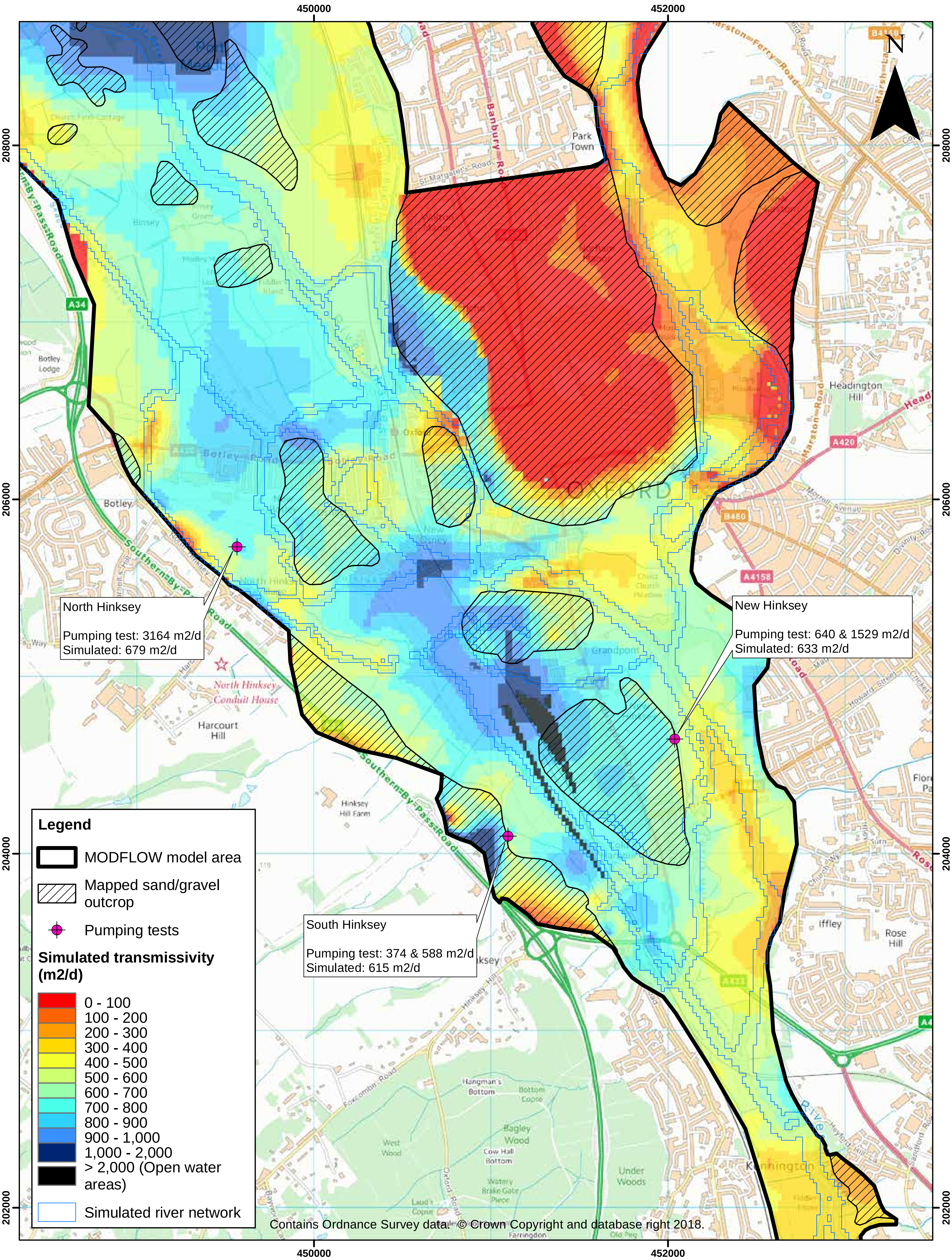
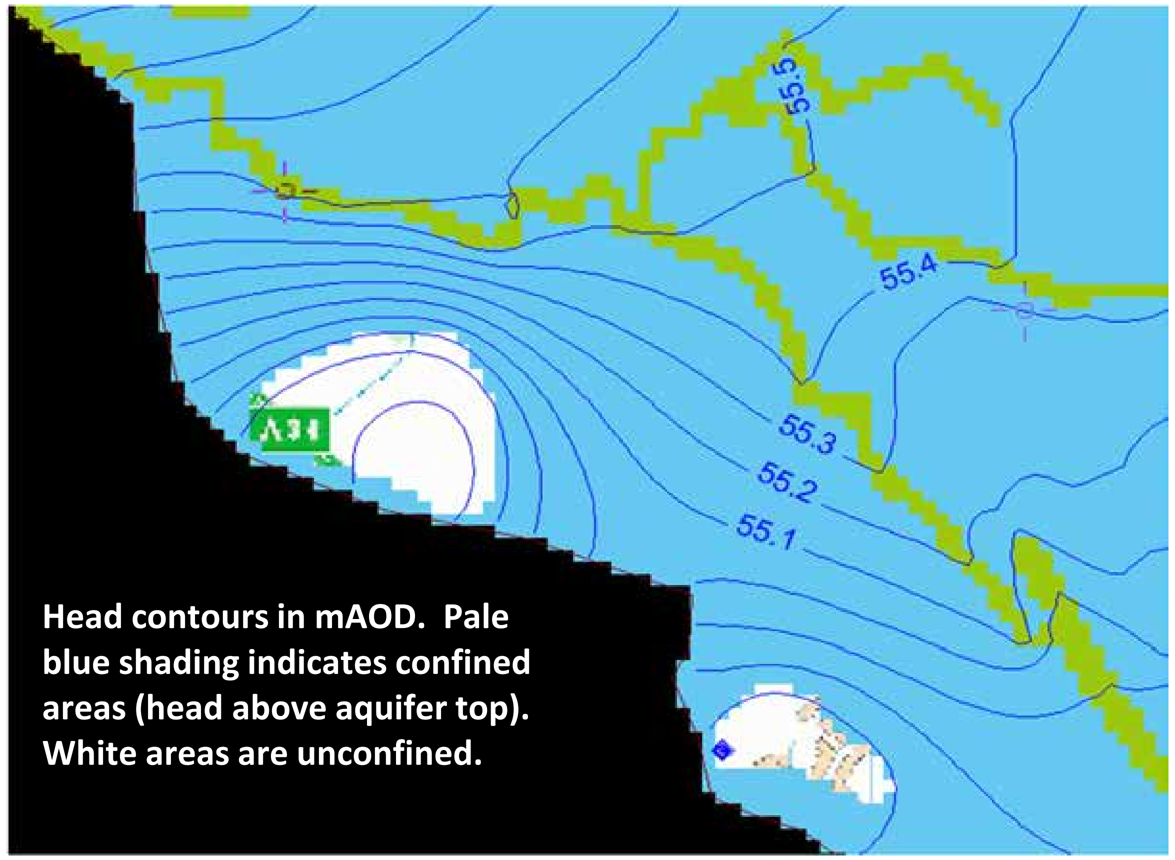



Figure A.4
Simulated transmissivity (from calibrated steady-state model)

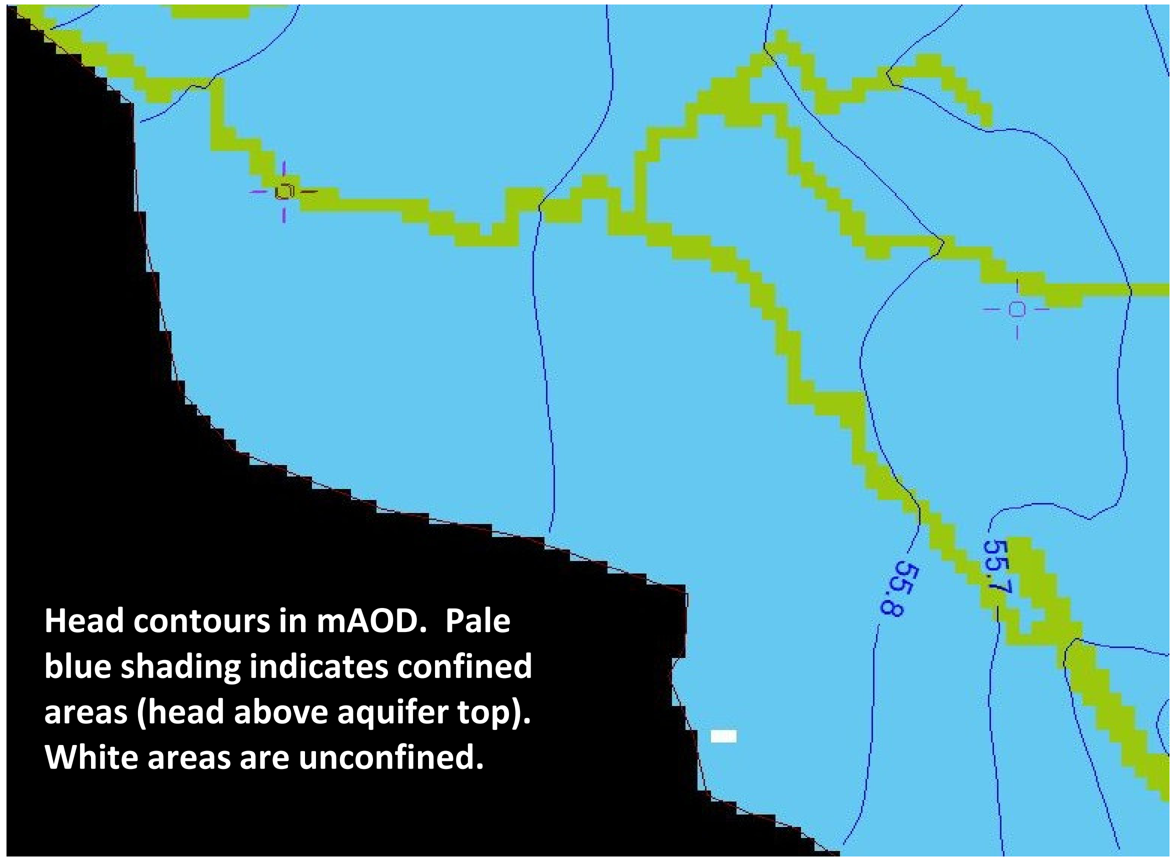
| | |
|---|---|
| Date Jan 2018 | Drawn IJG/SNB |
| Scale 1:20,000 | Checked SNB |
| Original A3 | Revision 1 |
| File Reference O:\63294 Oxford FAS\GIS\UPDATE JULY_AUGUST 2017\Map documents\Figures for report\Fig A4 for TN02 Transmissivity Steady | |

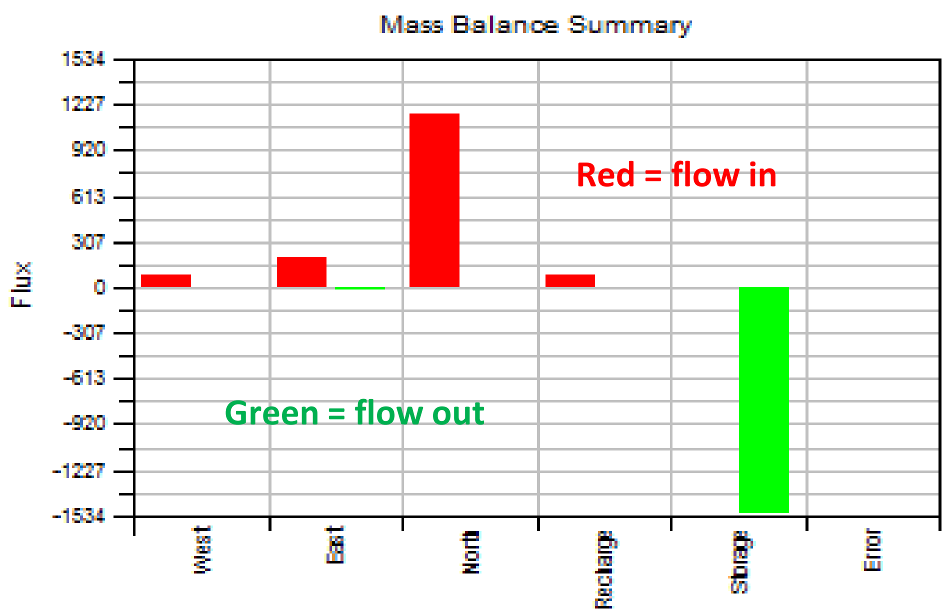
esi consulting

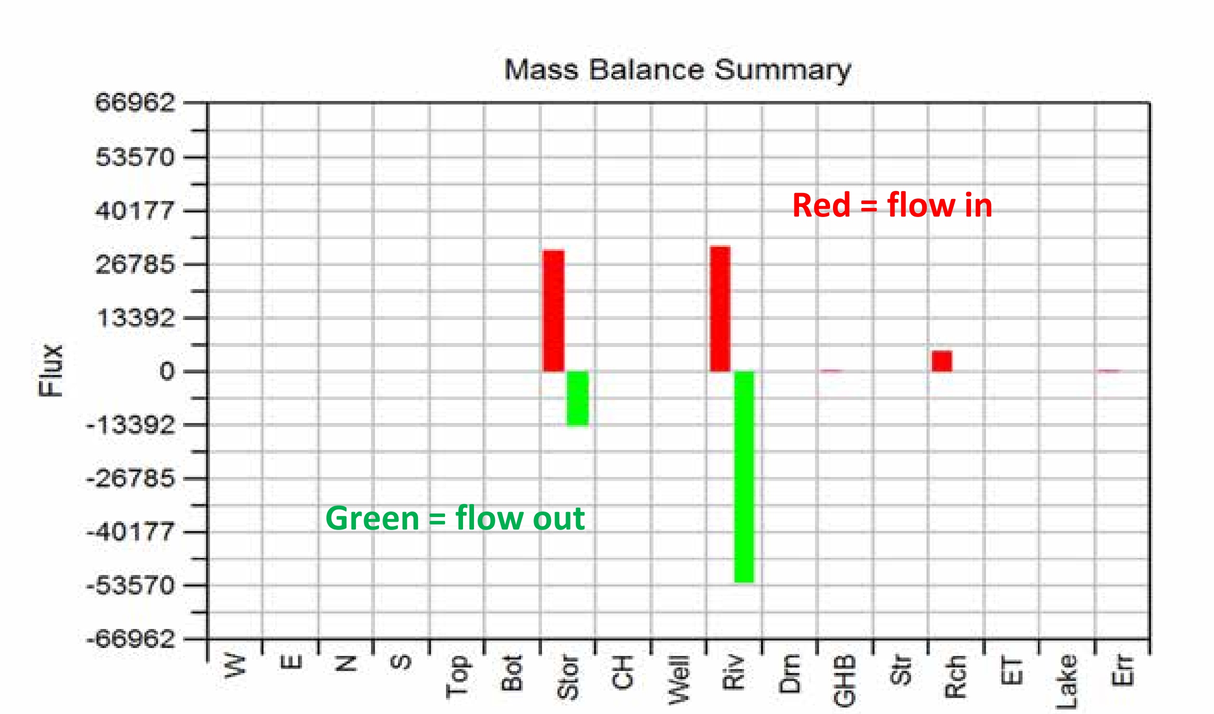
**Stress Period 18, time step 3: time = 51 hrs (rising limb of flood peak)**




**Stress Period 80, time step 3: time = 237 hrs**




**Fluxes are in m$^3$/d. The mass balances relate to a rectangular area slightly smaller than the plan view shown above (but including both the apparent anomaly and the area to the south east).**

Figure A.5

Filling of unconfined storage during 1 in 20 year flood event

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

| Date | Drawn |
| --- | --- |
| Jan 18 | SNB |
| Scale dns | Checked BCH |
| Original A3 | Revision 1 |

File Reference
O:\63294 Oxford FAS\Reports\63294 TN02D1_Investigation of GW level anomaly\Individual figures\f63294

Environment Specialists

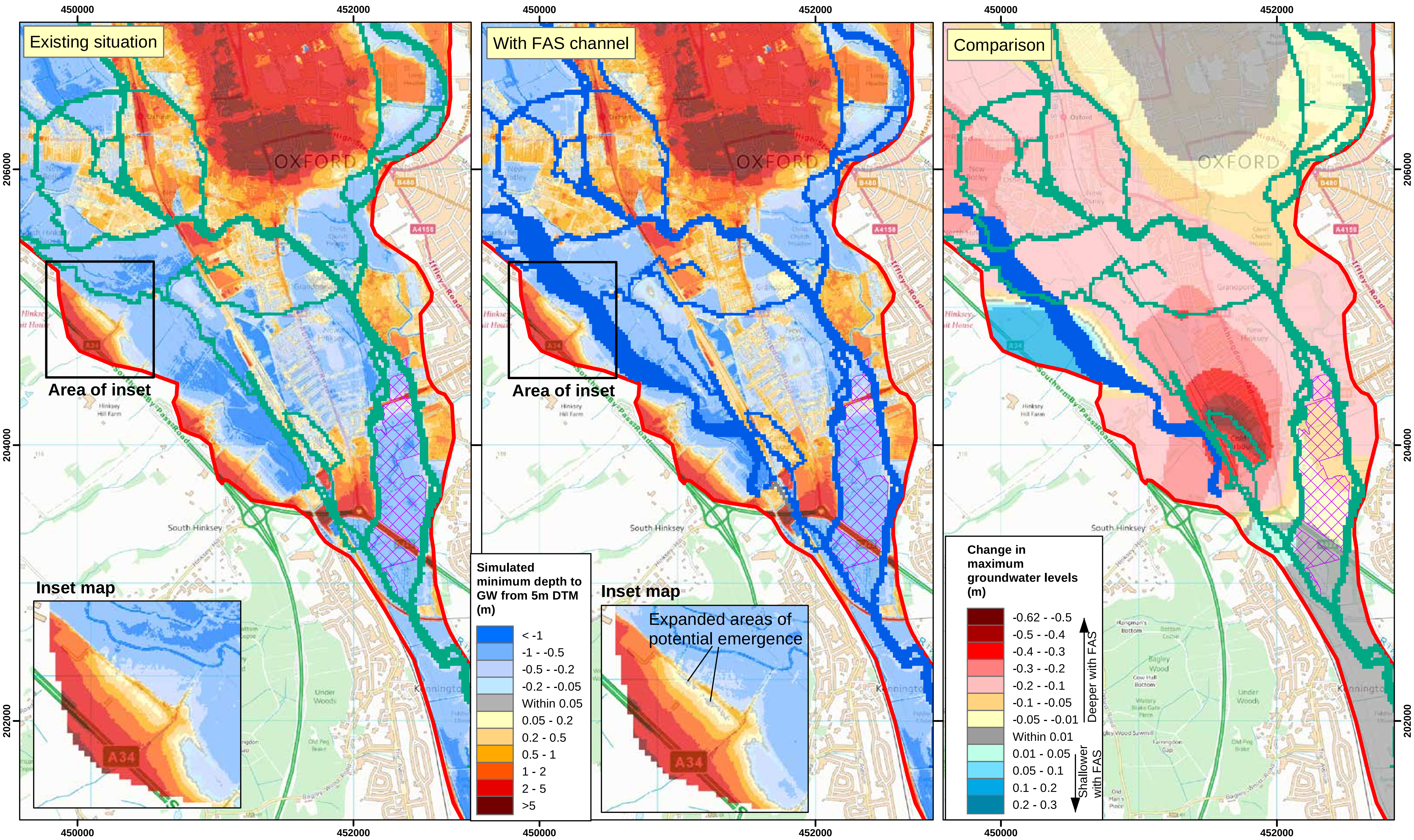



Figure A.6
1 in 20 year flood scenario: minimum depth to groundwater (from 5 m DTM)



- Simulated rivers
- Simulated river and FAS channel
- Lined FAS channel
- MODFLOW model area
- Historical groundwater flooding
- Oxford Meadows SAC
- Iffley Meadows SSSI

| | | | |
|---|---|---|---|
| Date | Jan 2018 | Drawn | IJG/SNB |
| Scale | 1:25,000 | Checked | SNB |
| Original | A3 | Revision | 2 |
| File Reference | D:\63294 Oxford FAS\GIS\UPDATE JULY_AUGUST 2017\Map documents\Figures for report\Fig A6 for Technical Note | | |

esi consulting

# APPENDIX C

## Technical Note: Review of Modelling Approach at Hinksey Meadow and Hogacre Park

# Technical Note:

## Oxford FAS Groundwater Model: Review of Modelling Approach at Hinksey Meadow and Hogacre Park

Published by ESI Limited
February 2018

Document reference:
*63294 TN03*

Report status:
*Final*



CONFIDENTIAL

t. 01743 276 100
e. info@esi-consulting.co.uk | www.esi-consulting.co.uk
@ESI_consulting

ESI Ltd., New Zealand House, 160-162 Abbey Foregate, Shrewsbury, Shropshire SY2 6FD

**Shrewsbury** 01743 276 100 **Reading** 01189 572 915 **Cardiff** 02920 660 144

# Prepared for CH2MHill (Jacobs)

Document reference: 63294 TN03, February 2018



| | Name | Signature |
|---|---|---|
| Author | Samuel Bishop | |
| Checked by | Barnaby Harding | |
| Reviewed by | Barnaby Harding | |

# Summary

This Technical Note relates to a numerical groundwater model built by ESI (2016, 2017) to represent the superficial sand/gravel aquifer beneath the floodplain of the River Thames near Oxford. The model was built to simulate the likely effects of the proposed Oxford Flood Alleviation Scheme (FAS) on groundwater flood risk and on several areas of ecologically-important grassland habitat.

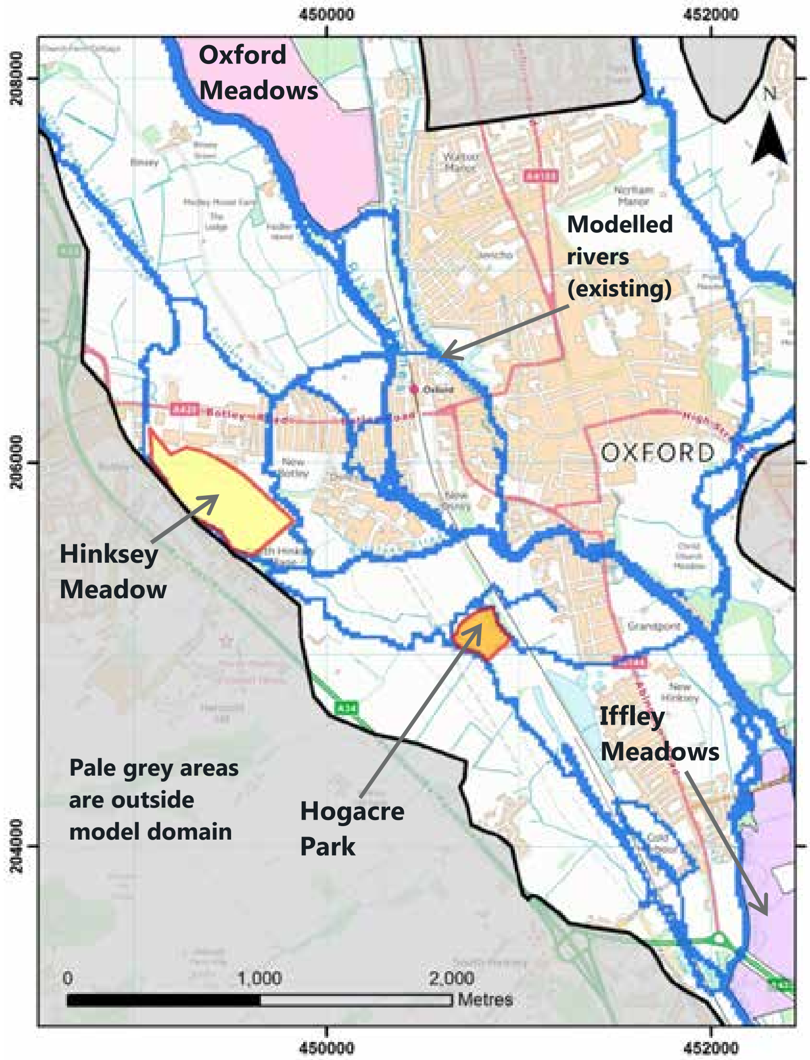
This document considers the possibility of undertaking more detailed groundwater modelling of the Hinksey Meadows and Hogacre Park areas (both of which are included within the domain of the existing model). It is not a standalone report and should be read in conjunction with the ESI reports that describe the model in detail (ESI 2016, 2017).

# Contents

# 1 Introduction

A Flood Alleviation Scheme (FAS) is proposed for Oxford which 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 in MODFLOW 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 aquifer beneath the floodplain of the River Thames and its tributaries. River levels derived from a separate fluvial model (Flood Modeller Pro, formerly ISIS) are used as boundary conditions for the groundwater model.

The focus of the 2015/16 modelling was on predicting the likely impact of the FAS on groundwater flood risk and on dry year groundwater levels beneath areas of ecologically-important grassland habitat (Oxford Meadows and Iffley Meadows). The model was updated by ESI (2017) to reflect new ground investigation data and also changes to the FAS design. The update included consideration of potential effects on groundwater levels beneath an additional area of MG4 grassland, Hinksey Meadow (Figure 1.1).




Contains Ordnance Survey data. © Crown copyright and database right 2018.

**Figure 1.1 Map showing locations of Hinksey Meadow and Hogacre Park within the area covered by the existing groundwater model (note that only a portion of the modelled area is shown)**

The Floodplain Meadows Partnership[1] commented on ESI (2016) and expressed concerns about the precision of the groundwater model:

> *"A general note is that the model (as described in section 3.10.1) only claims to achieve a precision in the range of 0.2 m, which is good in the context of a hydrogeological model, but poor for an ecohydrological one. Therefore, if there are perceived to be threats to the protected sites, a field-scale hydrological model using site-specific estimates of conductivity and porosity would be needed to give adequate precision. However, for the current purpose of estimating future groundwater flooding and for targeting broad areas in terms of their suitability for grassland restoration, the current model seems adequate.*
>
> *...I would recommend this exercise be extended to include the species-rich areas of Hinksey Meadow, which although lacking a statutory designation, holds ecological interest of comparable value to some of the protected areas and it is the area most likely to be affected by the scheme. The area supporting the Apium repens re-introduction could be included in the more detailed exercise, though the ecohydrological requirements of that species tend to be less exacting than the species-rich sward."*
>
> (Professor David Gowing, Floodplain Meadows Partnership)

In the light of these concerns, the Environment Agency (EA) has requested that the possibility of a more detailed modelling exercise focusing on Hinksey Meadow and/or nearby Hogacre Park be considered and a recommendation made as to whether such an exercise would be useful or justified (e-mail from Penny Burt of the EA to Phil Marsh of CH2M, 8th December 2017). ESI has carried out this review and the results are provided in this Technical Note.

[1] 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).

# 2 Discussion

## 2.1 Area of interest within the wider context of the existing model

Figure 1.1 shows that Hinksey Meadow and Hogacre Park lie within the area of the existing groundwater model. Hinksey Meadow has an approximate area of 210,000 $m^2$, and Hogacre Park of about 50,000 $m^2$; together these sites make up less than 1% of the total model area of some 29,254,100 $m^2$ (~29 $km^2$). Both are in areas mapped by the British Geological Survey (BGS) as being covered by alluvium (BGS, 1982; BGS website).

Hinksey Meadow is a traditional hay meadow (Oxford Preservation Trust website). Hogacre Park, also known as Hogacre Common Eco Park, is a community space dedicated to biodiversity, renewable resources and local production; the site is managed by a Community Interest Company (CIC) called Hogacre Common Eco Park CIC (Hogacre Common website).

## 2.2 Limitations of the existing groundwater model

This section summarises briefly the limitations of the existing model with respect to simulating local (site-scale) groundwater levels. A detailed description of the model can be found in ESI (2016, 2017).

The model is designed to simulate groundwater levels and flows on a regional scale. A single model layer is used to represent the sand/gravel aquifer, with a grid resolution of 20 m. Hydraulic properties (hydraulic conductivity, specific yield, specific storage) are represented as uniform; this simplification is reasonable in the context of a regional model and limited data, but local heterogeneity, such as might be significant at a site scale, is not represented.

The alluvium and made ground that overlie the sand/gravel aquifer across much of the Thames Valley are not explicitly represented in the model, and groundwater heads are calculated for the sand/gravel layer only. There is no representation of shallow perched groundwater above the main aquifer, and also no representation of shallow ditches or field drainage. It may be that the meadows owe their wetness to poor drainage of alluvial soil/subsoil rather than to a direct influence of groundwater in the deeper sand/gravel. Although high heads in the sand/gravel aquifer may help to keep the upper layers of the ground profile wet, the details of any relationship between soil moisture and deeper groundwater levels are not known and are certainly not represented in the model.

River levels are derived from the fluvial model. Simulated river levels can deviate from observed levels by some 0.1 to 0.2 m. As the fluvial model simulates river levels at discrete nodes within a 1D channel network, these levels must be interpolated spatially in order to allow river levels to be assigned to river cells within the grid of the groundwater model. Simulated groundwater levels are strongly controlled by the specified river levels. The riverbed “conductance”, which determines how well connected the rivers are to groundwater, varies only with channel width; there is no allowance for local variations in the thickness or permeability of riverbed sediment.

The calibration of the groundwater model to the July 2007 flood event, with residuals (differences between observed and simulated levels) typically of the order of tens of centimetres, is good for a regional groundwater model. Although this is relatively large compared to some ecological tolerances, it should be noted that models are often better at simulating relative water level changes (i.e. comparing two scenarios) than they are at reproducing absolute levels.

It is the dry year scenario that is most relevant for assessing the effects of the FAS on flood meadows. Originally, the dry year model predicted that the FAS would give a groundwater level fall of up to

0.3 m beneath Hinksey Meadow; however, allowing for the introduction of weirs along the Bulstake Stream reduces this to a maximum of about 0.1 m (ESI, 2017). The dry year scenario simulated with the model is artificial in the sense that it does not represent a particular historical year; instead it uses constant low (Q95-equivalent) river levels combined with recharge data for 2011. Although this is considered conservative for the purposes of assessing the effects of the FAS at low flows, the fixing of river levels means that simulated fluctuations in groundwater level are of unrealistically low amplitude. In reality, river levels will fluctuate and such fluctuations will be transmitted (at least to some extent) through the connected aquifer in the form of rises and falls in groundwater level.

## 2.3 More detailed local-scale modelling

It would be possible to build a local higher-resolution (finer grid) groundwater model of Hinksey Meadow and/or Hogacre Park, with an additional layer to represent the alluvium and made ground. However, this would only be worth doing if there were sufficient data available to allow development of a more detailed conceptual understanding of the local hydrology and ground conditions. In particular, the following would be required:

- Site-specific rainfall and evapotranspiration data (allowing more accurate estimation of groundwater recharge). These data would need to overlap in time with the water level monitoring described below.
- Detailed information on site drainage, including ditch networks and any underdrainage. Site drainage may be very important in controlling near-surface groundwater levels and soil moisture profiles.
- Site-specific measurements of aquifer properties. The values used in the regional model domain may not be appropriate for the smaller “sub-area” of interest.
- Detailed information on the nature and thickness of alluvium overlying the sand/gravel (with good spatial coverage of data points across the meadow). This would be needed to inform a multi-layer model. It is likely that further ground investigation would be needed.
- Information on the distribution and availability of moisture in the alluvium, including how this is influenced by deeper groundwater, and how it affects the plant communities of interest. Any conclusions drawn from the modelling about potential impacts on plant communities would need to be based on a good conceptual understanding of the system.
- Groundwater level monitoring data from the alluvium as well as from the underlying sand/gravel. Ideally these data would be collected from “nested” piezometers so that vertical hydraulic gradients could be measured. A three-dimensional distribution of observed heads would be needed to allow reliable calibration of a multi-layered model.
- Water level monitoring data from the river channels passing close to the meadows and also from any relevant ditches.
- River flow monitoring data – spot gauging data to define accretion profiles, and ideally continuous flow data from points immediately upstream and downstream of the area of interest. This would allow baseflow (and therefore riverbed conductance) to be estimated.

Monitoring would need to be undertaken for a sufficiently long period of time to include not just seasonal variations, but also a suitably “dry” year. This would allow both the fluvial and groundwater models to be calibrated to real low flow conditions (the existing model was calibrated to a flood and then used to predict the response of the system to a hypothetical dry year).

As the groundwater and surface water monitoring data referred to above are not available, it is considered that there would be little to be gained from higher-resolution modelling using relatively coarse scale data at this time. Given the small magnitude of the predicted effect of the FAS on groundwater levels (see Section 2.1), and the current lack of monitoring data, it would make more sense to put a suitable monitoring network in place (and develop a more detailed conceptual understanding) than to build a finer-scale local model at this time.

# 3 Recommendations

It is recommended that detailed groundwater modelling (of Hinksey Meadow or Hogacre Park) not be undertaken at this time. Instead it is suggested that a monitoring strategy be developed. The details of such a strategy are outside the scope of this Technical Note.

# GLOSSARY

| | |
|---|---|
| EA | Environment Agency |
| FAS | Flood Alleviation Scheme |
| mAOD | Metres above Ordnance Datum |
| MODFLOW | MODular three-dimensional groundwater FLOW model |
| PAR | Project Appraisal Report |

# REFERENCES

**BGS (British Geological Survey), 1982.** Witney. Sheet 236, Solid and Drift Edition, 1:50,000 Series.

**BGS website:** http://www.bgs.ac.uk/geoindex/

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

**ESI, 2017.** Oxford Flood Alleviation Scheme: Groundwater Model Update. Draft report prepared for CH2M, ref. 63294 R2D1, November 2017.

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

**Fugro Engineering Services, 2014.** Oxford Relief Channel: Route Geology Volume Assessment. Desk Study Report. Report prepared for the Environment Agency, 7th July, 2014. Contract No. G140027U.

**Hogacre Common website:** http://www.hogacrecommon.org.uk/

**Oxford Preservation Trust website:** https://www.oxfordpreservation.org.uk/content/hinksey-meadow-0

# APPENDIX D

## Technical Note: Hydraulic Connectivity between Rivers and Groundwater

# Technical Note:

## Oxford FAS Groundwater Model: Hydraulic Connectivity between Rivers and Groundwater

Published by ESI Limited
February 2018

Document reference:
*63294 TN04*

Report status:
*Final*



CONFIDENTIAL

t. 01743 276 100
e. info@esi-consulting.co.uk | www.esi-consulting.co.uk
@ESI_consulting

ESI Ltd., New Zealand House, 160-162 Abbey Foregate, Shrewsbury, Shropshire SY2 6FD

| **Shrewsbury** | **Reading** | **Cardiff** |
|---|---|---|
| 01743 276 100 | 01189 572 915 | 02920 660 144 |

# Prepared for CH2MHill (Jacobs)

Document reference: 63294 TN04, February 2018



| | Name | Signature |
|---|---|---|
| Author | Samuel Bishop | |
| Checked by | Barnaby Harding | |
| Reviewed by | Barnaby Harding | |

# Summary

This Technical Note relates to a numerical groundwater model built by ESI (2016, 2017) to represent the superficial sand/gravel aquifer beneath the floodplain of the River Thames near Oxford. The model was built to simulate the likely effects of the proposed Oxford Flood Alleviation Scheme (FAS) on groundwater flood risk and on several areas of ecologically-important grassland habitat.

This document is concerned with the degree of hydraulic connectivity between rivers and groundwater, as represented in the model by the bed conductance parameter. It is not a standalone report and should be read in conjunction with the ESI reports that describe the model in detail (ESI 2016, 2017).

# Contents

# 1 Introduction

A Flood Alleviation Scheme (FAS) is proposed for Oxford which 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 in MODFLOW 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 aquifer beneath the floodplain of the River Thames and its tributaries. River levels derived from a separate fluvial model (Flood Modeller Pro, formerly ISIS) are used as boundary conditions for the groundwater model.

The focus of the 2015/16 modelling was on predicting the likely impact of the FAS on groundwater flood risk and on dry year groundwater levels beneath areas of ecologically-important grassland habitat, namely Oxford Meadows (including Port Meadow) and Iffley Meadows. The model was updated by ESI (2017) to reflect new ground investigation data and also changes to the FAS design. The update included consideration of potential effects on groundwater levels beneath an additional area of MG4 grassland, Hinksey Meadow.

The Floodplain Meadows Partnership[1] commented on ESI (2016) and expressed concerns about the way the model represents the hydraulic connectivity between rivers and groundwater:

> *"My main concern is with the assumption that the rivers and associated water courses are in good connection with the gravel aquifer. This is certainly true for some reaches, but it is not a safe universal assumption. The work on Port Meadow (Dixon 2004; Gowing and Youngs, 2005) clearly suggests that the groundwater under the site drains to the Seacourt Stream, by-passing the Thames, which is assumed to have isolated itself from the surrounding aquifer through deposition of fine silts. I agree with the authors that data on river bed permeability is not currently available across the area and to assume different permeabilities in different reaches would add substantially to the complexity of the model and would not necessarily be justified in terms of the model's current objectives. However, it should again be borne in mind that the model is not necessarily suitable for use in future assessments of areas such as Port Meadow, where its assumptions do not hold. It is important that the local effect of the new channel on Port Meadow be considered at a finer scale to ensure the new channel does not substantially increase the drainage of the site. The current model may not identify such a risk because it assumes the stage level in the Thames would act to buffer drainage. There may be a need to mitigate for such drainage by ensuring any low-flow channel in the environs of Binsey and Medley Manor is not deeper than can be avoided and that water levels in it are retained to minimise any increase in head differential between Port Meadow and the new channel."*
>
> (Professor David Gowing, Floodplain Meadows Partnership)

This Technical Note discusses the issues raised by the Floodplain Meadows Partnership and considers whether the representation of river-aquifer connectivity in the model is appropriate. Dixon (2004) was reviewed as part of ESI's 2015/16 modelling study (ESI, 2016). However, Gowing and Youngs (2005) was not made available for review.

[1] 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).

# 2 River-Aquifer Connectivity

## 2.1 Representation of river-aquifer connectivity within the model

Within the MODFLOW model, rivers are represented using river cells, each of which has a specified (time-varying) river stage derived from the fluvial model. The river is considered to be separated from the aquifer by bed material that may be less permeable than the aquifer (Figure 2.1).

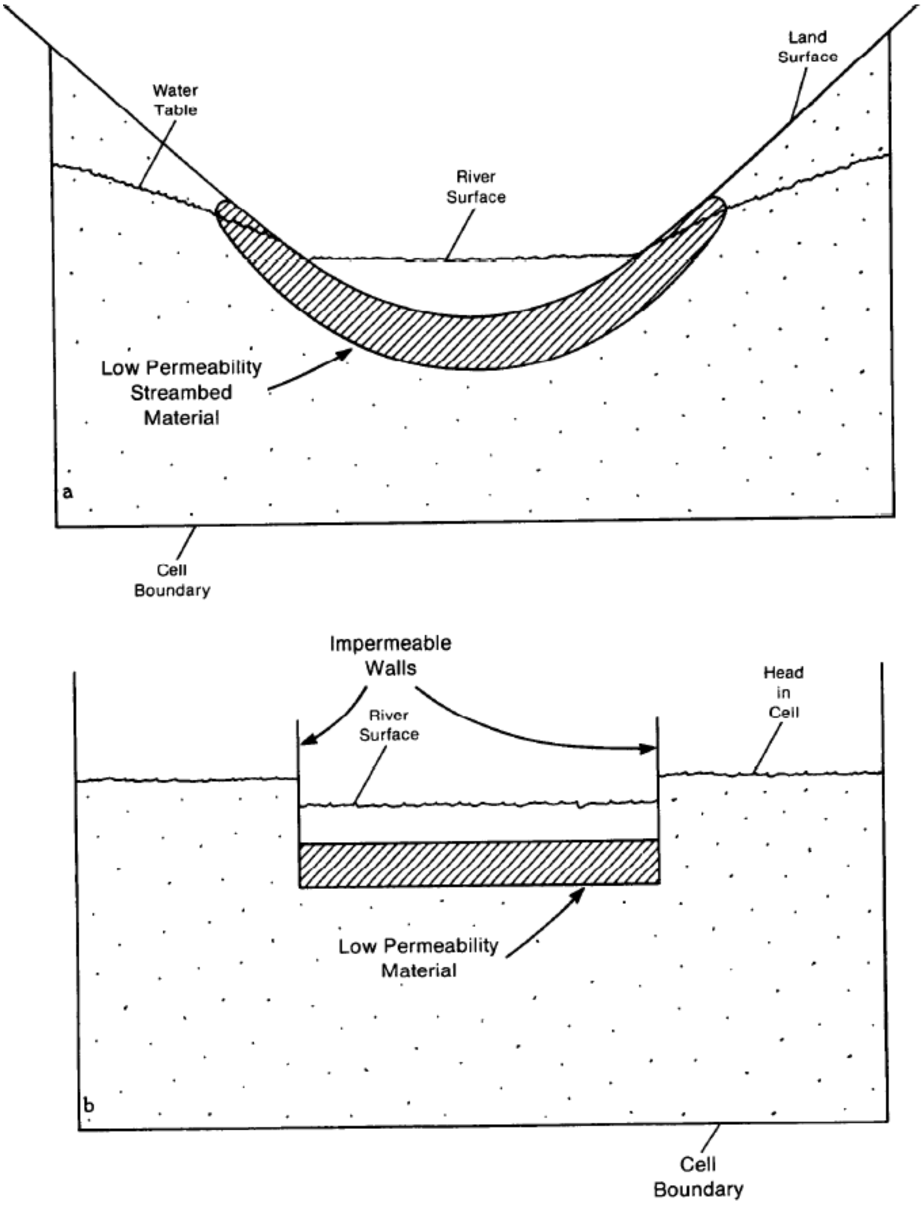



**Figure 2.1 MODFLOW river cells: (a) real situation and (b) conceptual representation in MODFLOW (from McDonald and Harbaugh, 1988)**

The bed conductance, C, of a river cell represents the degree of hydraulic connectivity between the river and the aquifer and can be expressed as follows (McDonald and Harbaugh, 1988):

$$C = \frac{K_v . W . L}{b'}$$ **Equation 1**

where:

$K_v$ = vertical hydraulic conductivity of river bed sediment [m/d];

b′ = thickness of river bed sediment [m];

W = width of channel [m]; and

L = length of channel crossing model cell [m].

With lengths in metres and time in days, C has units of $m^2$/d.

The greater the value of C, the greater the connectivity between the river and the aquifer. Within the model, all the river cells have the same values for $K_v$ and b′, i.e., the conductance per unit area of channel remains constant (being equal to the ratio $K_v$/b′). There is therefore no allowance for variations in the thickness or permeability of river bed sediment. Nevertheless, C varies between individual river cells because of variation in the contact area (W x L) between the rivers and aquifer. However, for a given river reach the channel dimensions vary little and so C is fairly constant.

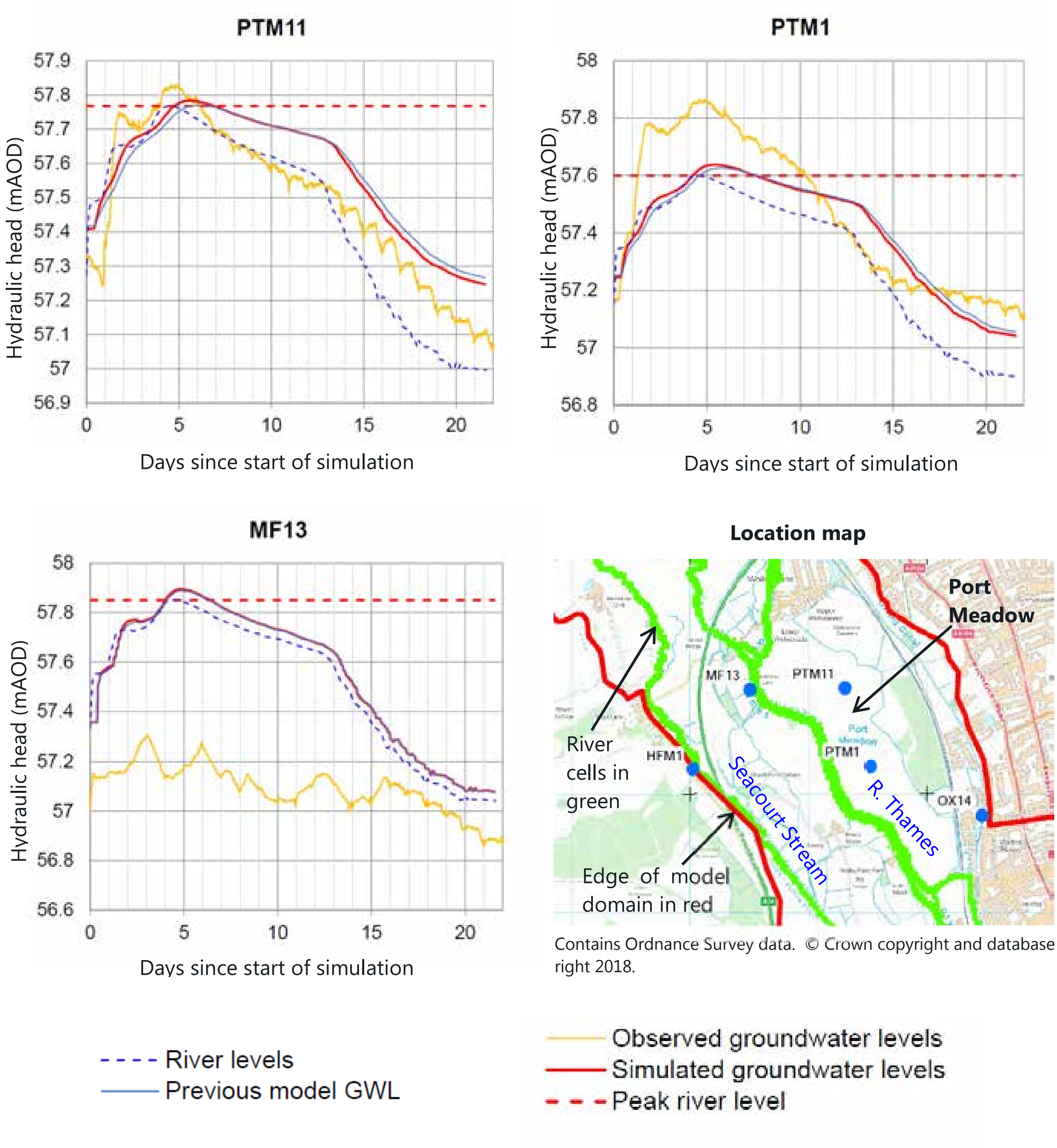
In the model, $K_v$ is set to 10 m/d and b′ to 1 m (ESI, 2016). These values are reasonable for rivers with sandy/gravelly beds and a good connection to groundwater. It should be noted that it is the ratio of $K_v$ to b′ that is important, so a thicker bed with a proportionately higher $K_v$ value would have the same vertical flux, all else being equal. The hydraulic conductivity of the river bed material is represented as being lower than that in the adjacent aquifer (200 m/d), so the river beds do provide some resistance to flow between the surface water and groundwater systems. In general the specified values for $K_v$ and b′ give a good calibration to groundwater levels (ESI, 2016 and 2017).

## 2.2 Discussion

It has been suggested that the reach of the River Thames flowing alongside Oxford Meadows has a relatively poor degree of hydraulic connectivity with the sand/gravel aquifer and that groundwater levels beneath the meadows are controlled by the more distant Seacourt Stream (see quote in Section 1; Figure 2.2 shows locations).

As shown in Figure 2.2, the model is well-calibrated to observed groundwater levels at boreholes PTM11 and PTM1, which are within Port Meadow. Observed groundwater levels in the sand/gravel aquifer respond rapidly to the level of the River Thames, and track river levels quite closely. This suggests that there is a good connection between the River Thames and the aquifer, and is apparently at odds with the quote in Section 1.

At borehole MF13, which is not in Port Meadow, there is a greater difference between modelled and observed groundwater levels (Figure 2.2). Simulated groundwater levels track river levels closely, whereas the observed hydrograph suggests only a muted groundwater response to the flood event. At this location there does appear to be a poor connection with the river and/or some other influence such as local drainage. A poor hydraulic connection could reflect aquifer heterogeneity (locally lower permeability) and need not reflect a significant change in the nature, or thickness, of river bed sediment. Indeed, Dixon (2004) notes that there are three layers within the aquifer beneath Oxford Meadows: a middle layer of highly permeable clean gravel, and upper and lower layers consisting of less permeable, clayey, gravel. These layers are not consistently developed across the area (Dixon, 2004). It may be that MF13 is screened in a less permeable part of, or layer within, the aquifer.




Contains Ordnance Survey data. © Crown copyright and database right 2018.

**Figure 2.2 Modelled and observed water levels in the vicinity of Port Meadow, part of Oxford Meadows: July 2007 flood event (from ESI, 2016 and 2017). Note that the river levels shown (including peak values) are simulated levels derived from the fluvial model.**

Overall the evidence suggests that groundwater in the sand/gravel aquifer beneath Port Meadow is fairly well-connected to the River Thames. However, there are indications (as at MF13) that the simple regional model, with its uniform hydraulic properties and lack of drains, does not account for certain local variations/features that exert an influence on observed groundwater levels. It may also be the case that there is shallow groundwater perched within the alluvial deposits beneath the meadow, and that this groundwater is not as well connected to the River Thames as is that in the deeper sand/gravel aquifer. Dixon (2004) notes, "For much of the summer some areas of the Meads are not in contact with groundwater, and plants rely on rainfall and stored water in the alluvium for their water needs." (p.6).

In general the model appears well-calibrated in the area of Port Meadow, and so the conductance of the river bed is considered reasonable, at least for a regional model. Results from the "dry year" scenario suggest that the scheme is unlikely to have a significant effect on groundwater levels in the sand/gravel aquifer beneath the meadow (ESI, 2016 and 2017). Furthermore, it is understood that water levels in the Seacourt Stream north of Botley Road will be maintained close to pre-scheme levels, under both typical and dry conditions. Given these considerations, it is not thought necessary to update, or refine, the model in the Port Meadow area.

The model was designed (and is considered suitable) for a regional assessment of the likely effects of the FAS on groundwater levels in the sand/gravel aquifer. However, in its current form it is not suitable for detailed site-scale assessment of soil moisture conditions. As ecological receptors are likely to be dependent on such detailed conditions, care should be exercised when interpreting the modelling results in a hydro-ecological context.

# 3 Recommendations

It is considered that for the purposes of the ESI (2016, 2017 and ongoing) study the FAS groundwater model does not need to be updated, or refined, in the Port Meadow area. However, it is emphasised that in its current form the model is not suitable for a detailed site-scale hydro-ecological assessment of soil moisture conditions.

# GLOSSARY

| | |
|---|---|
| EA | Environment Agency |
| FAS | Flood Alleviation Scheme |
| mAOD | Metres above Ordnance Datum |
| MODFLOW | MODular three-dimensional groundwater FLOW model |
| PAR | Project Appraisal Report |

# REFERENCES

**Dixon, A. J., 2004.** The hydrology of the Oxford Meadows cSAC. Report prepared for the Environment Agency by Andy Dixon of Groundwater Monitoring and Drilling Limited.

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

**ESI, 2017.** Oxford Flood Alleviation Scheme: Groundwater Model Update. Draft report prepared for CH2M, ref. 63294 R2D1, November 2017.

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

**Fugro Engineering Services, 2014.** Oxford Relief Channel: Route Geology Volume Assessment. Desk Study Report. Report prepared for the Environment Agency, 7th July, 2014. Contract No. G140027U.

**Gowing, D, and Youngs, E., 2005.** The requirements of *Apium repens* – an ecohydrological assessment. English Nature Final Report, February 2005.

**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.