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Groundwater and the Forres (River Findhorn & Pilmuir) Flood Alleviation Scheme, Morayshire

Groundwater Management Programme

Commissioned Report CR/08/023N

11 July 2008

BRITISH GEOLOGICAL SURVEY

GROUNDWATER MANAGEMENT PROGRAMME

COMMISSIONED REPORT CR/08/023N

Groundwater and the Forres (River Findhorn & Pilmuir) Flood Alleviation Scheme, Morayshire

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11 July 2008

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Keywords

Groundwater flooding, Quaternary, Scotland.

Front cover

The River Findhorn.

Bibliographical reference

MACDONALD A M, HUGHES A G, VOUNAKI T, GRAHAM M T, LILLY A, MANSOUR M & STEPHENS C A. 2008. Groundwater and the Forres (River Findhorn & Pilmuir) Flood Alleviation Scheme, Morayshire. *British Geological Survey Commissioned Report*, CR/08/023. 94 pp.

Keyworth, Nottingham British Geological Survey 2008

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Acknowledgements

This study was funded by Moray Flood Alleviation. The authors would particularly like to thank Paul Winfield of Royal Haskoning for his help in facilitating the study. Stuart Well Services carried out the 20-hour pumping tests and AEG the Ground Investigation drilling. The water chemistry analysis and dissolved gases analysis were carried out by the laboratories in BGS Wallingford.

Summary

The Forres area was subjected to one of the most catastrophic floods in UK history when the River Findhorn flooded in 1829. In recent times, Forres has also flooded (notably in 1997 and 2001) but to a much lesser extent. To help protect the town of Forres a flood alleviation scheme against flooding from the River Findhorn is proposed for west Forres and the Pilmuir area. This scheme involves a series of embankments and river channel engineering to stop the eastward flow of water through Forres, and an open drainage channel to drain storm water in the Pilmuir sub catchment. A critical issue in the operation and effectiveness of the flood alleviation scheme is the role of groundwater.

WORK UNDERTAKEN

Groundwater investigations and modelling in the Pilmuir area of Forres were first undertaken by BGS from Jan – May 2007 (reported in MacDonald et al. 2007). The investigations showed that the superficial deposits are highly permeable, contain much groundwater, and could therefore impact the success of the flood alleviation measures. Therefore, a second phase of work was proposed which examined the groundwater conditions around the area of the proposed embankments and modelled the effect of various flooding scenarios on general groundwater conditions and the flows in the drains/channels. BGS were commissioned to carry out this work during a study from November 07 to March 08. The following work was undertaken.

1. The hydrogeology of the area to be inundated was characterised by undertaking 13 short pumping tests in newly drilled piezometers, supervising 7 others and analysing and interpreting results. Groundwater-level data from installed divers were also interpreted.
2. Groundwater samples for chemistry analysis and residence time indicators were also taken at 13 sites and the samples analysed and interpreted.
3. Topsoil permeability was measured in 33 locations by the Macaulay Institute using a Guelph Permeameter.
4. Using the new data, the groundwater flow model initially developed in Phase 1 was modified and extended to help test the effect on general groundwater levels and drain/channel flows of storing floodwater on the floodplain behind the bund and explore the influence of a cut-off wall in the vicinity of the garden centre.
5. Using existing rainfall data, hydrogeological understanding and the groundwater model, a worst case groundwater flooding scenario was estimated.

HYDROGEOLOGY

The data collection and analysis from both phases of work have allowed the hydrogeology of the west Forres area to be understood in greater detail and with greater confidence. Below are some of the main issues:

- There is a dual aquifer system in the Pilmuir catchment, with a shallow superficial aquifer that is generally highly permeable, and a deeper bedrock aquifer which is less permeable. The two aquifers are not strongly connected.
- The bedrock aquifer comprises sandstones of Devonian age: groundwater flow is primarily through fractures and residence time may be greater than 25 years. The

chemistry of the water is similar over much of the area and the water is generally reducing.

- The shallow superficial aquifer comprises Quaternary deposits dominated by sands and gravel. Transmissivity is generally high at shallow depths (< 8 m) and in excess of 1000 m^2/d (this can be interpreted as permeability in the range of 100 – 1000 m/d). The deeper (> 8 m) deposits tend to have transmissivity less than 10 m^2/d, although transmissivity can be higher within deeper channels of more permeable material.
- Groundwater flow is generally from south to north and discharges to the lower reaches of the rivers and the Findhorn Bay. Flow is mostly within the top 8 m of the superficial deposits; at depth flow is more sluggish, due to the lower permeability.
- Groundwater is recharged from various sources: the River Findhorn, recharge in the upper parts of the Pilmuir catchment (e.g. around Knockomie) and direct recharge from rainfall on the floodplain. Groundwater residence times are less than 10-15 years in the superficial deposits.
- The River Findhorn is well connected to the aquifer system. In the south of the area, the river is losing water to the superficial deposits (and may possibly lose water to the bedrock aquifer). Further north, water-levels in the aquifer and river are similar and there is a complex interaction between river and aquifer depending on river stage.
- Groundwater discharges constantly through the existing storm drain system in Pilmuir.

FLOODING

From the groundwater investigations it is possible to infer mechanisms for flooding in the Pilmuir area:

- Very shallow groundwater gives rise to marshy areas, some peat development and willow growth in the Pilmuir area. The water-logged soils also reduce the ability of rain to infiltrate. The existing storm drain continually discharges groundwater at a rate of 20 – 30 l/s, which will reduce the capacity of the drain to take runoff.
- To the north of Forres, e.g. around the distillery and to the north of Broom of Moy, it is likely that groundwater naturally floods, and is only being kept dry by the presence of pre-existing drains and ditches.
- Increased urbanisation in the upper part of the catchment is likely to have increased runoff, and the use of soakaways has raised groundwater levels slightly in the lower part of the catchments.
- In flood events of > 25 years return period, modelling by Moray Flood Alleviation / Royal Haskoning indicates that, without the proposed scheme, floodwaters from the River Findhorn will flow through western Forres. Given the high permeability of the soil (0.3 m/d) a great proportion of this water is likely to infiltrate the aquifer (possibly up to 700,000 m^3). Since the floodwaters cross urban and industrial sites this could cause significant groundwater contamination, and also elevated groundwater levels (with associated groundwater flooding) for many months.

PREDICTIVE MODELLING

This modelling work builds on the work carried out for the Phase 1 report using the ZOOM suite of numerical groundwater models. The model was run initially as a steady state simulation. A dynamic balance approach was used for all prediction runs to give a better understanding of how the system responds to seasonal variations. Seven different scenarios were modelled which explored the groundwater response under base conditions, the response to the engineering works, heavy recharge, the storage of floodwaters on the floodplain, and also 6 months of heavy recharge.

Outcomes from the modelling on general groundwater responses in the area:

- The observed shallow groundwater levels (< 1 m deep) and flow in the existing storms drains under base conditions observed in the Pilmuir area are well represented by the model.
- The model also indicates that shallow groundwater conditions can exist all year round, and are related to rainfall events, rather than a more predictable winter high. This matches the observations from piezometers.
- The model predicts shallow groundwater-levels and in some cases groundwater flooding to the north of Forres under base conditions. This indicates the important role of the existing network of drains and open ditches in this area (not included in the model) in discharging shallow groundwater and lowering groundwater levels.
- Heavy rainfall events raise groundwater-levels across the entire area and considerably increase the extent of shallow groundwater levels and potential groundwater flooding.
- The existing stormwater drains in Pilmuir have the effect of reducing groundwater-level variations in that area. However, this depends critically on the capacity of these drains, and effectively reduces their capacity to remove storm runoff.

Comments on the effect of the engineering works on groundwater flow under non-flooding conditions:

- Groundwater contribution to flow in the proposed new channel under non flooding base conditions, even with heavy rainfall is negligible.
- The grout curtain adjacent to the garden centre will have a negligible effect on the overall groundwater flow under the floodplain.

Comments on the effect of the engineering works on groundwater conditions during flooding:

- The effect of impoundment behind the embankments for 1 day allows flood water to enter the groundwater system and raise groundwater levels beneath the impounded area. For a 1 in 50 year event the amount of water may be in the order of 100,000 m^3, and for a 1 in 200 year event 200,000 – 300,000 m^3. This is considerable less than what would be expected if there was no flood alleviation scheme and the flood waters were allowed to spread over a larger area (700,000 m^3).
- This additional water enters groundwater storage and discharges over the next few months back to the River Findhorn and the new channel.
- The industrial area is protected from groundwater flooding by the grout curtain, additional groundwater flows northward and discharges to the River Findhorn.
- The area of significant groundwater levels rise (> 0.5 m) is largely constrained to near the river and the additional groundwater flooding in the Pilmuir area from the impoundment is not predicted to be significant.

Comments on the worst case scenario:

- High rainfall (recharge of 60 mm in one day) coupled with exceptionally high groundwater levels in the preceding 6 months, and a 1 in 200 year river flooding event has the most significant effect on groundwater flooding and flows in the existing drain. There is a high likelihood of groundwater flooding.

- Crucially, the modelling indicates that the short term storage of river floodwaters on the floodplain has a much smaller effect on groundwater flooding than the sustained high groundwater recharge across the area from above average rainfall in the preceding 6 months.

RECOMMENDATIONS

This study focussed on the response of groundwater to flooding and the proposed engineering works. However, some wider recommendations can be given.

- The existing drain in the Pilmuir area is required to discharge groundwater, and has little capacity for runoff. The proposed new Pilmuir channel should therefore take most of the runoff, and, if possible, also be used to intercept groundwater.
- The West Forres Embankment is located on highly permeable gravels. Although the modelling in this study has demonstrated that this is unlikely to lead to catastrophic groundwater flooding, detailed modelling of the engineering stability of the embankment should be undertaken.
- The topsoil is an important factor in limiting the volume of water entering the groundwater, therefore, care should be taken not to remove the topsoil from the flood plain when undertaking the engineering works.
- The use of soakaways and SUDs in the Pilmuir area will lead to increased groundwater levels and the potential for more groundwater flooding. Alternatives should be sought.
- It is essential to continue to monitor the groundwater levels, rainfall and river flow across the flood plain to build up a more comprehensive picture of groundwater response to rainfall and elevated river stage.
- To model the area to the north of Forres more accurately, flows in the existing drains and ditches should be routinel measured.

1 Introduction

1.1 BACKGROUND

The Forres area was subjected to one of the most catastrophic floods in UK history when the River Findhorn flooded in 1829 (McEwen and Werritty 2007). Since that time, the floodplain has been built on as the town of Forres has expanded (Figure 1). In recent times, Forres has also flooded (notably in 1997 and 2001) but to a much lesser extent. These floods were mainly a result of elevated flows in the Burn of Mosset which flows through the centre of Forres (Choudhury and Patterson 2006). A separate flood alleviation scheme has been designed for the Burn of Mosset, and the implications for groundwater are described in MacDonald et al. (2006).

A flood alleviation scheme against flooding from the River Findhorn is proposed for west Forres and the Pilmuir area. This scheme involves a series of embankments and river channel engineering to stop the eastward movement of water through Forres, and a series of drains to accommodate storm water in the Pilmuir sub catchment. A critical issue in the operation and effectiveness of the flood alleviation scheme is the role of groundwater.

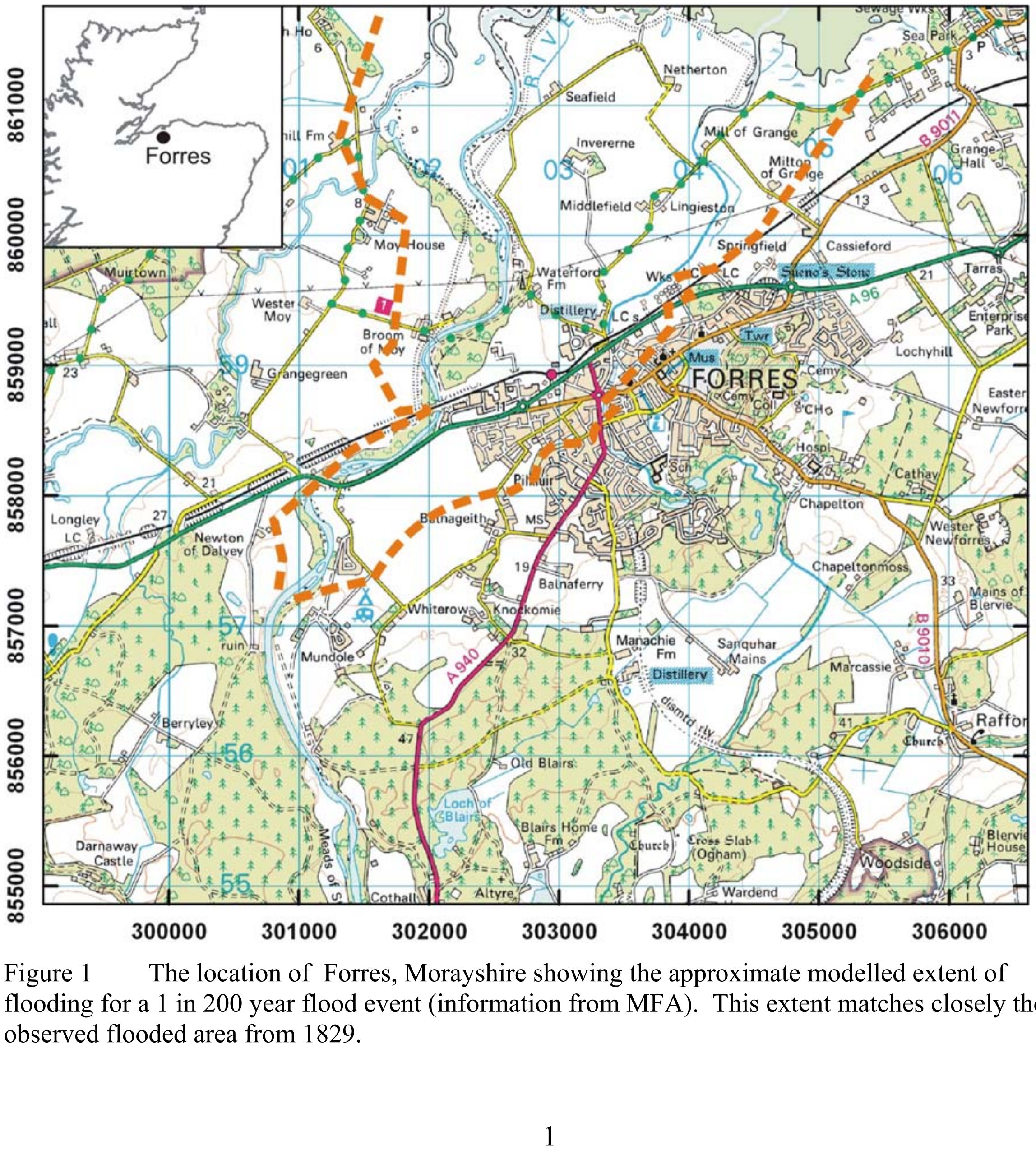

Figure 1 The location of Forres, Morayshire showing the approximate modelled extent of flooding for a 1 in 200 year flood event (information from MFA). This extent matches closely the observed flooded area from 1829.

Groundwater investigations and modelling in the Pilmuir area of Forres were first undertaken by BGS from Jan – May 2007 (MacDonald et al. 2007). The investigations have shown that the superficial deposits are highly permeable, and contain much groundwater. Shallow groundwater may be responsible for much of the annual flooding in the low-lying Pilmuir area; therefore, any change in the groundwater regime may affect flooding in the area. This phase of work explored how the design of the proposed Pilmuir drain may affect groundwater levels in the area.

However, this first study also highlighted the high permeability of the ground and topsoil, which could pose a risk for the proposed embankments. The high permeability of the ground could result in considerable 'leakage' of the flood water under any embankment structures. Therefore, a second phase of work was proposed which examined the groundwater conditions around the area of the proposed embankments and modelled the effect of various flooding scenarios on general groundwater conditions and the flows in the drains and channels.

1.2 SCOPE OF WORK

To help quantify the effect of 'storing' floodwater on the River Findhorn's floodplain on local groundwater it is essential to: characterise the permeability of the deposits in the area to be inundated; assess groundwater flow under baseline conditions and; model future scenarios. BGS were commissioned to carry out this work during a study from November 07 to March 08.

There are four main parts to the work:

1. Characterise the hydrogeology and the infiltration capacity of the soils in the area to be inundated by supervising, analysing and interpreting permeability and pumping tests and sampling, analysing and interpreting groundwater chemistry as indicators of flow.
2. Modify the numerical groundwater flow model for the area (developed in Phase 1 and described in MacDonald et al. (2007)) to help test the effect on general groundwater levels and drain/channel flows of storing floodwater on the floodplain behind the bund.
3. Using existing rainfall data, hydrogeological understanding and the groundwater model, to estimate a worst case groundwater flooding scenario.
4. Modify and extend the groundwater model to explore the influence of a cut-off wall in the vicinity of the garden centre on groundwater flow under normal, and flood, scenarios.

This report discusses the results of this study and should be read in conjunction with the earlier report MacDonald et al. (2007)

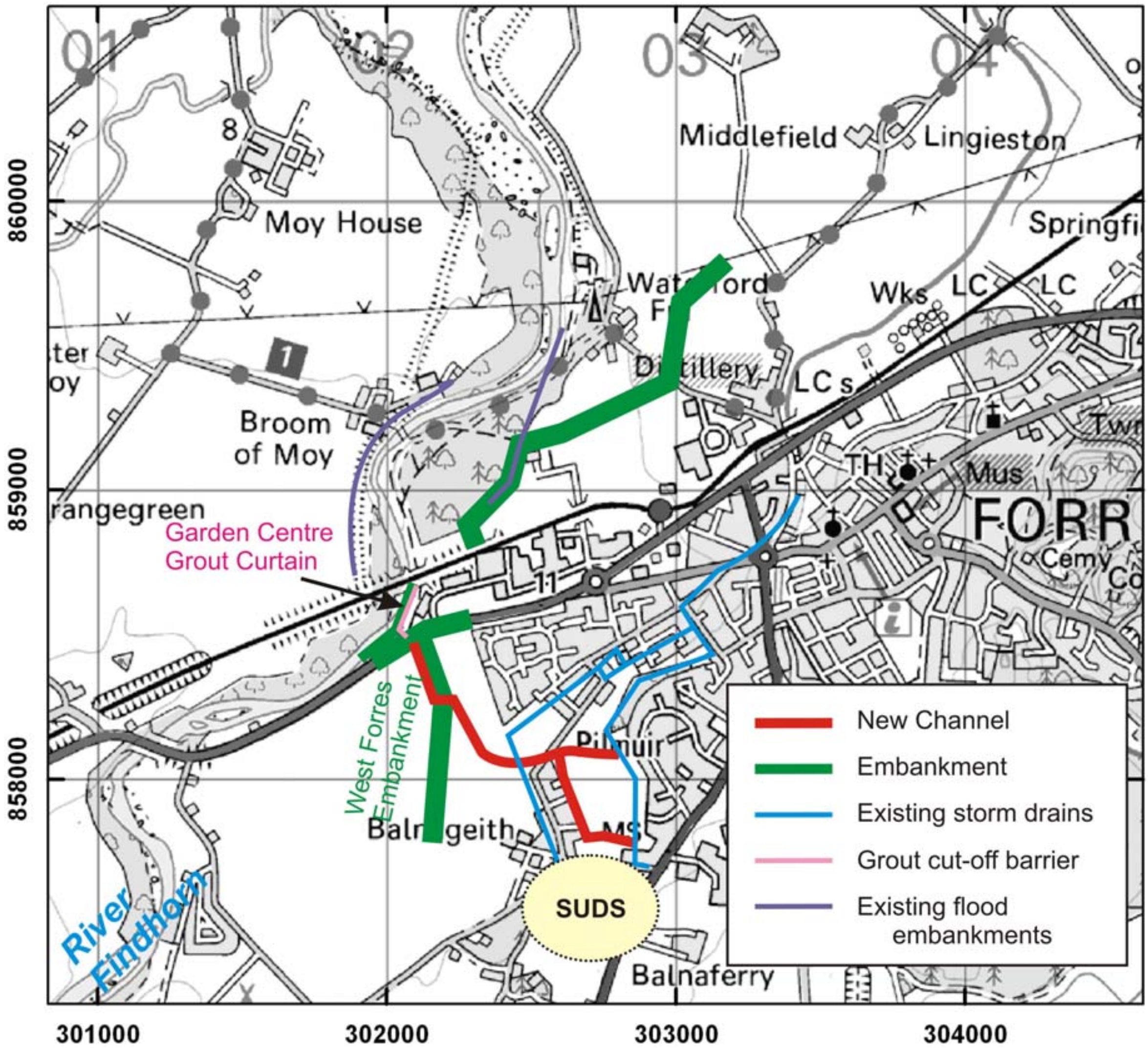

Figure 2 The approximate location of flood alleviation measures and existing hydrological infrastructure referred to in this report. The Findhorn River Channel will also be significantly altered by the removal of vegetation and gravel.

2 Hydrogeological data collection

2.1 INTRODUCTION

Hydrogeological information was collected to help understand groundwater flow in the Pilmuir area. Much of the information was collected using the piezometers drilled by AEG under the supervision of Moray Flood Alleviation / Royal Haskoning. Following an initial phase of drilling and data collection from November 06 to March 07, thirteen additional boreholes/piezometers were drilled between October and December 2007. The locations of the piezometers from both phases of work are given in Figure 3. The hydrogeological fieldwork for the second phase of work was carried out during November and December 2007.

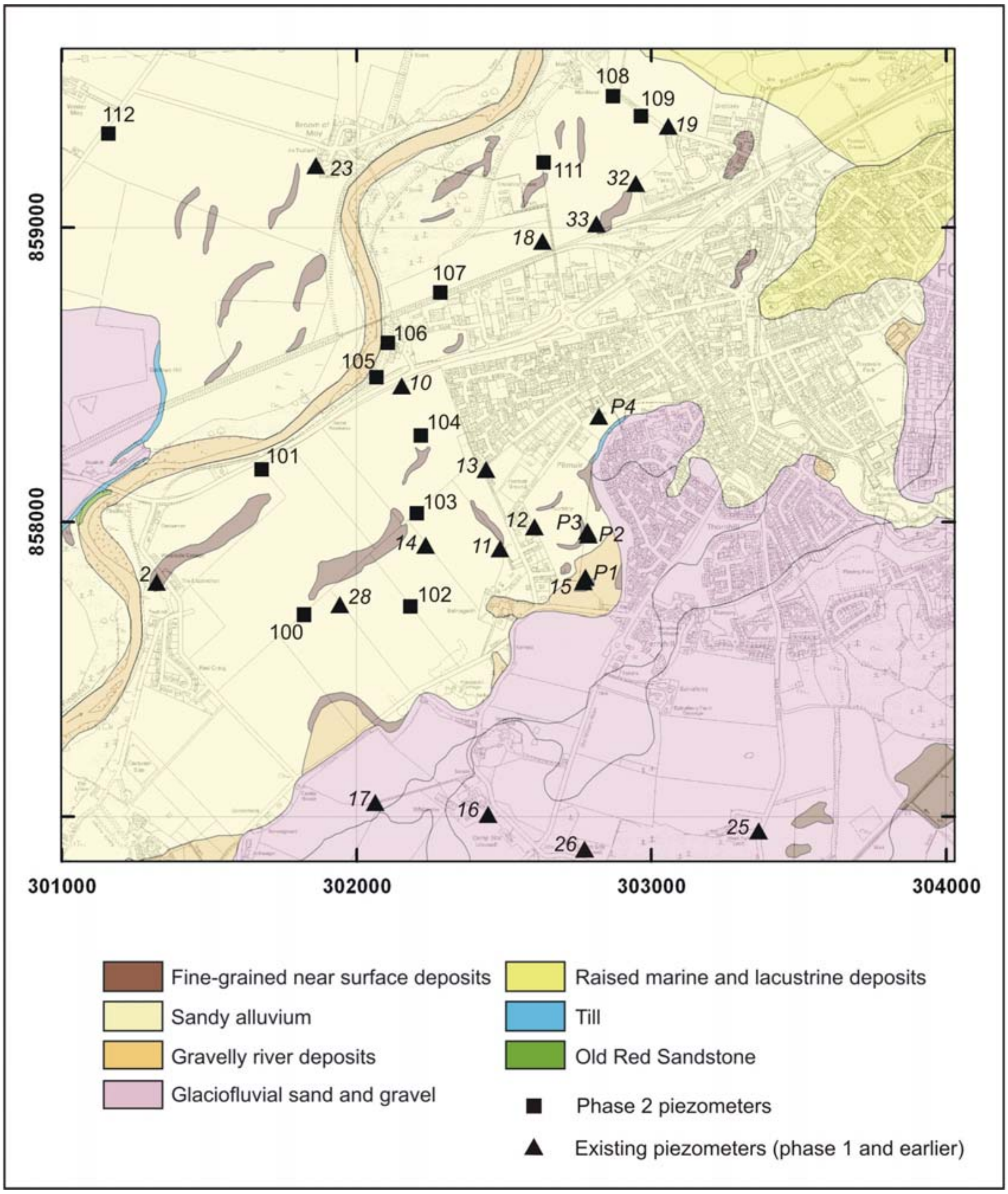

Figure 3 Geology of western Forres and the location of piezometers drilled in phases 1 & 2. The location of earlier piezometers is also shown.

2.2 PUMPING TESTS

2.2.1 Short pumping tests

To give an approximation of the permeability of the superficial deposits, short pumping tests, of at least one hour's duration, were carried out at all thirteen of the newly drilled boreholes. These did not take the form of rigid tests, but were carried out while purging the borehole before taking groundwater samples for chemical analysis. Higher yielding boreholes were tested using a centrifugal pump, which could pump up to 2 l/s. Lower yielding boreholes were pumped using a narrow diameter 0.1 l/s Whale® pump.

The results of the short pumping tests are given in Appendix 1 and a summary given in Table 1. All have been analysed using either the Jacob's approximation or the Theis Recovery Method (see Kruseman and deRidder 1990). The most appropriate method has been chosen for each test, given the test conditions and data.

2.2.2 Stuart Well Services (SWS) pumping tests

Short constant rate tests of between 2 and 5 hours were carried out in seven piezometers: BH101, 102, 103, 104, 105, 106 and 109. These tests were carried out by Stuart Well Services (SWS) using a centrifugal pump. The pumping rate for the tests was limited by the narrow diameter of the piezometers which limited the size of pump that could be used. The data for BH 101, 103, 104 and 106 are shown in Appendix 1. Reliable pumping test data from BH 105 and 109 were provided to BGS in time for analysis by SWS. The data from the shorter (1 hr.) pumping test carried out at BH 102 were deemed to be of a higher quality than the SWS data and have therefore been used instead. All the tests have been analysed using the Jacob's approximation or the Theis Recovery Method and most were checked using a radial flow model. A summary of the results is given in Table 1.

2.2.3 Interpreting the data

The pumping tests indicate high variability of permeability in the superficial deposits across the Pilmuir area. Measured transmissivity (permeability integrated over depth) varies by over three orders of magnitude, from less than 1 m^2/d to > 3000 m^2/d. With the exception of BH 106, which was installed into bedrock, the lowest transmissivity values occur in the southeastern part of the study area, around 0.5 km to 1 km away from the River Findhorn. The northern part of the study area is characterised by high transmissivity values, commonly > 500 m^2/d (Figure 4).

Based on the results of Phase 1 of this study, there was an apparent correlation between the transmissivity data and the depth to the base of the screened section of each borehole, with the shallowest installations giving the highest transmissivity values (MacDonald et al. 2007). It was inferred that these shallower boreholes may be exploiting a highly permeable layer of gravel and reworked alluvium, overlying less permeable glacial till, sand and silt at depth.

Following the inclusion of additional data from phase 2, a more complex pattern to the measured transmissivity values emerges (Figure 5). While there is still a detectable trend with depth (transmissivity is generally low below 8 m), there is additional variability in the shallow data with some piezometers in the depth range 6 – 7 m having low transmissivity as well. This is interpreted as variations in superficial geology and possibly silt filled channels. However the overall pattern is clear: transmissivity is generally high at shallow depths and in excess of 1000 m^2/d. Given the thickness of the gravel sequences, this can be interpreted as the permeability of the shallow deposits generally being in the range of 100 – 1000 m/d.

Table 1 Summary of pumping test data from Phase 2 of the study. All boreholes, with the exception of borehole 106 have been installed in superficial deposits. Tests of 1 hour duration were carried out by BGS; 2 – 5 hour tests by Stuart Well Services.

BH	Easting	Northing	Ground Level (mOD)	Top of screen (mbgl)	Base of screen (mbgl)	T (m^2/d)	Comments
100	301822	857696	15.212	2	5	497	1 hr. test analysed using Theis recovery
101	301682	858187	13.461	4	7	69	2 hr. test analysed using Jacob's approximation
102	302183	857720	15.208	3	6	0.63	1 hr. test analysed using Jacob's approximation
103	302204	858041	13.944	4.5	7.5	31.3	2 hr. test analysed using Jacob's approximation
104	302216	858298	13.055	5	8	2839	5 hr. test analysed using Theis recovery
105	302069	858501	12.4	2.7	5.7	1750	1 hr. test analysed using Theis recovery
106	302101	858631	12.488	9	12	4.19	5 hr. test analysed using Jacob's approximation
107	302285	858791	10.86	4	5	2035	1 hr. test analysed using Theis recovery
108	302871	859456	7.511	3.85	6.85	62.8	1 hr. test analysed using Jacob's approximation
109	302962	859390	7.744	3.6	6.6	1722	1 hr. test analysed using Theis recovery
110	302996	859639	6.379	2.6	5.6	351	1 hr. test analysed using Jacob's approximation
111	302636	859231	8.511	3.5	6.5	3099	1 hr. test analysed using Theis recovery
112	301156	859330	9.875	5.1	8.1	760	1 hr. test analysed using Theis recovery

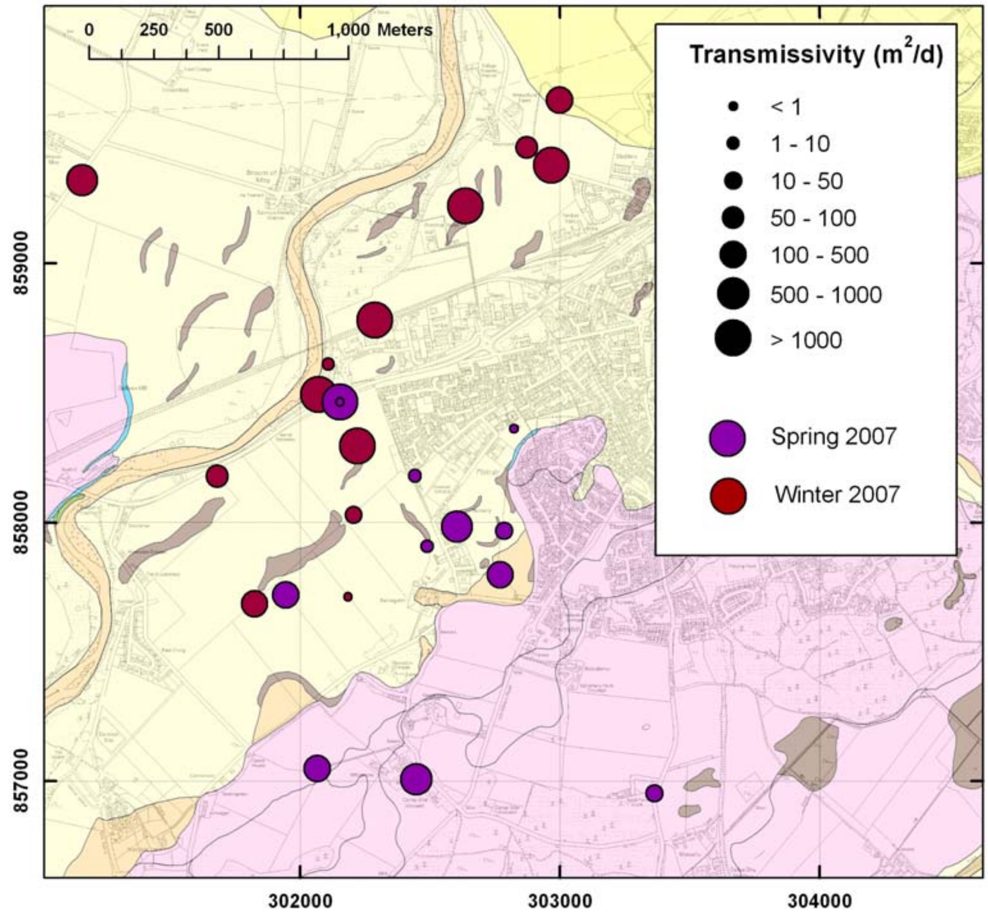

Figure 4 Distribution of transmissivity values from Phases 1 and 2 of the Pilmuir study.

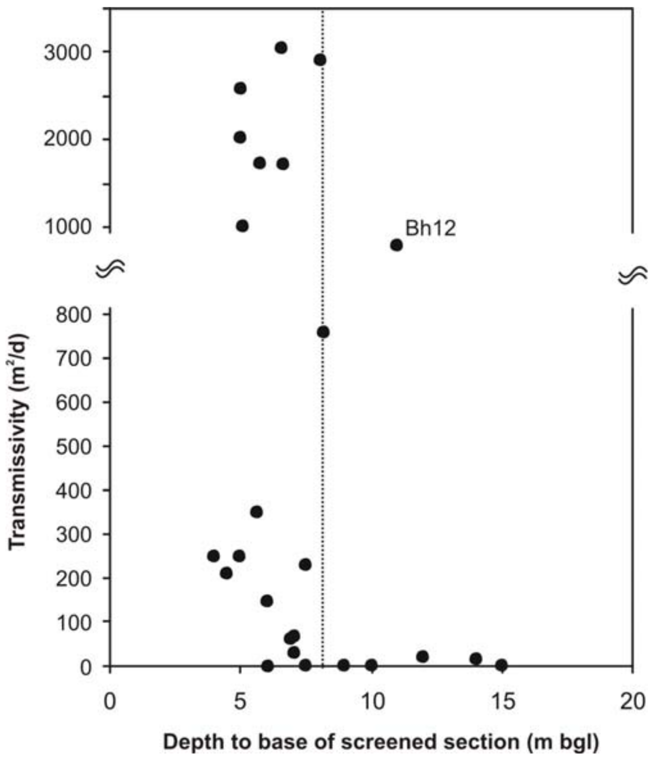

Figure 5 Transmissivity (calculated from pumping tests) versus the depth of the screened section for phase 1 and 2 of the study.

2.3 GROUNDWATER CHEMISTRY

Chemical analysis was carried out on water samples from thirteen piezometers in the west Forres area. The samples were collected during November and December 2007. Field measurements were made of pH, dissolved oxygen (DO), redox potential (Eh), water temperature, specific electrical conductance (SEC) and alkalinity. All the sources were purged prior to sampling, to ensure that the sample was representative of the groundwater. The locations of the sample points are given in Figure 6. Selected data are shown in Table 2 and plotted on a piper diagram in Figure 7.

Samples were also taken for analysis of the dissolved gas SF_6, which can be used to help understand the residence times of groundwaters. The build-up sulphur hexafluoride (SF_6) in the atmosphere over the last 50 years provides a way of determining the age of 'young' groundwaters. CFC samples were not taken as widespread CFC contamination was found during the Phase 1 sampling.

The current sampling substantiates the interpretations offered in Phase 1, and allows the interpretations of MacDonald et al. (2007) to be extrapolated over the rest of the area.

Sandstone water: Samples from the sandstone are dominated by Ca-HCO_3 type water, with low total dissolved solids (as indicated by SEC < 400 μScm^{-1}), pH 7.5 – 8, and low concentrations of NO_3, Cl, Na and dissolved organic carbon (DOC). They have a distinctive Br-Cl ratio which lies on the seawater/rainwater line (see Figure 7 and Figure 8). The chemistry measured at the bedrock site 106, is similar to that at P3. The residence time of groundwater at both sites is approximately 25 years (although this may comprise a composite age, of younger water mixing with older water). As discussed in the previous report (MacDonald et al. 2007), a sample from Piezometer 10b which was completed in sandstone does not show typical sandstone water, but is much closer to superficial waters. This is likely to be due to mixing in the borehole.

Shallow superficial water: Samples are dominated by high concentrations of Na-Cl which give higher total dissolved solids (indicated by SEC > 450 μScm^{-1}). The waters have a lower Br/Cl ratio than would be expected from rainwater, and pH is in the range 6.4 – 7.2. These groundwaters are similar in quality to the superficial deposits around Chapeltonmoss (MacDonald et al. 2006) and probably reflect increased transpiration from the forested areas, and uptake of bromide by peaty soils. Samples 108, 109 and 112 fall into this category, as do 15, 16, 25 and 19 from Phase 1.

River Bank water: Some samples close to the river show distinctive chemistry. Samples 101 and107 (and to a lesser extent 100) have low SEC (< 350 μScm^{-1}) a mixed chemistry (Na-Ca-HCO_3-Cl) and moderate nitrate (2 – 8 mg/l). These samples may include a high component of river water which has recharged the aquifer. Borehole 105, which is right next to the river, has distinctive chemistry, with elevated NO_3-N and a low Br/Cl ratio, and relatively high concentrations of NaCl. This may indicate local contamination.

Flood plain water: Some of the most distinctive groundwaters are samples taken from piezometers 102, 103, 104 and 111. These samples are also similar to those taken in the first phase from piezometers 10a, 28 and 18. These samples all have moderate SEC (400-500 μScm^{-1}) have pH *circum* neutral and are characterised by Ca-HCO_3-Cl and have Br/Cl ratios close to the rainwater/seawater line. Most distinctly, the nitrate is elevated (10-20 mg/l NO_3-N) and ages are generally similar (mid 1990s). These waters have a large component of local recharge from the arable floodplain, and are well mixed, indicating continuity of groundwater flow across much of the floodplain.

Table 2 Selected water chemistry data for new piezometers drilled in Phase 2.

	pH	**SEC** µS	**T** °C	**DO_2** mg/l	**Age**[a] year	**Ca** mg/l	**K** mg/l	**Mg** mg/l	**Na** mg/l	**Cl** mg/l	**HCO_3** mg/l	**SO_4** mg/l	**NO_3N** mg/l	**DOC** mg/l	Br mg/l
BH 100	6.92	287	10.5	10.8	1990	49.2	3.7	4.2	43.3	65.9	116	22.1	8.3		0.12
BH 101	6.93	352	10.5	7.3	1999	34.9	2.6	2.6	27.2	42.5	103	12.4	4.9	1.8	0.07
BH 102	6.95	481	10.3	6.4	1997	65.6	2.8	4.6	21.2	44.8	102	16.4	15.0	1.6	0.11
BH 103	7.06	453	9.9	8.5	1996	60.0	2.7	4.1	19.7	42.1	90.2	16.7	14.8	1.5	0.12
BH 104	6.74	413	10.4	8.2	1995	52.9	2.7	4.0	17.2	38.1	81.7	16.9	16.0	1.3	0.11
BH 105	6.54	177	10.2	2.4	1994	59.4	5.2	7.8	48.8	98.1	35.5	45.8	17.0		0.18
BH 106	7.26	241	10.7	0.8	1984	54.8	2.7	2.6	10.8	19.7	166	6.2	0.0	3.4	0.05
BH 107	6.83	341	11.3	4.5	1996	17.7	2.0	1.6	12.0	22.4	45.1	6.1	2.2		0.03
BH 108	6.80	446	10.7	6.5	1994	44.4	3.7	3.8	49.0	71.2	118	20.3	6.0		0.11
BH 109	6.60	494	10.7	5.4	1999	48.2	3.5	3.8	36.7	56.7	119	19.5	6.5		0.11
BH 110	6.76	500	10.1	7.1	1990	39.1	2.5	3.2	13.5	17.6	94	17.9	6.3		0.09
BH 111	5.13	416	10.5	6.3	1992	49.5	3.4	4.1	18.2	37.8	67	20.0	13.7	1.8	0.11
BH 112	6.42	658	10.7	4.0	1987	35.8	3.3	3.2	21.7	35.0	68	15.0	8.3		0.07

[a] estimated time of recharge from SF_6 concentrations.

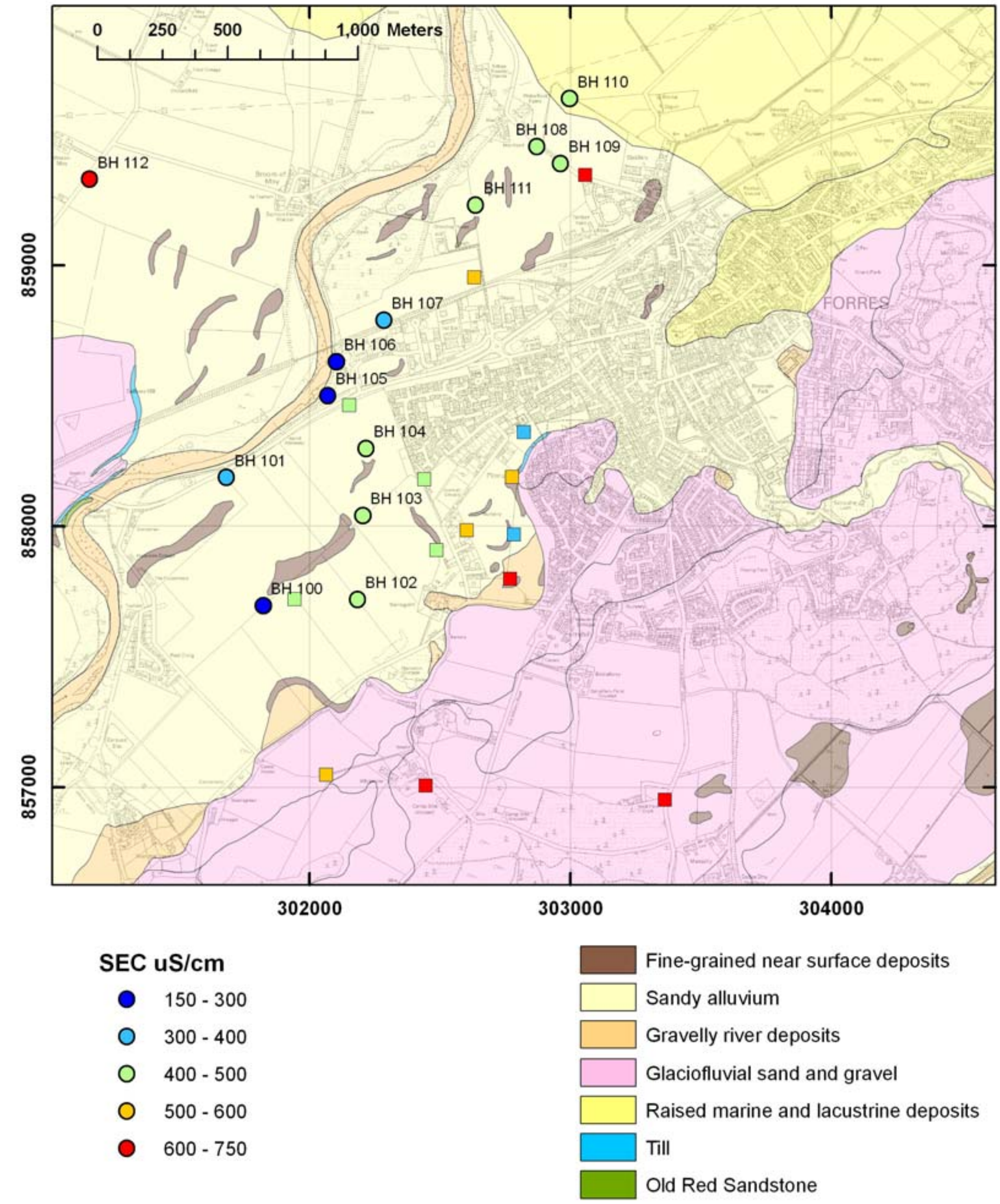

Figure 6 Location of chemistry samples, and the measured SEC. See text for description of the different groundwaters.

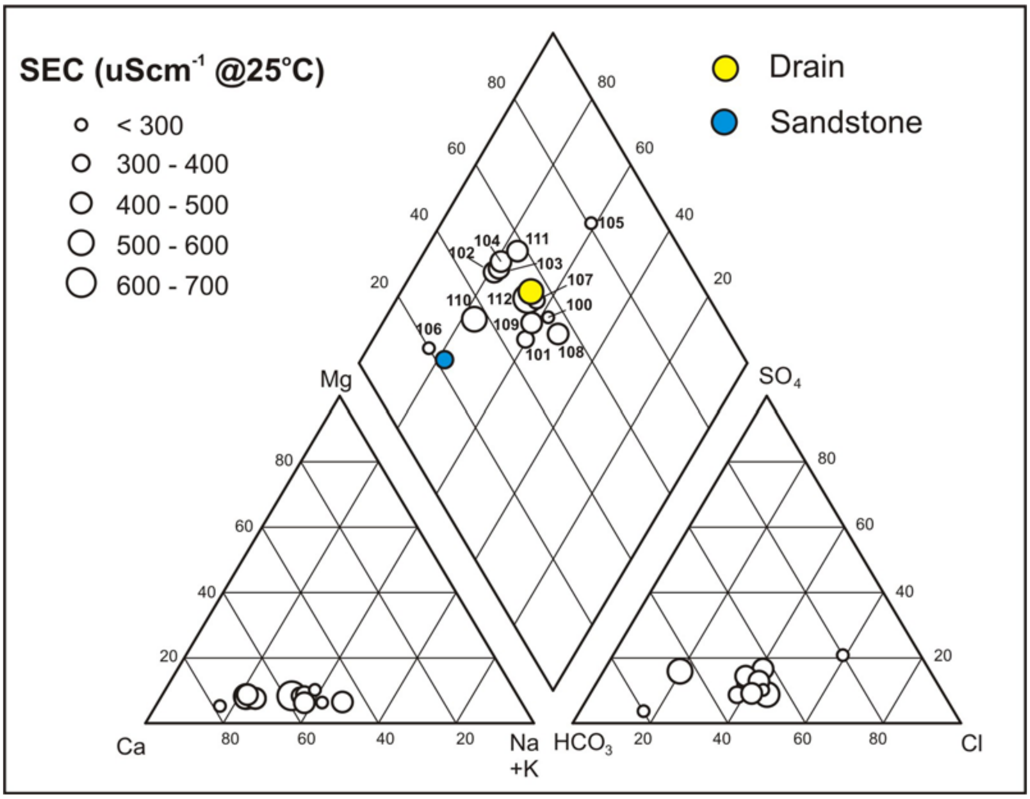

Figure 7 Piper diagram of the chemistry samples taken during Phase 2. The chemistry of the groundwater measured in the existing stormwater drain and the Devonian Sandstone is given for comparison.

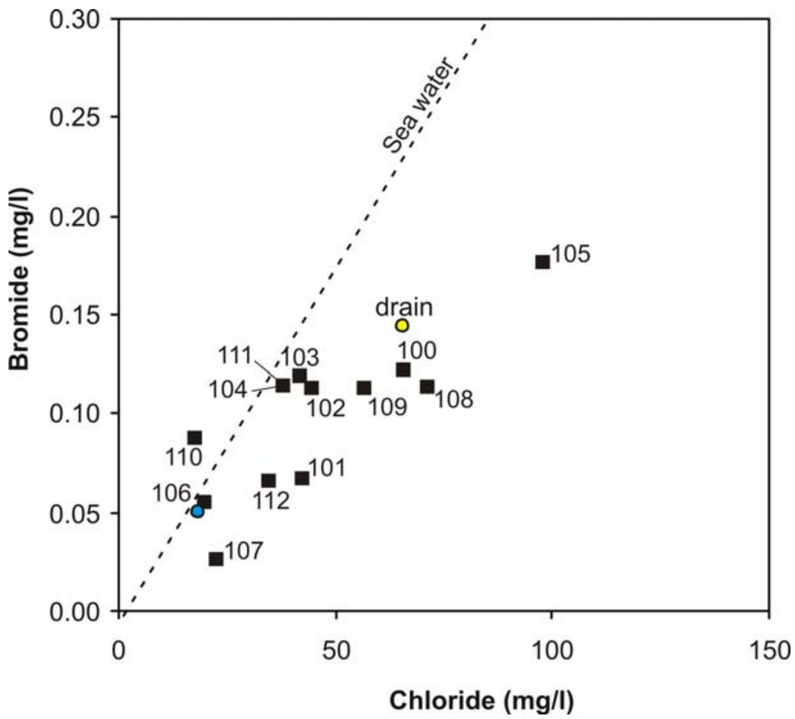

Figure 8 Plot of bromide versus chloride for samples taken during Phase 2.The chemistry from the stormwater drain is shown for comparison (yellow) and the chemistry from the Devonian Sandstone (blue), along with the seawater line, which is the ratio expected in seawater and rainfall.

2.4 TOPSOIL PERMEABILITY

2.4.1 Method

The topsoil permeability was measured by the Macaulay Institute using a Guelph Permeameter. The soils of the site have been derived from alluvial deposits and are predominantly sandy loam topsoil textures though soils with loamy sand, fine sandy loam and fine sandy silt loam can also found. Auger borings made in the cultivated fields would indicate that the topsoil is around 40 cm thick in most cases.

An auger hole approximately 12-15cm deep was made at each of the 33 sites using a 6 cm diameter soil auger. The auger holes were sited to avoid any areas where the soil structure had been recently damaged such as wheel ruts. Any smear present on the sides of the holes was removed using a long bladed knife and the resulting debris removed. The diameter of the hole was recorded along with land use information and any features that would affect the hydraulic conductivity. The permeameter was set into the hole which was then back-filled with clean, coarse sand to minimize slaking or collapse of the sides. The rate of fall of water in the permeameter reservoir was recorded at one minute intervals until it reached a steady rate over three successive readings.

The method proposed by Reynolds & Elrick (1985) for determining field saturated hydraulic conductivity (Kfs) was to pond two pressure heads sequentially within a single hole and measure the steady state recharge at each head. They then used the Richards analysis, which apportions the rate of flow into a saturated and an unsaturated component. Simultaneous equations are then used to calculate Kfs. Although the procedure is reported to work well in homogeneous porous media (Reynolds & Elrick 1987), undisturbed field soils are mostly heterogeneous and negative Kfs values can be obtained which indicate an anisotropic distribution of pores or, in a layered soil, they can imply that the zone of saturation has intercepted a discontinuity, such as a horizon boundary. Elrick et al. (1989) proposed a one head method using the flow rate at only one pressure head and the Richards analysis to calculate Kfs. This method divides flow out of a well into saturated and unsaturated components by taking account of the effect of soil structure and texture on capillarity (Reynolds et al., 1992). By substituting a parameter (α^*) into the equations, Kfs can be calculated. Elrick et al. (1989) suggest α^* values of 1, 4, 12 or 36 m^{-1} for the combined structural and textural conditions from compacted clays through structured soils to coarse and gravelly sands (Table 3). The use of this fixed α^* procedure avoids the possibility of negative results and was used to calculate the Kfs values for the Pilmuir flood alleviation scheme. These α^* values were validated by Lilly (1994) using data from 72 soil horizons from around Scotland which gave calculated geometric mean α^* values of 6.9 and 16.3 m^{-1} for unstructured fine textured soils and for structured soils respectively.

Table 3 Relationship of the alpha parameter (α^*) to soil structural and textural conditions.

$\alpha^*=1m^{-1}$	Compacted clays e.g. landfill caps
$\alpha^*=4\ m^{-1}$	Unstructured fine textured soils
$\alpha^*=12\ m^{-1}$	Most structured soils with clays to clay loam textures and unstructured medium or fine sands and sandy loams.
$\alpha^*=36\ m^{-1}$	Coarse and gravelly sands mainly but also some highly structured soils with large macropores.

after Elrick *et al*. 1989.

2.4.2 Results

Table 4 shows summary statistics while Figure 9 shows a map of the results. Raw data are given in Appendix 2,

In general the woodland sites had greater hydraulic conductivity than the stubble fields, and sites that were compacted had lower permeability (GP7 and GP19). Soil texture had a lower influence on the hydraulic conductivity than land use. As Kfs is a rate process, the geometric mean was determined for all data (32.3 cm/d), for stubble fields only (28.7 cm/d) and for woodland only (76.2 cm/d). The woodland soils tend to have a more stable structure that has developed relatively undisturbed as well as larger roots that may provide preferential flow pathways compared with those fields that are cropped annually.

Table 4 Summary statistics from Phase 2 data (Kfs cm/d).

	All data	Stubble fields	Woodland
mean	43.6	34.3	82.8
median	30.2	30.2	77.8
Geometric mean	32.3	28.7	76.2
Standard deviation	33.17	21.73	32.30
Lower quartile	18.1	19.0	77.4
Upper quartile	60.5	44.1	90.3

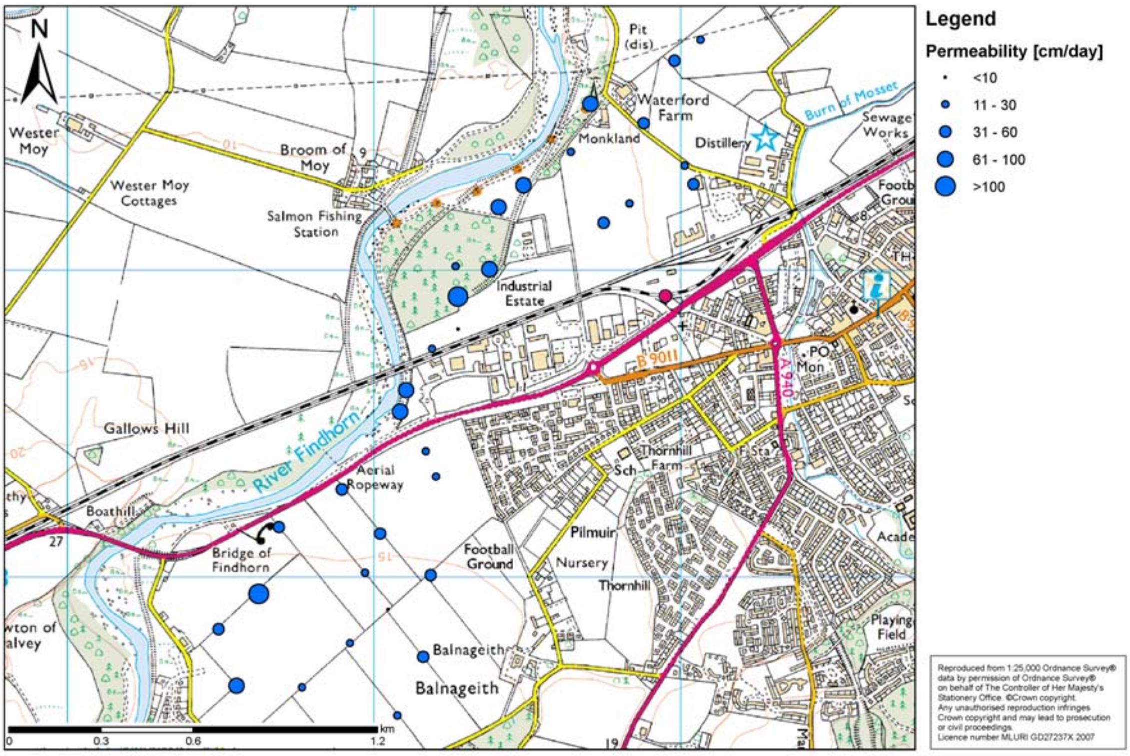

Figure 9 Results of the soil permeability testing in Phase 2.

2.5 PIEZOMETERS

Many of the piezometers in the Findhorn floodplain have been equipped with pressure transducers (divers) to measure and record variations in groundwater level. Figure 10 shows the available data for the past year. There is one years data for piezometers drilled in Phase 1. Piezometers drilled in Phase 2 have been monitored since December 2007. If the data are continually collected for several years the response of the groundwater to rainfall and flood can be directly measured.

Several preliminarily conclusions can be drawn from the data:

- All piezometers show little systematic annual variation. Water-levels are controlled by river stage, and the response to individual rainfall events.
- Piezometers close to the river show a marked connection to the river. Piezometers in this category include 101 and 106, 111, 110, and to a lesser extent 108 and 107. These piezometers respond closely to river stage. Piezometer 101 gives the greatest response, with the groundwater levels rising by more than 1 m in response to the high river levels in December 07. Water-levels took two weeks to recede and closely correspond to the recession of the river.
- Piezometers in the middle of flood plain (102, 103, 28, 14) show a slow response to recharge, and do not respond to individual events, either rainfall, or river stage. The amplitude of rises are in the order of 0.5 m, indicating a significant change in groundwater storage across the aquifer.
- Piezometers in the Pilmuir area close to the existing drain, most notably, P4, P3, P2, 11, 12, 13 show muted responses, with variations over 2007 of up to 0.5 m. Water-levels can rise (up to 0.3 m) rapidly – and generally in response to large rainfall events. Recession, however, is very slow and can take several months. P4 has very muted responses (0.2 m) and the water-levels may be controlled by the existing drains.
- Piezometer 104 (in the line of the proposed west Forres embankment) appears a composite response, with some influence from the river stage, superimposed on the more gradual response of the flood plain boreholes. P1 also appears to be a composite – with a response to individual rainfall events superimposed on the generally more muted response of the Pilmuir discharge area.

It is imperative that the piezometers continue to be monitored for several years, to build up a picture of groundwater response to river stage, rainfall and flood.

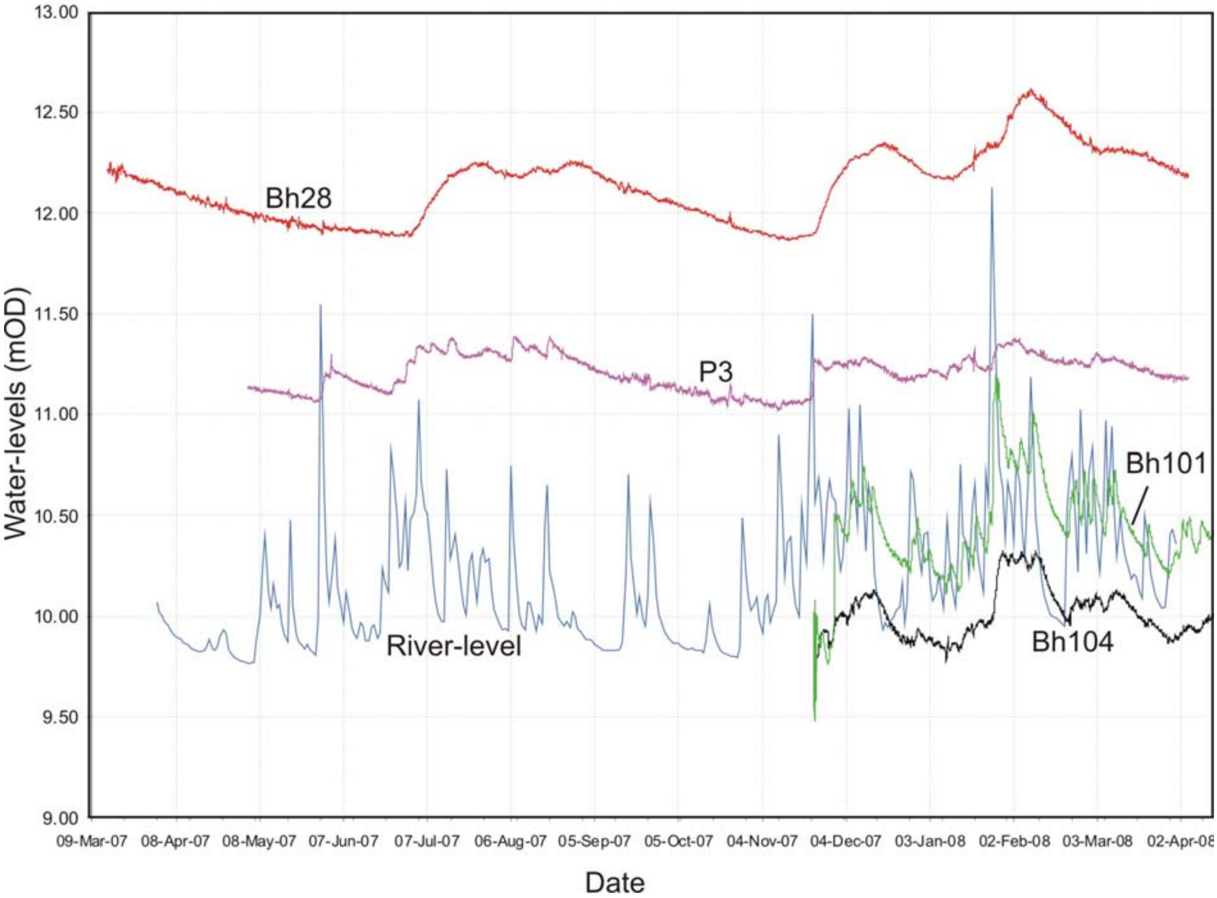

Figure 10 Water-levels for selected peizometers in the Forres River Findhorn flood alleviation scheme.

3 Hydrogeological summary

3.1 HYDROGEOLOGY

The data collection and analysis has allowed the hydrogeology of the west Forres area to be understood in greater detail and with greater confidence. The hydrogeological investigations indicate that there is a dual aquifer system in the Pilmuir catchment, with a shallow superficial aquifer that is generally highly permeable, and a deeper bedrock aquifer.

The **bedrock aquifer** comprises sandstones, of Devonian age, which in this area typically form a moderately to highly productive aquifer and groundwater flow is primarily through fractures. Transmissivity is approximately 50 m^2/d. and the water is weakly mineralised, is generally reducing in nature, and dominated by Ca-HCO_3 ions. The chemistry of the water is similar over much of the area and groundwater residence time may be greater than 25 years.

The shallow **superficial aquifer** comprises Quaternary deposits dominated by sands and gravel. Following the inclusion of additional data from Phase 2, a more complex pattern to the measured transmissivity values emerges. While there is still a detectable trend with depth (transmissivity is generally low below 8 m), there is additional variability in the shallow data with some piezometers in the depth range 6 – 7 m having low transmissivity. This is interpreted as variations in superficial geology and possibly silt filled channels. However the overall pattern is clear: transmissivity is generally high at shallow depths and in excess of 1000 m^2/d. Given the thickness of the gravel sequences, this can be interpreted as the permeability of the shallow deposits generally being in the range of 100 – 1000 m/d. The deeper (> 8 m) deposits tend to have transmissivity less than 10 m^2/d, although transmissivity can be higher within deeper channels of more permeable material.

Groundwater chemistry and water-level variations in the shallow Quaternary deposits are variable, depending on the origin of the recharging water. These data have helped provide a conceptual model of groundwater flow in the superficial deposits:

- Groundwater flow is generally from south to north and discharges to the lower reaches of the rivers, drains and channels, and the Findhorn Bay.
- Groundwater is recharged from various sources: the River Findhorn, recharge in the upper parts of the Pilmuir catchment (e.g. around Knockomie) and direct recharge from rainfall on the floodplain.
- On the floodplain, flow is mostly within the top 8 m of the superficial deposits; at depth flow is more sluggish, due to the lower permeability.
- Groundwater residence times are less than 10-15 years in the superficial deposits.
- The River Findhorn is well connected to the aquifer system. In the south of the area, the river is losing water to the superficial deposits (and may possibly lose water to the bedrock aquifer). Further north, water-levels in the aquifer and river are similar and there is a complex interaction between river and aquifer depending on river stage.
- Groundwater discharges constantly through the existing storm drain system in Plimuir, and in channels to the north of Forres.
- Groundwater levels are shallow and approach ground surface in parts of the nursery area at Plimuir.
- Groundwater from the sandstone mixes with the groundwater in the lower portions of the superficial aquifer, but volumes of flow are unlikely to be high.

3.2 FLOODING

From the groundwater investigations it is possible to infer mechanisms for flooding in the Pilmuir area:

- Very shallow groundwater gives rise to marshy areas, some peat development and willow growth in the Pilmuir area. The water-logged soils also reduce the ability of rain to infiltrate, leading to large areas of ponded water for parts of the year (this can be observed most years).
- The increased urbanisation in the upper part of the catchment is likely to have increased runoff, and the use of soakaways will have raised groundwater levels in the lower part of the catchments.
- Groundwater will also play a role in the larger flood events. Generally, the high infiltration capacity of the soil in the upper parts of the catchment means that runoff is limited, and the flood extent is reduced. However, as described above, infiltration in the low-lying areas is negligible where groundwater-levels are at the ground surface.
- The constant groundwater discharge through the existing storm water drain also reduces the capacity of the drain to discharge runoff during flood events. It is likely that in an extreme flood the drain will exceed capacity causing additional flooding, possibly along the line of the drain.
- In flood events of > 25 years return period, floodwaters from the River Findhorn flow through western Forres (see Figure 2). Given the high permeability of the soil (0.3 m/d) a great proportion of this water is likely to infiltrate the aquifer[1]. Since the floodwaters cross urban and industrial sites this could cause significant groundwater contamination, and also elevated groundwater levels (with associated groundwater flooding) for many months. This is consistent with observations from the 1829 flood where it was reported that the land surface remained flooded in certain areas for a very long time after the flood events (McEwen and Werritty 2007).

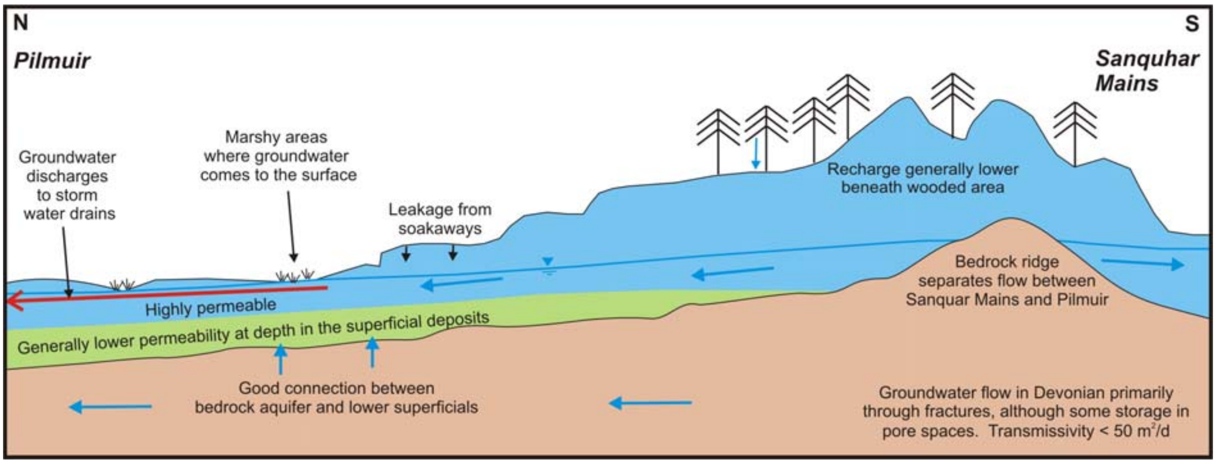

Figure 11 A schematic cross section of the hydrogeology of the Pilmuir sub-catchment.

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[1] Assuming similar conditions to the modelled area (soil permeability 0.3 m/d, soil depth 0.4 m, flooding for 1 day and flood extent as shown in MFA/Royal Haskoning 1 in 200 year do nothing option) the amount of water entering the groundwater would be in the region of 700,000 m^3, and of poor quality since it has passed through urban and contaminated areas.

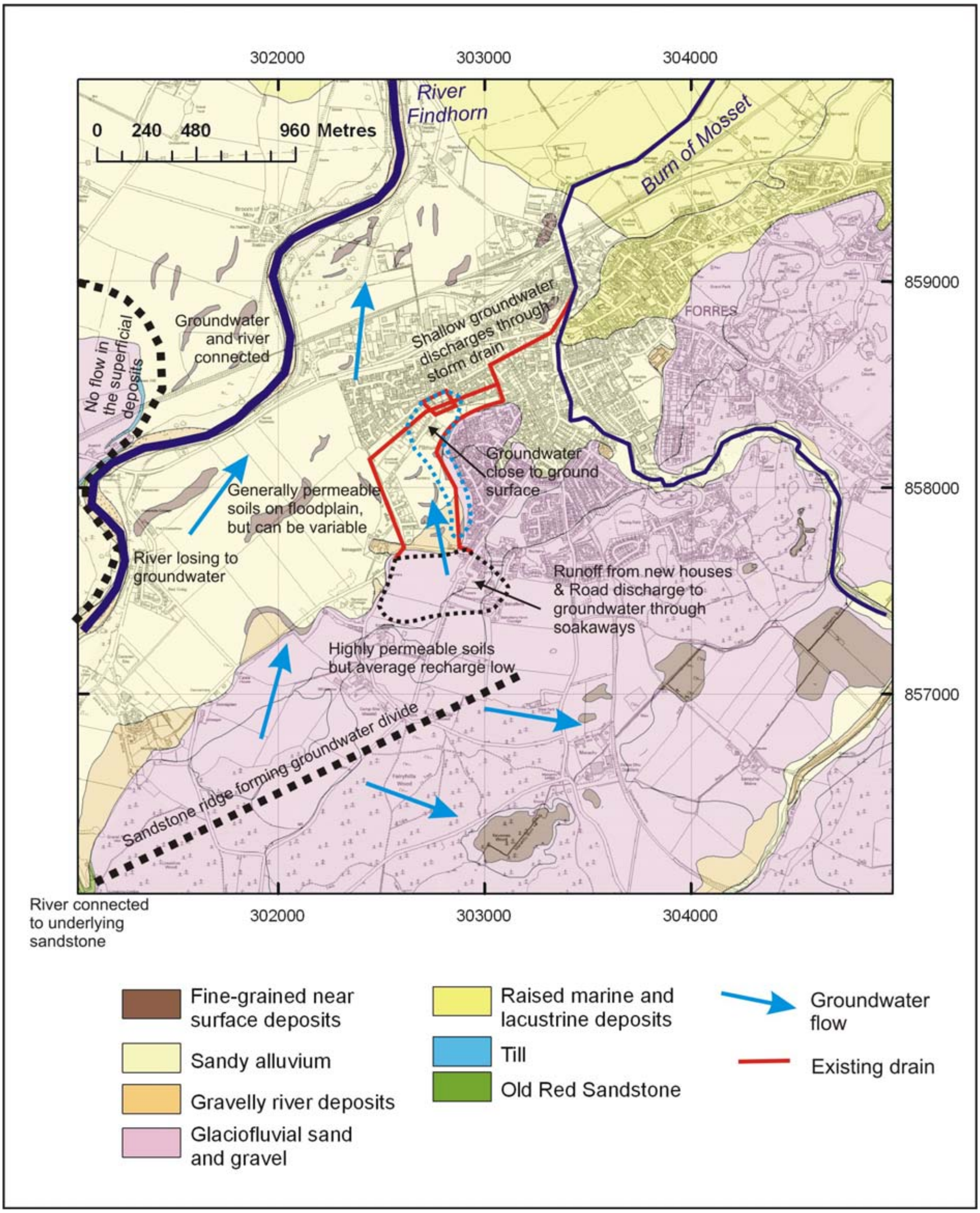

Figure 12 A summary of the main hydrogeological features of western Forres.

4 Groundwater modelling and flood predictions

4.1 GROUNDWATER MODEL

The aim of the groundwater flow modelling was to determine the impact of the flood alleviation scheme (FAS) on groundwater in west Forres. The main aspects of the FAS modelled were: the new Pilmuir drain, the impoundment caused by the new embankments on the right bank of the river Findhorn, and the installation of a grout curtain at the Garden Centre to protect the Industrial Estate area. Figure 2 shows the location of these engineering measures.

This modelling work builds on the work carried out for the Phase 1 report using the ZOOM suit of numerical groundwater models (MacDonald et al. 2007). More detail on the model construction and runs is given in the Appendix 3. A summary of the model features is given below.

- The model boundaries have been revised from Phase 1 work. The western boundary is now to the west of Muckle Burn (See Figure 13).
- There are three rivers in the model: Muckle Burn, River Findhorn and the Burn of Mosset. The model also allows leakage to the Findhorn Bay.
- The model is constructed as having two layers representing the superficial deposits and the sandstone.
- The recharge is calculated using the ZOODRM recharge model using daily rainfall data (see Appendix 3) and additional inputs from the soakaways around the newer housing developments.
- The transmissivity (T) distribution is based on the pumping test data from the site investigations. T is 1000 m^2/d over much of the floodplain, and 50 m^2/d in the superficial deposits away from the flood plain, reflecting the thin saturated zone as described in MacDonald et al. (2006) for Chapeltonmoss.
- The rivers are connected to the superficial aquifer, and to the bedrock aquifer where bedrock is exposed in the river bed.
- The existing drain in the Pilmuir area (refined area marked in Figure 13) has been included in the model. The flow in this drain has been measured on two occasions and is in the range of 20 – 30 l/s.
- The model was run initially as a steady state simulation. Figure 14 shows the comparison between measured heads in November 2007 and the steady state model for the refined area. There is good agreement over much of the area of interest (12 – 8 m head contours), although heads are slightly too high to the north of the area of interest towards the Findhorn bay. This is likely to be due to drains not being mapped and modelled for this northern area.
- A dynamic balance approach was used for all prediction runs to give a better understanding of how the system responds to seasonal variations.

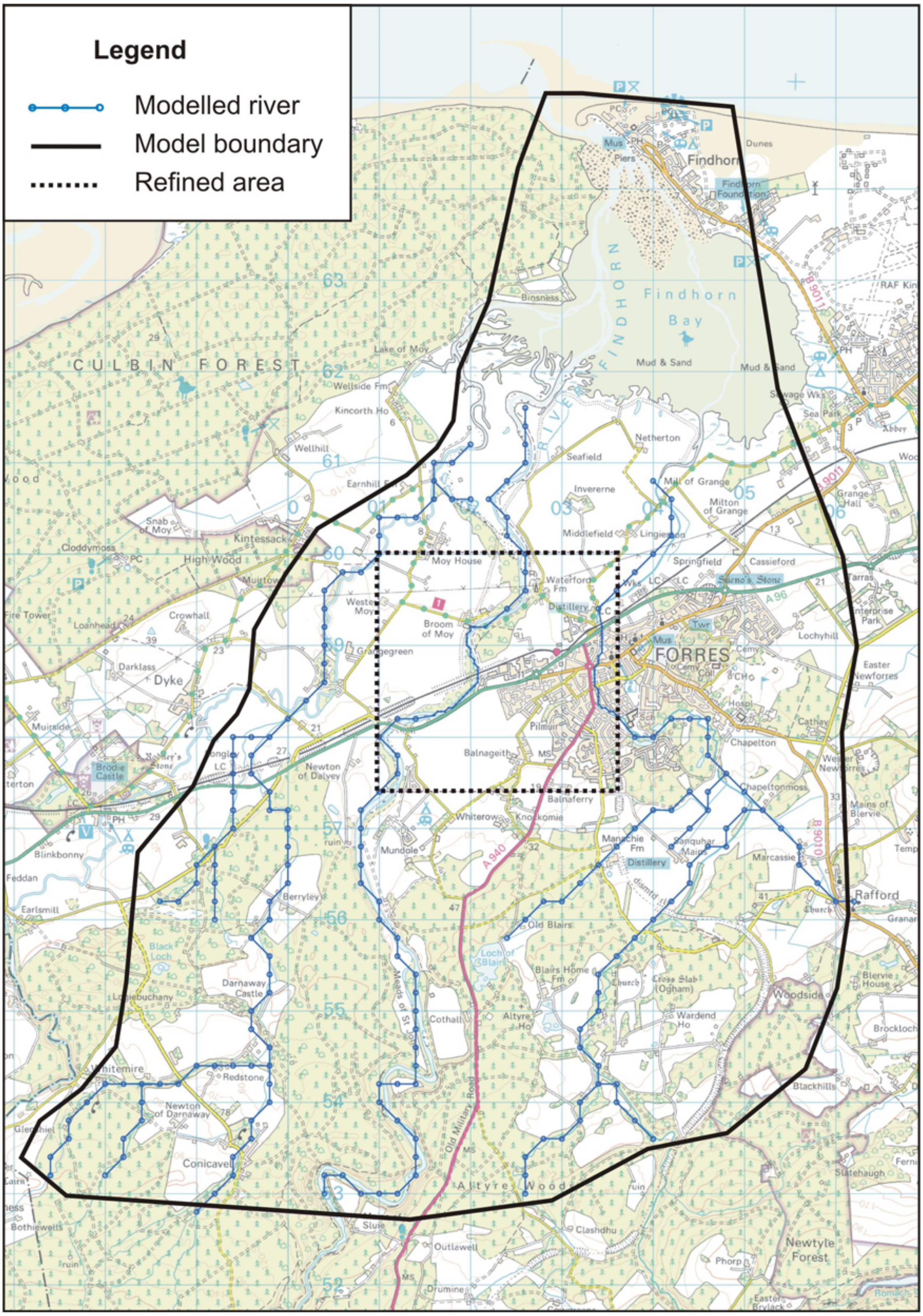

Figure 13 Modelled area and boundary conditions.

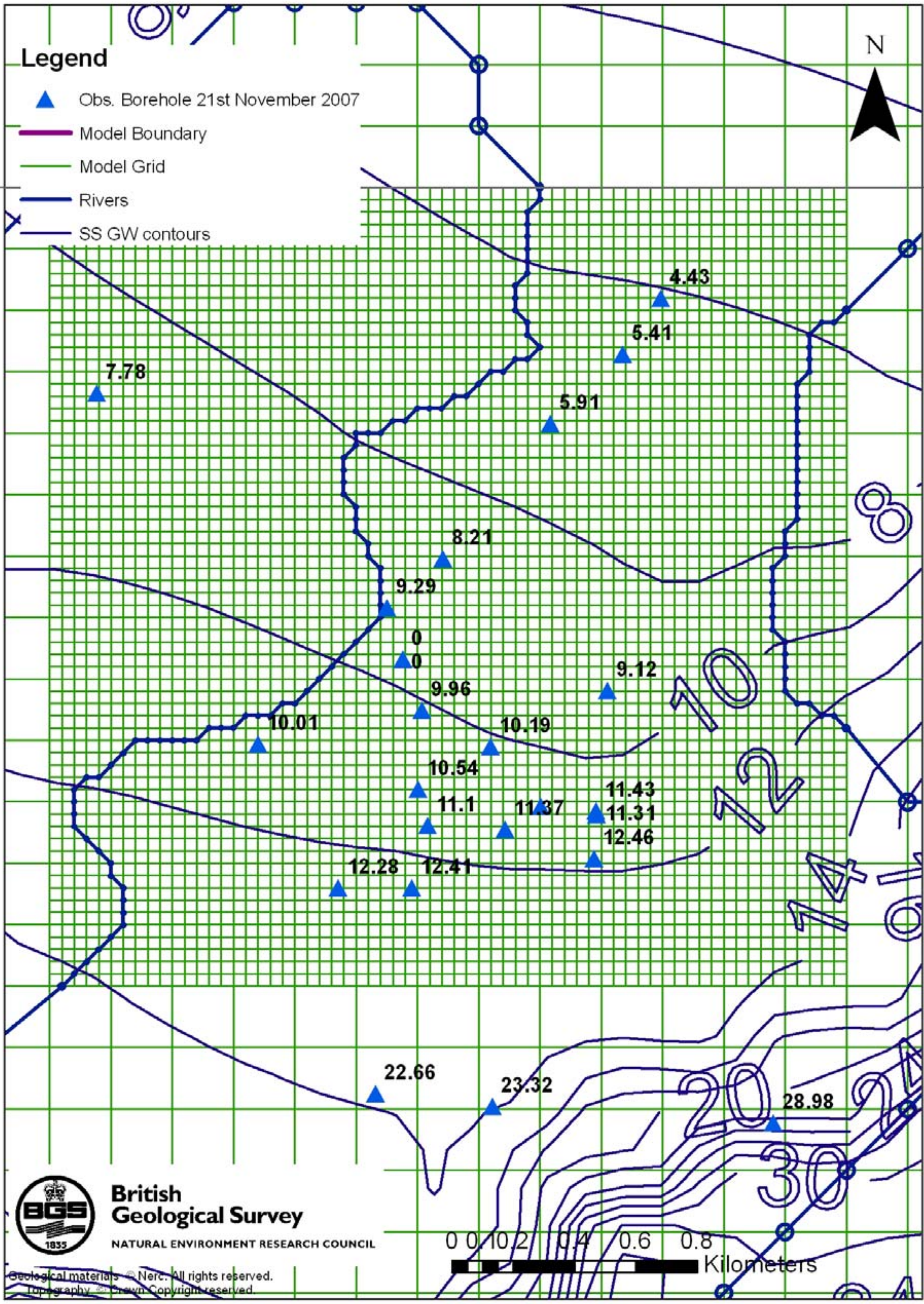

Figure 14 Steady-state head contours for the best steady state model compared to the observed data from 21 Nov 2007.

4.2 MODEL RUNS

4.2.1 Overview

Seven different scenarios were modelled. These were undertaken using a dynamic balance approach. A dynamic balance is a model run using a repeated series of monthly average recharge. The model is run until the groundwater heads and outflows in any particular month are identical from one year to the next. For this project, the use of dynamic balance run serves two purposes: (1) to get the model operating in a time variant mode to determine if the model reproduces seasonal responses; and (2) to see if the "expected" pattern of flooding on the Pilmuir area is reproduced.

During the flood predictions the river stage in the River Findorn is raised, and the inundated area is represented as a series of additional recharge and river nodes. For some of the scenarios additional recharge was given to the entire modelled area to represent intense rainfall during the flooding. The flooding was assumed to happen in June since climate modelling suggests that the highest risk of flooding will occur during intense summer storms. As a worst possible scenario high recharge antecedent conditions were applied for the preceding 6 months before the flood (December to May).

The seven dynamic balance prediction runs:

Basecase (0): average monthly rainfall, no engineering measures and no flooding.

Engineering Basecase (1a): as 0, but adding in the new drain, grout curtain and embankments.

Engineering Basecase with high rainfall (1b): as 1a, but adding in a 60 mm recharge event across the entire catchment over 1 day to simulate a summer storm.

1 in 50 year flood (2): using Engineering Basecase 1a and adding in the area inundated by 1: 50 year flood waters for 1 day.

1 in 200 year flood (3): using Engineering Basecase 1a and adding in the area inundated by 1: 200 year flood waters for 1 day.

1 in 200 year flood with rain (4): as 3 but adding in 60 mm recharge across who catchment for 1 day.

1 in 200 year flood, worst case (5): as 4 but adding in 6 months of exceptionally high recharge prior to the flood event.

After each flooding scenario, the recharge reverts to the Basecase, and the water-levels and discharge are monitored for a further 100 days. Areas of shallow groundwater are mapped and also the difference in groundwater levels between the flooding scenario and Basecase 0. These are shown in Appendix 3.

4.2.2 Basecase 0

The recharge time series used for the dynamic balance for the Basecase is presented in Appendix 3 and is calculated from existing daily data. The use of this recharge time series produces groundwater hydrographs which can be compared with measured data. This is the basecase against which each flooding scenario is compared. The modelled groundwater heads have been interpreted to give the groundwater levels with respect to the ground surface for 1 day, 10 days and 100 days after 1st June (Figure 15).

These plots indicate three features of base groundwater conditions:

- The shallow groundwater levels (< 1 m deep) observed in the Pilmuir area are well represented by the model.
- North of Forres, (most notably to the north of the Broom of Moy and the Benromach distillery) show shallow groundwater-levels and in some cases groundwater flooding. It is likely that these areas are not permanently wet, because of the extensive drainage network (in the form of open ditches) in the area (not included in the model) which lowers the groundwater heads.
- Shallow groundwater conditions can exist all year round, and are related to rainfall events, rather than a predictable winter high.

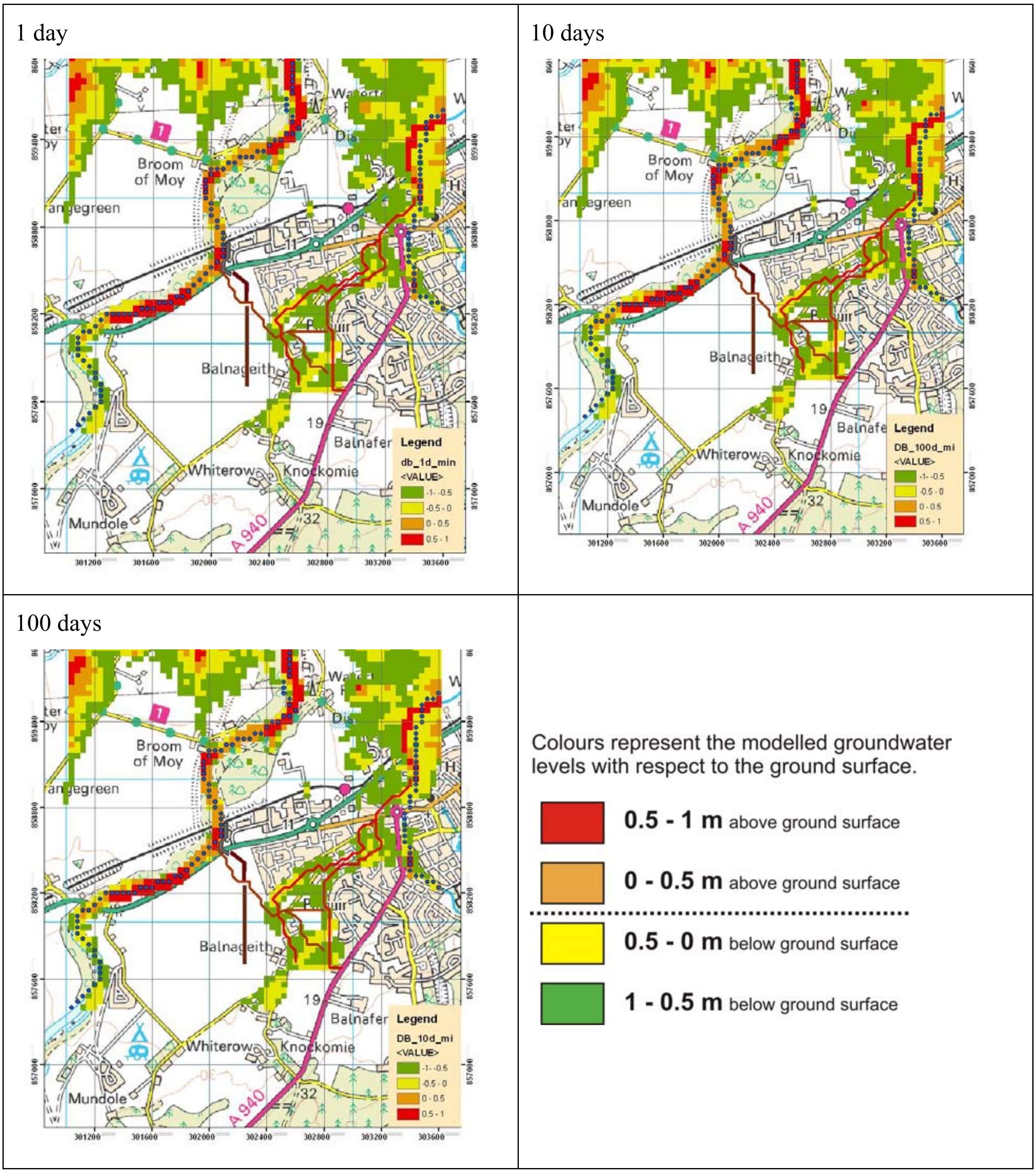

Figure 15 Shallow groundwater levels predicted for the Basecase 1a starting from 1 June.

4.2.3 Summary of prediction runs

Details and discussion of the prediction runs are given in Appendix 3, the main issues are summarised here. Table 5 summarises the flows for each scenario in the existing storm drain in Pilmuir, the proposed new Pilmuir channel and the outflow to the estuary. The maximum groundwater-level rise in five piezometers around the West Forres embankment is also given for comparison.

General comments from the modelling:

- The flow in the existing storms drains under base conditions (24 l/s) is in the range of that measured by Moray Flood Alleviation (20 - 30 l/s)
- Heavy rainfall events raise groundwater-levels across the entire area and considerably increase the groundwater contribution to flow in the existing storm drains, and increase the extent of shallow groundwater levels and potential groundwater flooding (Figure 16).
- The existing stormwater drains in Pilmuir have the effect of reducing groundwater-level variations in that area (see small variation in P4 in Table 5). However, this depends critically on the capacity of these drains, and effectively reduces their capacity to remove runoff (Figure 17).

Comments on the effect of the engineering works on groundwater flow under non-flooding conditions:

- Groundwater contribution to flow in the proposed new channel under non flooding base conditions (0, 1a), and even with heavy rainfall (1b) is negligible.
- The grout curtain adjacent to the garden centre (see Figure 2) will have a negligible effect on the overall groundwater flow under the floodplain (see data in Appendix 3).

Comments on the effect of the engineering works on groundwater conditions under flooding:

- The effect of impoundment behind the embankments for 1 day allows flood water to enter the groundwater system and raise groundwater levels beneath the impounded area. For a 1 in 50 year event the amount of water may be in the order of 100,000 m^3, and for a 1 in 200 year event 200,000 – 300,000 m^3. This is less than what would be expected if the flood waters were allowed to spread over a larger area.
- This additional water enters groundwater storage and discharges over the next few months back to the River Findhorn and the new channel (Figure 18).
- The industrial area is protected from groundwater flooding by the grout curtain, additional groundwater flows northward and discharges to the River Findhorn.
- The area of significant groundwater levels rise (> 0. 5 m) is largely constrained to near the river (Figure 18) and the additional groundwater flooding from the impoundment is not predicted to be significant (Figure 19).
- The predicted hydrograph responses (see Figure 20) suggest an abrupt rise in groundwater level in the flooded area and near to the river (BH02, BH101), followed by a decay to near normal levels after 60 – 90 days. At the west Forres embankment (BH104), groundwater levels are predicted to rise 1 – 1.5 m, and decay to only 0.5 m above normal in 30 days. In Pilmuir (P4) groundwater levels are not significantly affected by the additional groundwater.

Comments on the worst case scenario (5):

- High rainfall (recharge of 60 mm in one day) coupled with exceptionally high groundwater levels in the preceding 6 months, and a 1 in 200 year river flood event has the most significant effect on groundwater flooding and flows in the existing drain (see Appendix 3 and Table 5).
- The effect is more to do with the high local groundwater recharge across the area than the short term floodwaters. In fact, the amount of floodwaters entering the aquifer actually decreases (Table 5) relative to other scenarios since the elevated groundwater levels allow less water to enter the system,

Table 5 Summary flow and groundwater-level information for the various model scenarios.

Run	Outflow from groundwater system (l/s)			Flow into model due to flooding (l/s)	Maximum groundwater head (m OD)				
	Estuary	Existing Drain	Proposed Pilmuir channel		02	101	14	104	P4
0	206.40	24.01	n/a	n/a	12.75	11.05	11.60	10.21	8.94
1a	206.34	23.65	0.09	n/a	12.76	11.07	11.61	10.22	8.94
1b	548.94	45.97	0.86	n/a	12.98	11.31	11.84	10.45	9.14
2	206.53	25.96	5.18	1271.90	12.79	11.17	11.67	10.46	8.95
3	206.59	27.46	18.27	2761.21	13.22	12.27	11.94	11.50	8.96
4	549.24	45.99	20.87	3200.59	13.51	12.44	12.09	11.58	9.14
5	749.07	79.53	32.00	2309.87	14.23	13.05	12.68	12.01	9.31

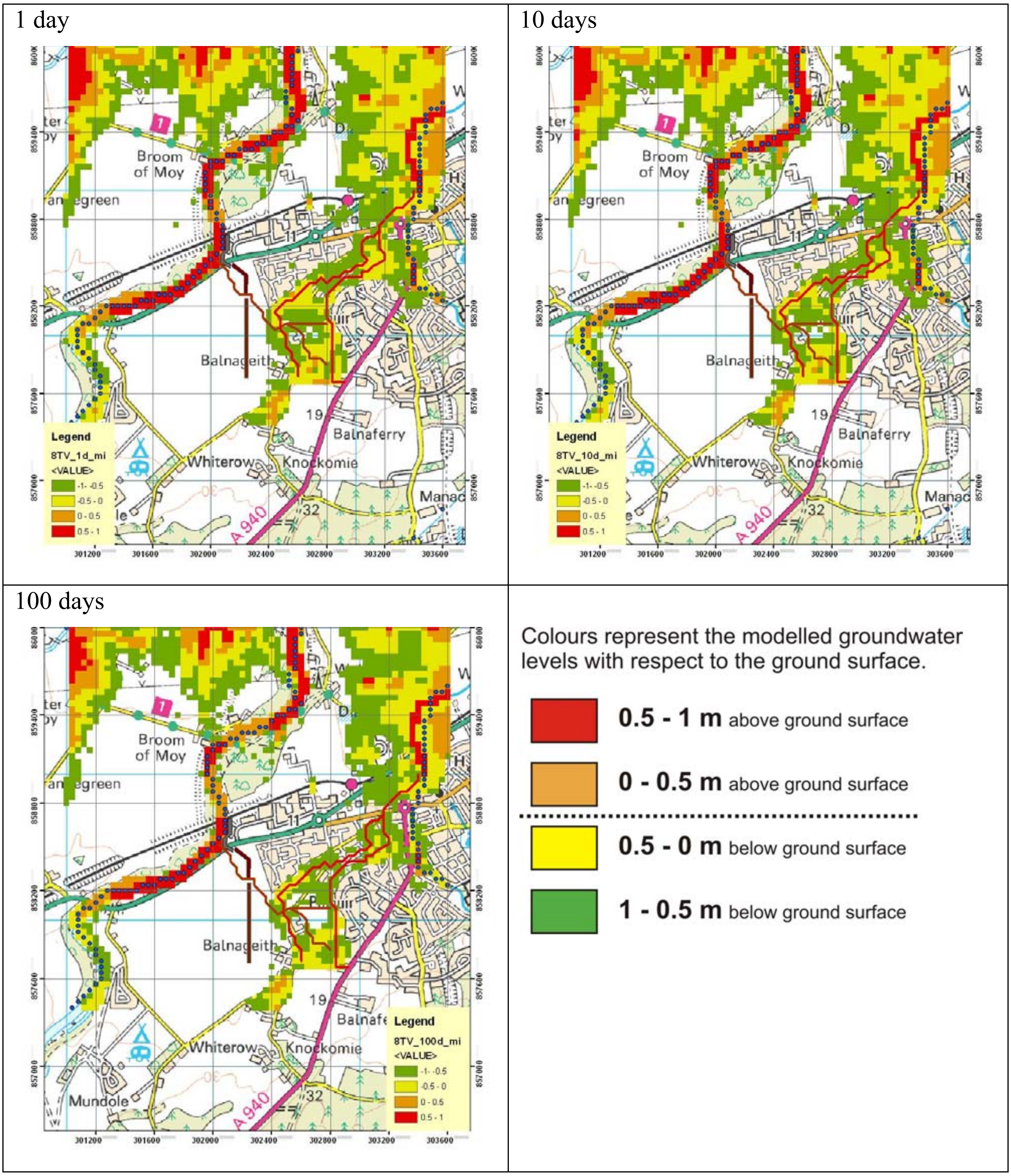

Figure 16 Modelled shallow groundwater after heavy local (60 mm) recharge (Run 1b).

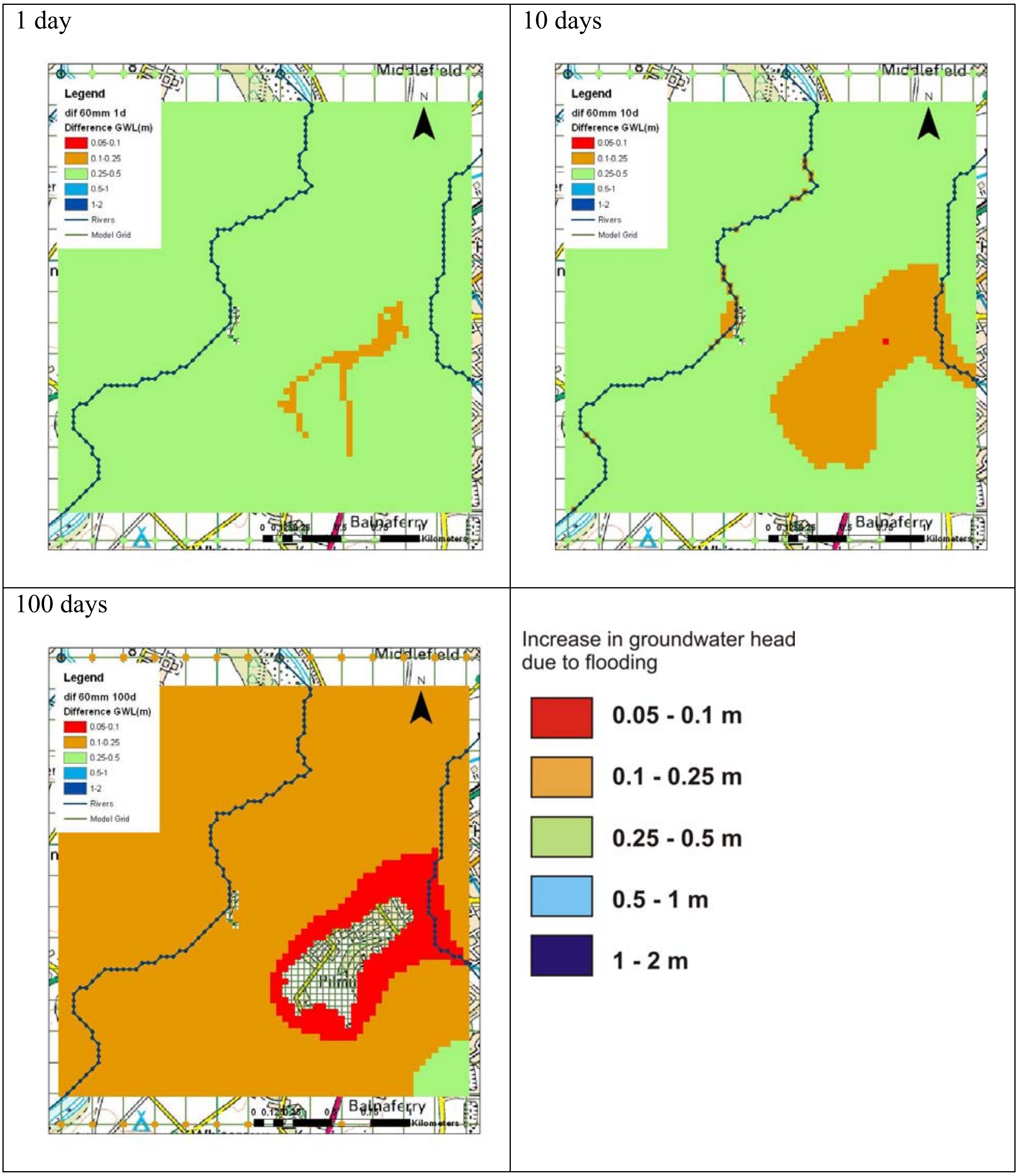

Figure 17 Difference in groundwater levels between model Run 1b (60 mm recharge event) and basecase 1a for 100 days after the rainfall event (mode plots in Appendix 3).

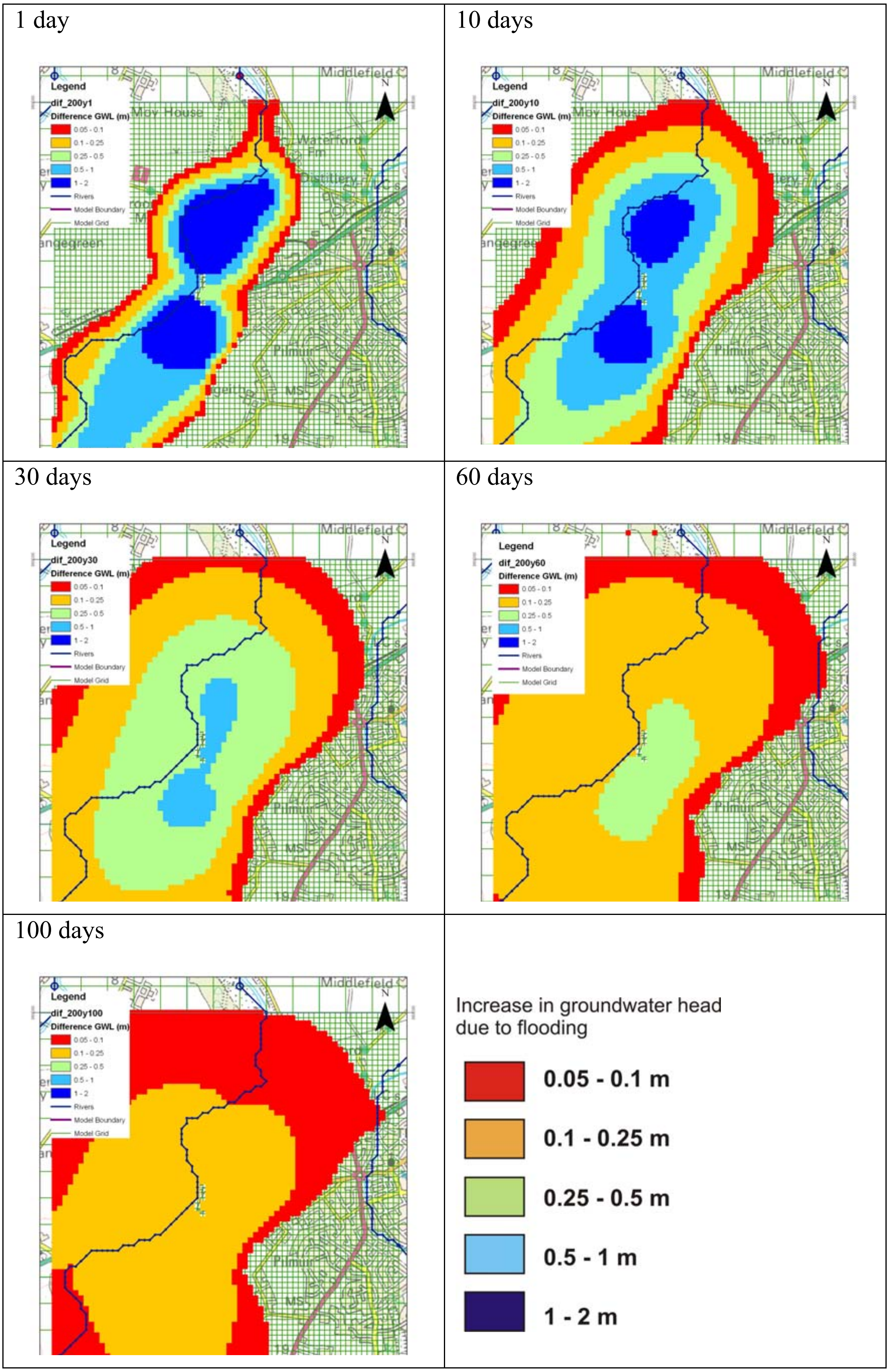

Figure 18 The difference between groundwater levels for a 1in 200 year flooding event and the Basecase (Run 1a).

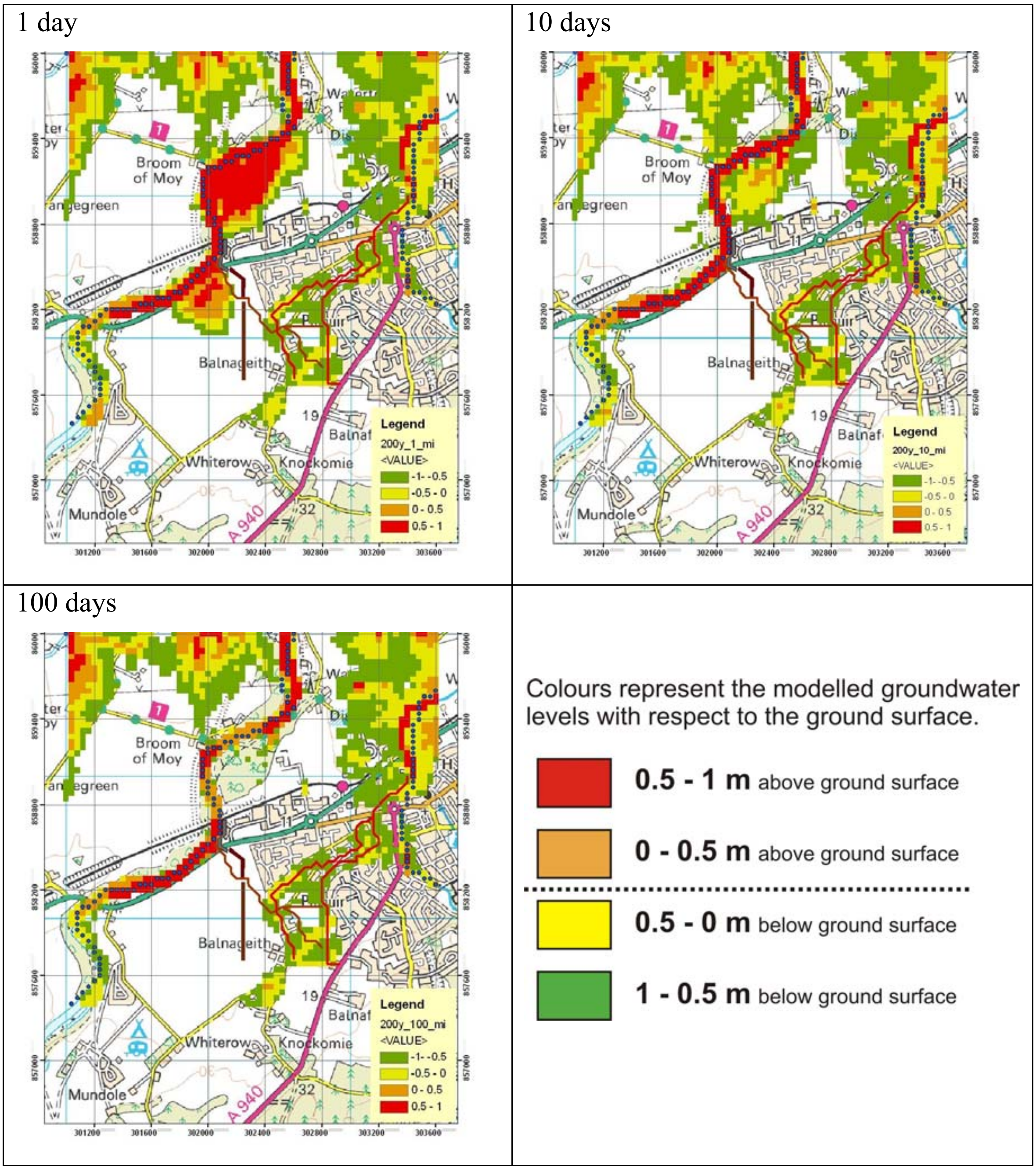

Figure 19 Areas of shallow groundwater associated with the 1 in 200 year flooding event.

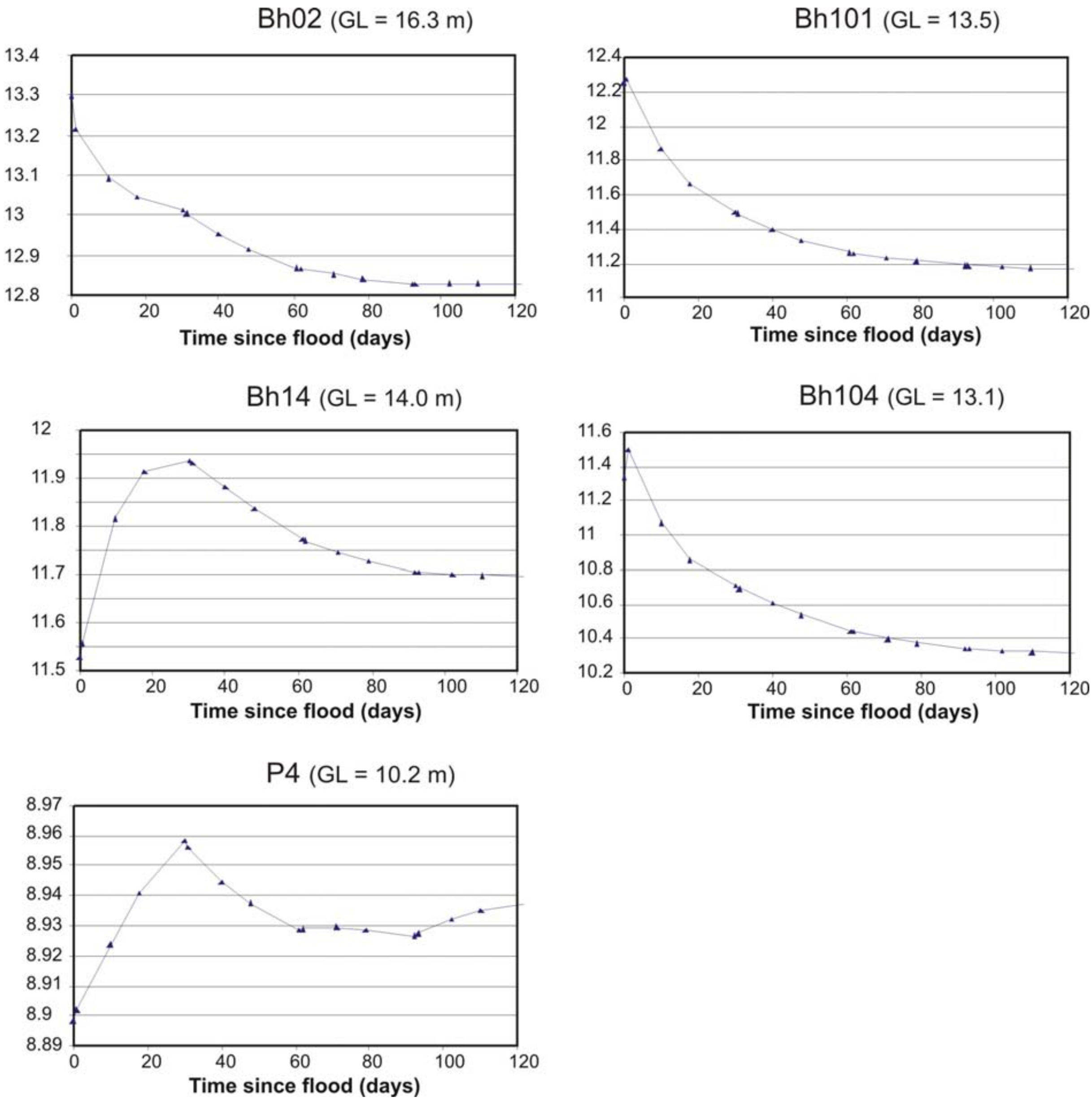

Figure 20 Modelled borehole hydrograph response for 1 in 200 year flooding event for selected piezometers.

5 Conclusions

The additional data collection and numerical modelling has helped build up a better understanding of the groundwater system between Forres and the River Findhorn and the relation between groundwater and flooding. The situation is complex, and detailed comments are contained within this report on how groundwater is likely to behave under different scenarios. Several broad important conclusions are drawn out here:

1 The superficial deposits in the area where the flood alleviation scheme is proposed are highly permeable at shallow depths (100 – 1000 m/d).

2 The permeability (0.3 m/d) and extent of the top soil is highly significant in controlling the volume of floodwaters entering the aquifer.

3 The proposed engineering works (embankments, channel and grout curtain) will have negligible impact on groundwater flow in the flood plain under normal situations

4 Storing floodwaters on the floodplain between the river Findhorn and the west Forres embankments is likely to result in up to 300,000 m^3 of floodwaters entering the groundwater system. This is considerably less than what would be expected if the flood waters were allowed to spread over a larger area (up to 700,000 m^3).

5 The additional floodwaters entering the groundwater system from a 1 in 200 year river flood event, are unlikely to lead to groundwater flooding: most of the water will discharge to the proposed new Pilmuir channel and the River Findhorn over the following weeks and months.

6 The area of significant groundwater levels rise (> 0.5 m) after flooding is largely constrained to near the river – additional groundwater flooding in the Pilmuir area from the impoundment is not predicted to be significant.

7 Modelling indicates that the short term storage of floodwaters on the floodplain has a much smaller effect on groundwater levels, flow in existing drains, and groundwater flooding than sustained high local groundwater recharge from rainfall across the area for 6 months, followed by an intense rainfall event.

This study focussed on the response of groundwater to flooding and the impact of the proposed engineering works. However, some wider recommendations can be given.

- The existing drain (pipe) in the Pilmuir area is required to discharge groundwater, and has little capacity for runoff. The proposed new Pilmuir channel should therefore by designed to take most of the runoff, and if possible also used to intercept groundwater.
- The West Forres Embankment is located on highly permeable gravels, although the modelling in this study has demonstrated that this is unlikely to lead to catastrophic groundwater flooding, detailed modelling of the engineering stability of the embankment should be undertaken.
- The use of soakaways and SUDs in the Pilmuir area, associated with recent and proposed housing development, will lead to increased groundwater levels and the potential for more groundwater flooding in the lower catchment. Alternatives should be sought for future housing developments.

- It is essential to continue to monitor the groundwater levels, rainfall and river flow across the flood plain to build up a more comprehensive picture of groundwater response to rainfall and elevated river stage.
- Flows in the existing drains and ditches in the area to the north of Forres should be measured to improve mode accuracy to the north of Forres.

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Appendix 1 Pumping test data

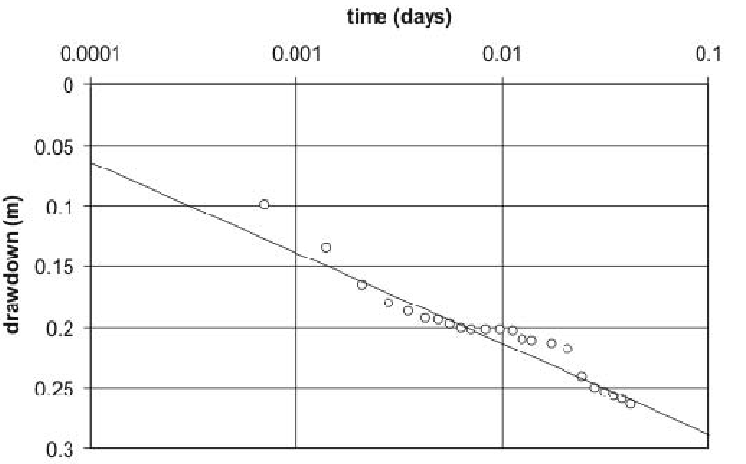
Bh100

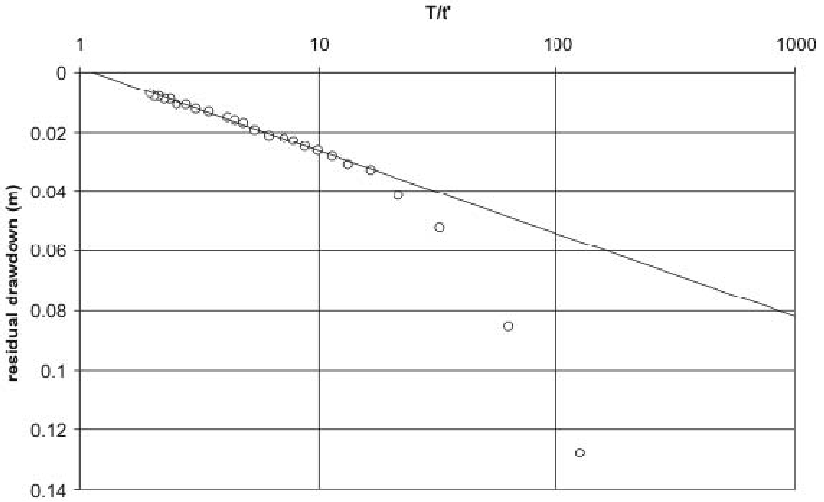
Depth:
Diameter: 102 mm
Date test: 12/12/07
Pumping rate: 0.88 l/s
Length of test: 60 minutes
RWL: 3.2 mBGL

Transmissivity:

188 m²/d (Jacob's approximation)

497 m²/d (Theis recovery)

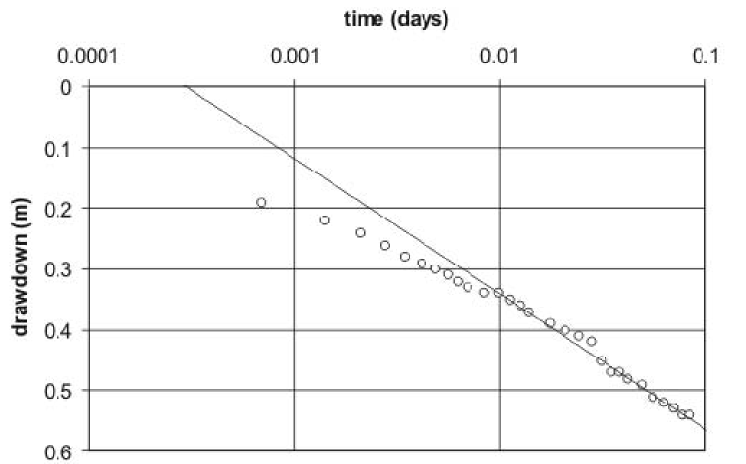




Bh101

Depth: 8 mBGL
Diameter: 102 mm
Date test: 22/11/07
Pumping rate: 0.98 l/s
Length of test: 120 min.
RWL: 3.03 mBGL

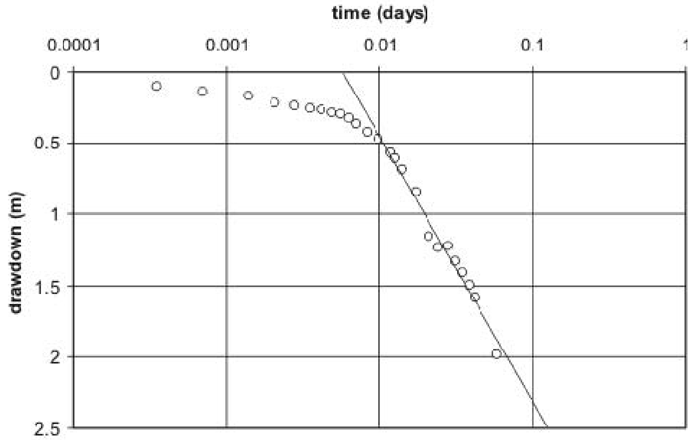
Transmissivity: 69 m²/d (Jacob's approximation)



Bh102

Depth: 7 mBGL
Diameter: 102 mm
Date test: 29/11/07
Pumping rate: 0.08 l/s
Length of test: 85 minutes
RWL: 2.97 mBGL

Transmissivity: 0.63 m²/d
(Jacob's approximation)



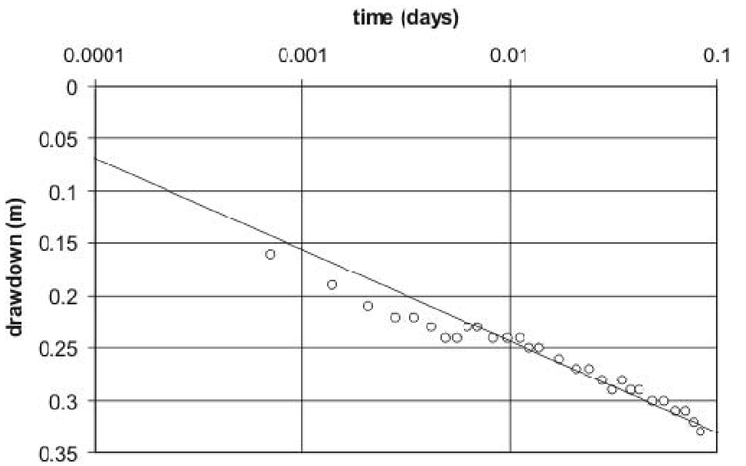
Bh104

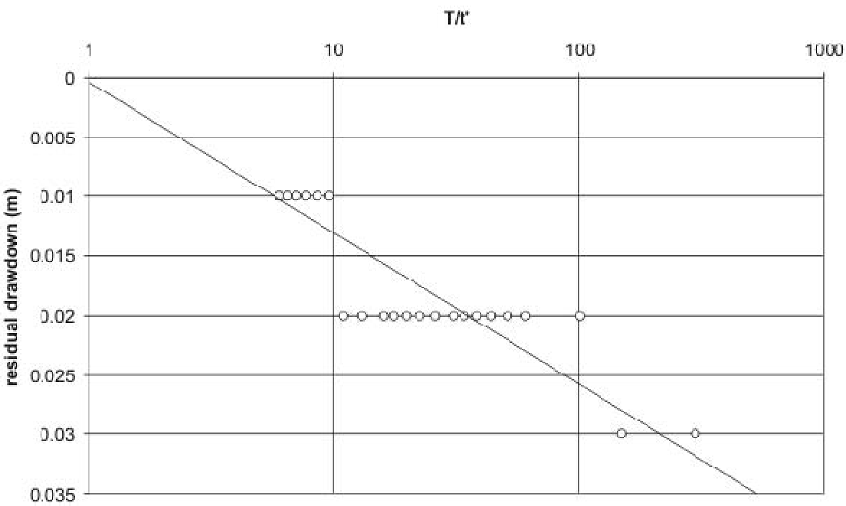
Depth: 9 mBGL
Diameter: 102 mm
Date test: 28/11/07
Pumping rate: 2.38 l/s
Length of test: 300 minutes
RWL: 3.14 mBGL

Transmissivity:

434 m²/d (Jacob's approximation)

2839 m²/d (Theis recovery)



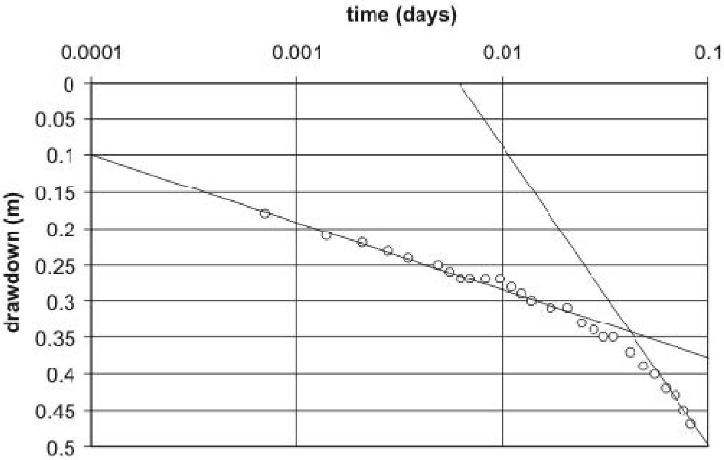


Bh103

Depth: 8.5 mBGL
Diameter: 102 mm
Date test: 23/11/07
Pumping rate: 0.28 l/s
Length of test: 120 minutes
RWL: 3.69 mBGL

Transmissivity:

31.26 m²/d
(Jacob's approximation - early)
11.46 m²/d
(Jacob's approximation – late)



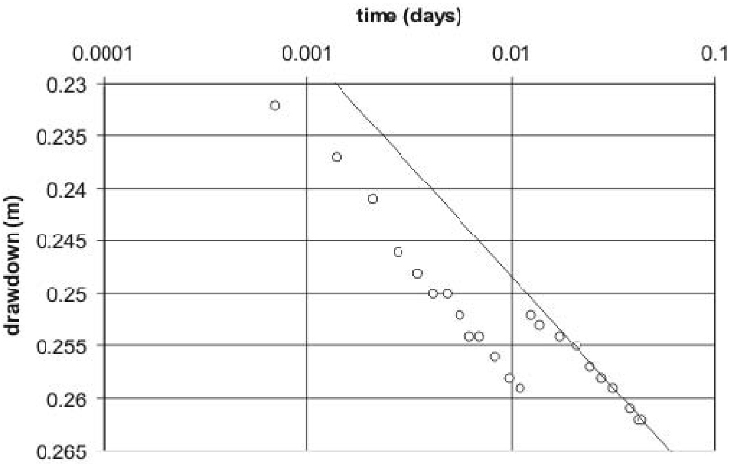
Bh105

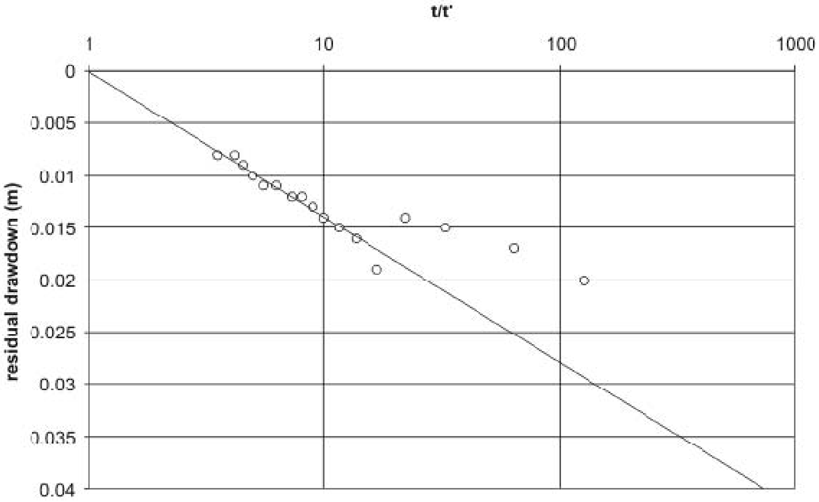
Depth: 7 mBGL
Diameter: 102 mm
Date test: 13/12/07
Pumping rate: 1.56 l/s
Length of test: 63 minutes
RWL: 2.55 mBGL

Transmissivity:

1259 m²/d (Jacob's approximation)

1750 m²/d (Theis recovery)



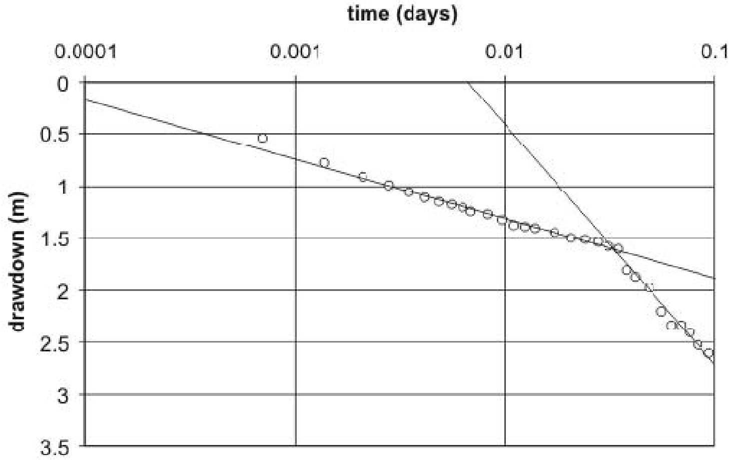


Bh106

Depth: 12.5 mBGL
Diameter: 102 mm
Date test: 25/11/07
Pumping rate: 0.13 l/s
Length of test: 300 minutes
RWL: 3.28 mBGL

Transmissivity:

4.19 m²/d
(Jacob's approximation - early)
0.91 m²/d
(Jacob's approximation – late)



Bh108

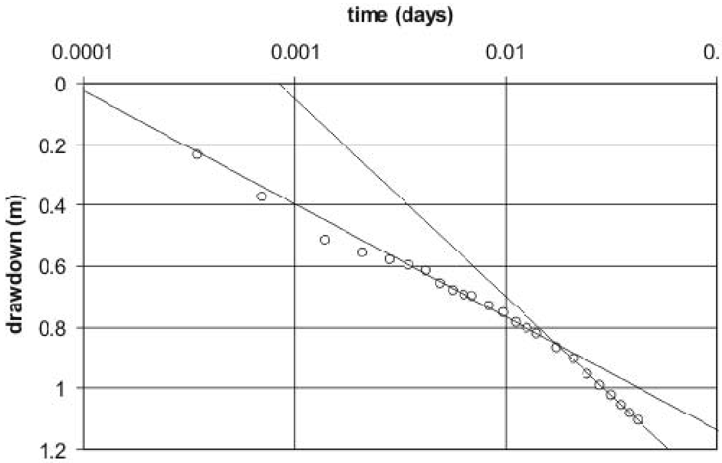
Depth: 7.85 mBGL
Diameter: 102 mm
Date test: 11/12/07
Pumping rate: 1.47 l/s
Length of test: 62 minutes
RWL: 1.81 mBGL

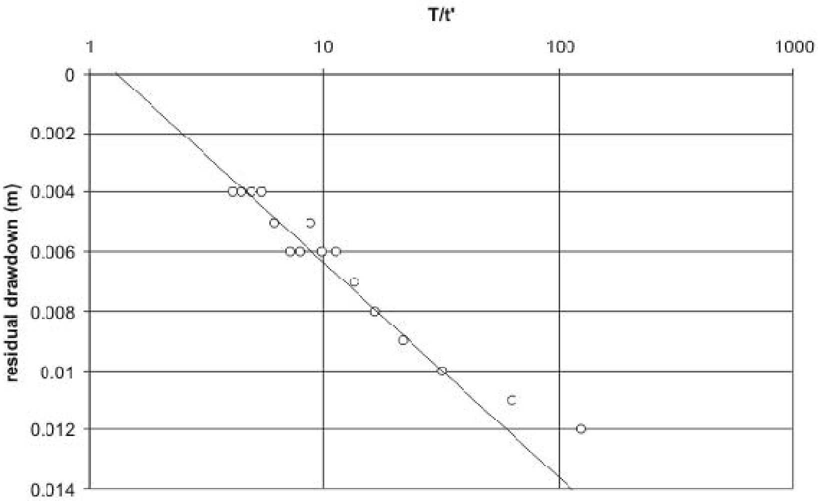
Transmissivity:

62.8 m²/d (Jacob's Approximation - early)

35.8 m²/d (Jacob's Approximation – late)

3274 m²/d
(Theis recovery)

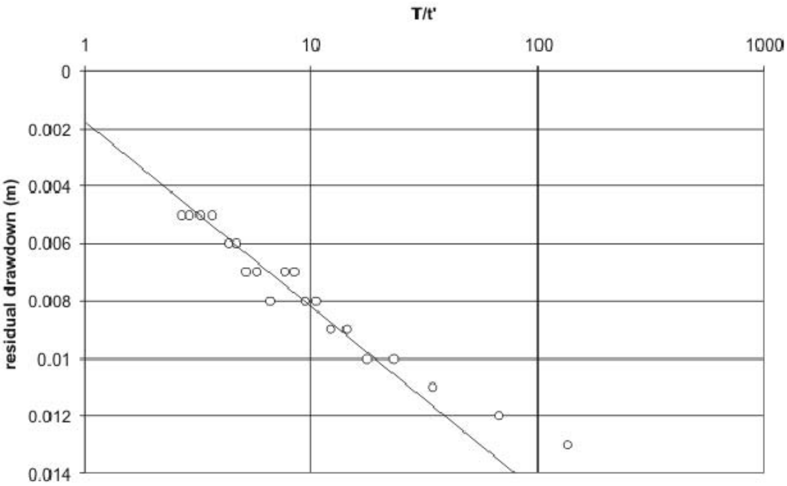




Bh107

Depth: 5.5 mBGL
Diameter: 102 mm
Date test: 13/12/07
Pumping rate: 0.83 l/s
Length of test: 67 min.
RWL: 2.36 mBGL

Transmissivity: 2035 m²/d
(Theis recovery)



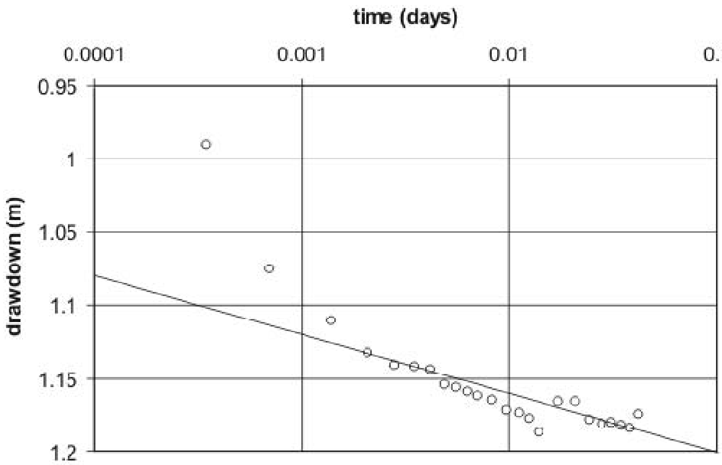
Bh109

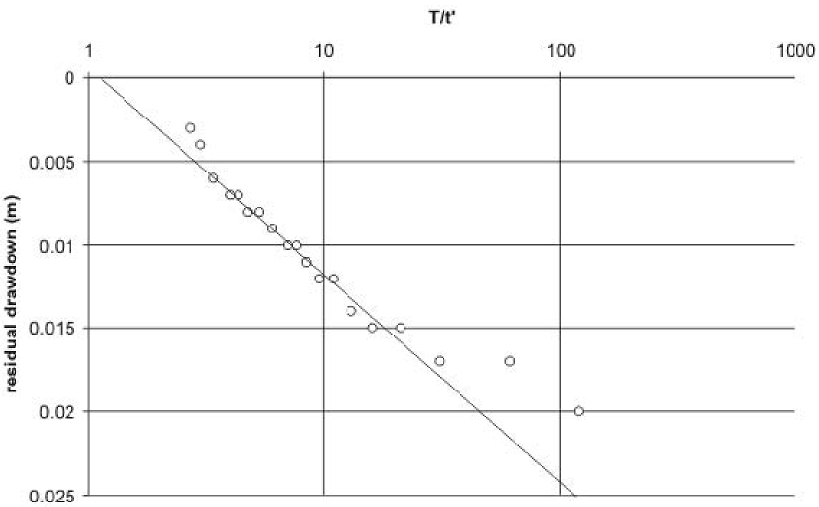
Depth: 7.6 mBGL
Diameter: 102 mm
Date test: 11/12/07
Pumping rate: 1.35 l/s
Length of test: 60 minutes
RWL: 1.97 mBGL

Transmissivity:

512 m²/d (Jacob's approximation)

1722 m²/d (Theis recovery)

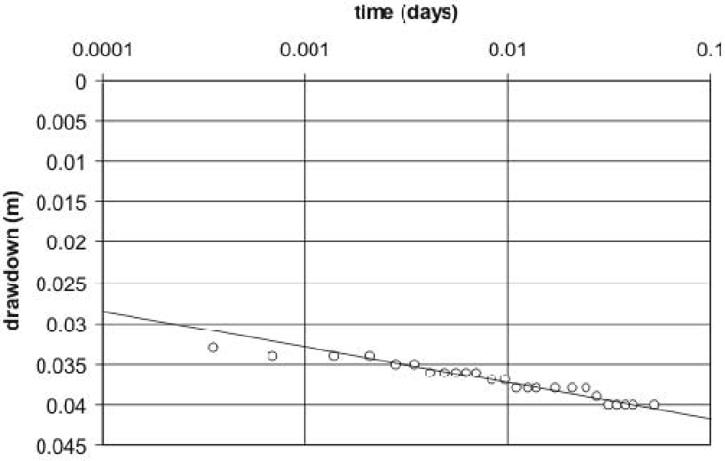




Bh110

Depth: 6.6 mBGL
Diameter: 102 mm
Date test: 12/12/07
Pumping rate: 0.1 l/s
Length of test: 77 minutes
RWL: 1.33 mBGL

Transmissivity: 351 m^2/d
(Jacob's approximation)



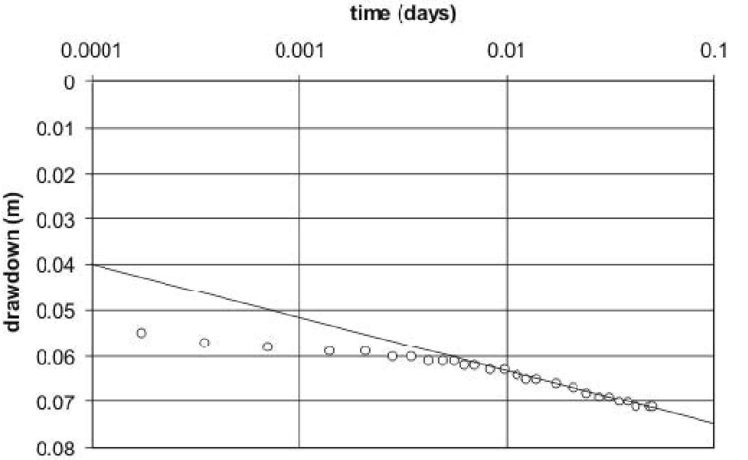
Bh111

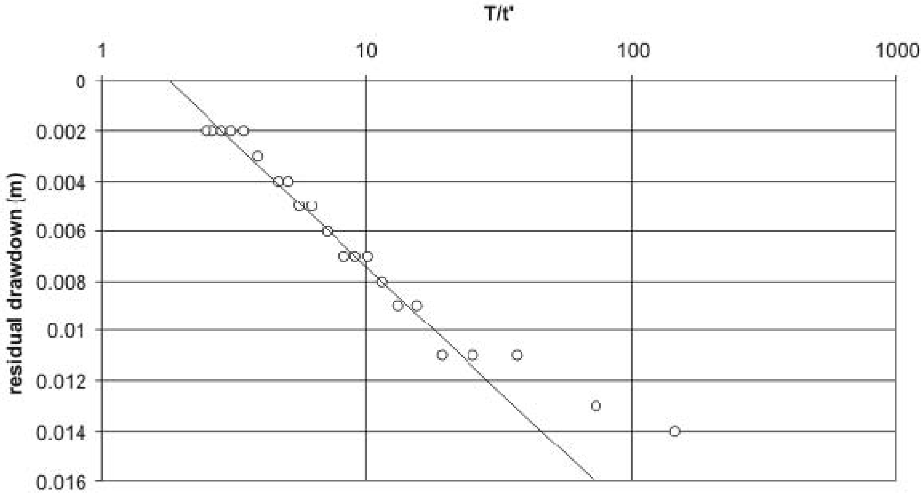
Depth: 7.5 mBGL
Diameter: 102 mm
Date test: 11/12/07
Pumping rate: 1.96 l/s
Length of test: 72.5 minutes
RWL: 2.28 mBGL

Transmissivity:

2695 m^2/d (Jacob's approximation)

3099 m^2/d (Theis recovery)





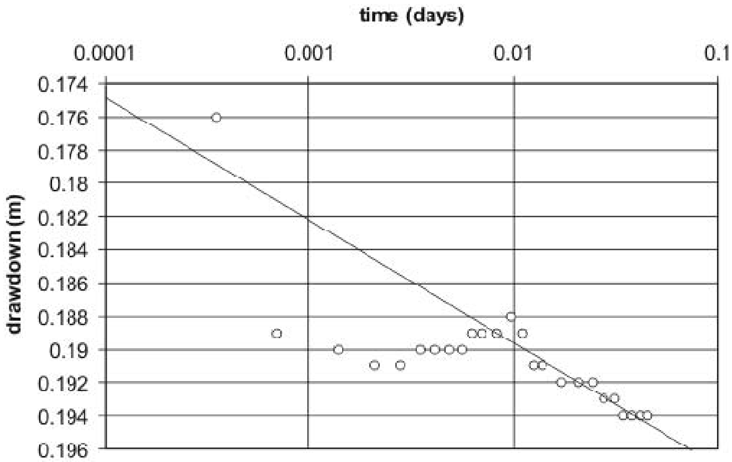
Bh112

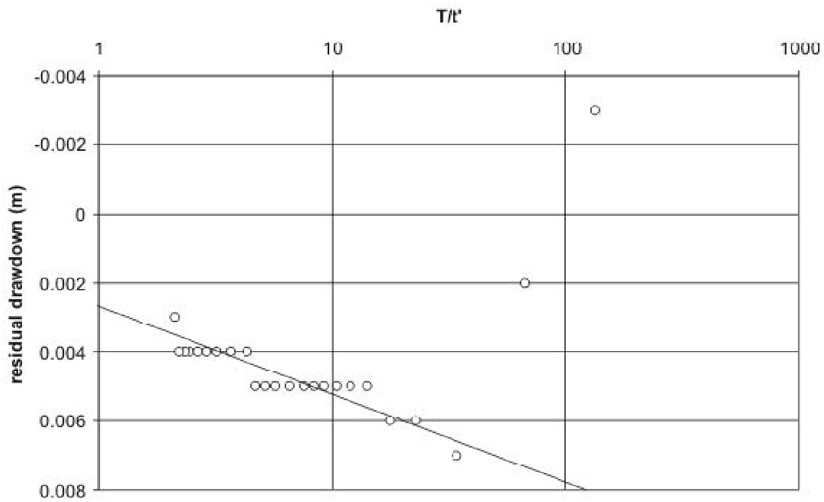
Depth: 8.9 mBGL
Diameter: 102 mm
Date test: 14/12/07
Pumping rate: 0.125 l/s
Length of test: 65 minutes
RWL: 2.02 mBGL

Transmissivity:

273 m²/d (Jacob's approximation)

760 m²/d (Theis recovery)





Appendix 2 Guelph Permeameter measurements

SiteNo	Horizon	East	North	GPX	SoilAlpha	Radius (cm)	Ponded height (cm)	Change (cm/min)
GP01	Ap	301555	857643	35.33	12	4	7	1
GP02	Ap	301768	857638	35.33	12	4	7	0.4
GP03	Ap	301496	857828	35.33	12	4	7	0.7
GP04	Ap	301924	857782	35.33	12	3.5	7	0.3
GP05	Ap	301626	857943	35.33	12	4	7	1.65
GP06	Ap	302163	857737	35.33	12	4	7	0.6
GP07	Ap	302048	857892	35.33	12	3.5	7	0.1
GP08	Ap	301973	858013	35.33	12	3.75	7	0.3
GP09	Ap	301693	858161	35.33	12	4	7	0.5
GP10	Ap	302188	858005	35.33	12	4.5	7	0.8
GP11	Ap	302022	858140	35.33	12	4.5	7	0.9
GP12	Ap	301897	858285	35.33	12	4	7	0.5
GP13	Ap	302078	857546	35.33	12	3.5	7	0.4
GP14	Ap	302205	858326	35.33	12	4.5	7	0.2
GP15	Ap	302172	858410	35.33	12	4.5	7	0.3
GP16	A	302087	858539	35.33	12	3.5	5	0.9
GP17	A	302108	858609	35.33	12	4.5	5	1.3
GP18	Ap	302192	858742	35.33	12	4.5	7	0.2
GP19	Ap	302277	858806	35.33	12	4.5	7	0.1
GP20	A	302277	858912	35.33	12	4.5	5	1.9
GP21	A	302379	859002	35.33	12	4	5	1
GP22	A	302269	859011	35.33	12	4.5	5	0.4
GP23	A	302409	859204	35.33	12	4	5	1.1
GP24	A	302490	859277	35.33	12	4	5	1
GP25	Ap	302644	859386	35.33	12	4	7	0.3
GP26	A	302708	859542	35.33	12	4	5	1.2
GP27	Ap	302751	859154	35.33	12	4.5	7	0.6
GP28	Ap	302835	859217	35.33	12	4	7	0.2
GP29	Ap	303044	859280	35.33	12	4	7	0.8
GP30	Ap	303015	859341	35.33	12	4	7	0.2
GP31	Ap	302881	859479	35.33	12	4	7	0.9
GP32	Ap	302983	859683	35.33	12	4	7	0.5
GP33	Ap	303067	859752	35.33	12	4	7	0.3

A: Surface Horizon
Ap: Surface Horizon which has been ploughed.

Appendix 3 Summary of groundwater flow modelling

1. AIMS OF MODELLING

The aim of the groundwater flow modelling is to understand the groundwater system around Pilmuir. Specifically, it is to determine whether the flooding in the Pilmuir area (around the School/allotments) is influenced by groundwater. Once the groundwater flow in the vicinity of the flooding is understood then the impact of the flood alleviation scheme (FAS) can be simulated. The FAS consists of an open channel running through the area and discharging to the River Findhorn in combination with a bund to exclude River Findhorn flood waters from western Forres. Other components of the FAS include a grout curtain to protect the industrial estate.

This modelling work builds on the work carried out for Phase 1 of the study (MacDonald et al. 2007).

2. CONCEPTUAL UNDERSTANDING

Summary

The system is two-layered: a gravel aquifer overlying a regionally extensive Devonian sandstone aquifer. The superficial deposits are variable and can be highly permeable (~ 100 m/d). The gravel deposits are themselves covered by 0.5 to 2 m of silty topsoil, which are relatively permeable to recharge, but may impede drainage of flood waters. The infiltration capacity of the superficial deposits are spatially variable with limited infiltration in some areas (silts). Recharge is low 150 – 200 mm/a due to the low rainfall.

The boundaries of the system conceptually are the sea/estuary to the north, and the interfluve of the River Findhorn to the west and east, and the outcrop of the basement rocks to south. However, the topography of the bedrock is important and highs in the bedrock could reduce the size of the "catchment" from which floodwater is drawn considerably. As the depth to the bedrock decreases, so the saturated thickness of the superficials is reduced, and the possibility exists of the superficial deposits drying out and these areas of dry superficial deposits result in compartmentalisation of the groundwater system.

Water balance

The groundwater system in the immediate vicinity of the site of groundwater flooding, south of Forres is not highly exploited. Therefore the main water balance components represent a natural system. Rainfall recharge is the main inflow with flow to rivers (baseflow) and discharge to the Findhorn Estuary comprising the main outflows.

Occurrence of flooding

Groundwater flooding occurs mainly to the south of Pilmuir and is controlled with a series of drains. These drains consist of pipes buried below ground in the bottom of depressions that have historically flooded.

3. GROUNDWATER MODELLING

Introduction

The following sections describe the modelling undertaken to enhance the understanding of the groundwater system around Pilmuir and to develop a credible model that can be used to simulate the flood events. The recharge model is first described and results presented, followed by the development of the steady-state model development and results. Finally, the dynamic balance runs are described and presented.

Recharge modelling

A distributed recharge model was developed for the surface water catchments surrounding Forres. Using the daily rainfall gauge at Forres in combination with Potential Evaporation at MORECS square 21, monthly recharge was calculated for the period January 1977 to December 1999. Four types of land-use were used to modify the coefficients used in the soil moisture balance calculation: urban areas (e.g. Forres); arable areas (crops, etc.); forested areas (especially to the south of Forres); and riparian zones. Run-off was generated using the Digital Terrain Model (DTM) to provide topography and slope direction and the surface water network. Run-off generated at each node was routed to the rivers. Recharge from the Sustainable Urban Development Scheme (SUDS) (see Figure A1) at a rate of 1.5 mm/day was included in the model.

A long-term average (LTA) recharge distribution was produced for the groundwater model area (Figure A1). The range of LTA recharge was between just under 0.05 mm/d to 6 mm/d. The highest values occurred due to run-off collecting in areas and recharging the groundwater system. Recharge generally was greatest in the northern part of the area as the land-use is arable and produces less actual evaporation than the forested area to the south of the model area.

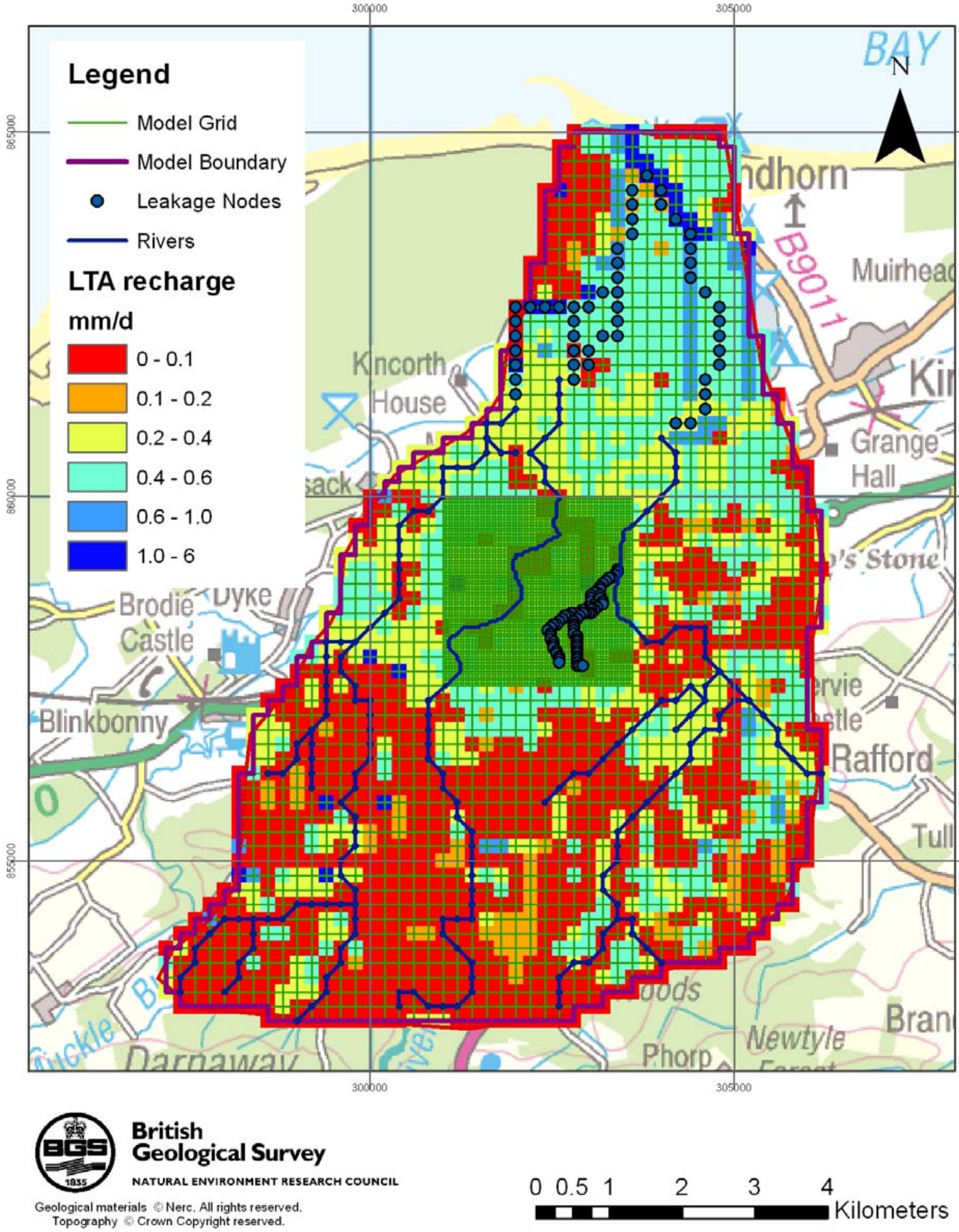


Figure A1. Long-term average recharge.

Development of steady-state model

BOUNDARY CONDITIONS

The model boundaries are defined, where possible, by physical features of the system (Figure A2). The boundaries are chosen to be far from the area of interest so that they will have little impact on the simulations of the FAS. The model software, ZOOM, is designed so that the area of interest can be modelled in detail, within a broad regional background.

To the south, the main model boundary is the contact between the Devonian sandstones and the Precambrian psammites. The northern boundary is defined by the coast and it is assumed that the groundwater system is in direct contact with the estuary. The eastern and western boundaries are more difficult to define. The eastern boundary is taken to be a groundwater divide boundary between the Burn of Mosset and the Black Burn. The western boundary is taken to be a groundwater flow divide between tributaries of the Muckle Burn. All boundaries, where possible, are represented as no-flow with the exception of the Estuary, which is represented as leakage nodes.

The western boundary for the Phase 1 work was taken as the Findhorn River as this is assumed to have sufficient flow to act as a boundary. However, it was discovered during this work that groundwater flow could potentially pass under the River Findhorn and contribute to flooding in the Broom of Moy. Therefore the boundary was extended westward to include this area in the model.

LAYERING

The system is conceptualised as two main layers, the superficial deposits, though highly variable, form one layer and the underlying sandstone, the other. Each layer is represented in the model as constant transmissivity (T), i.e. the T does not vary with saturated thickness. See below for more information on how the T distribution was developed.

RIVERS

Three rivers are included in the model, the Burn of Mosset, The River Findhorn and the Muckle Burn. Flow in the River Findhorn at the southern boundary is simulated as 756,000 m^3/d (8.75 m^3/s); this ensures that flow coming onto the model can recharge the groundwater system if groundwater heads are below the river stage. To the south of Northing 856000 the River Findhorn is connected to layer 2, representing the sandstone. This was undertaken as the river has cut down into the sandstone through the superficial deposits.

The inclusion of an increased number of rivers is an advance on the Phase 1 model, in which only one river is represented, the Burn of Mosset.

GRID

Since ZOOM allows grid refinement, this facility has been used to create two grid levels:

1. Base grid: 200 m square mesh
2. First level refinement: 40 m mesh (from 301000, 857400 to 303600, 860000)

The grid used for the modelling study is illustrated in Figure A2.

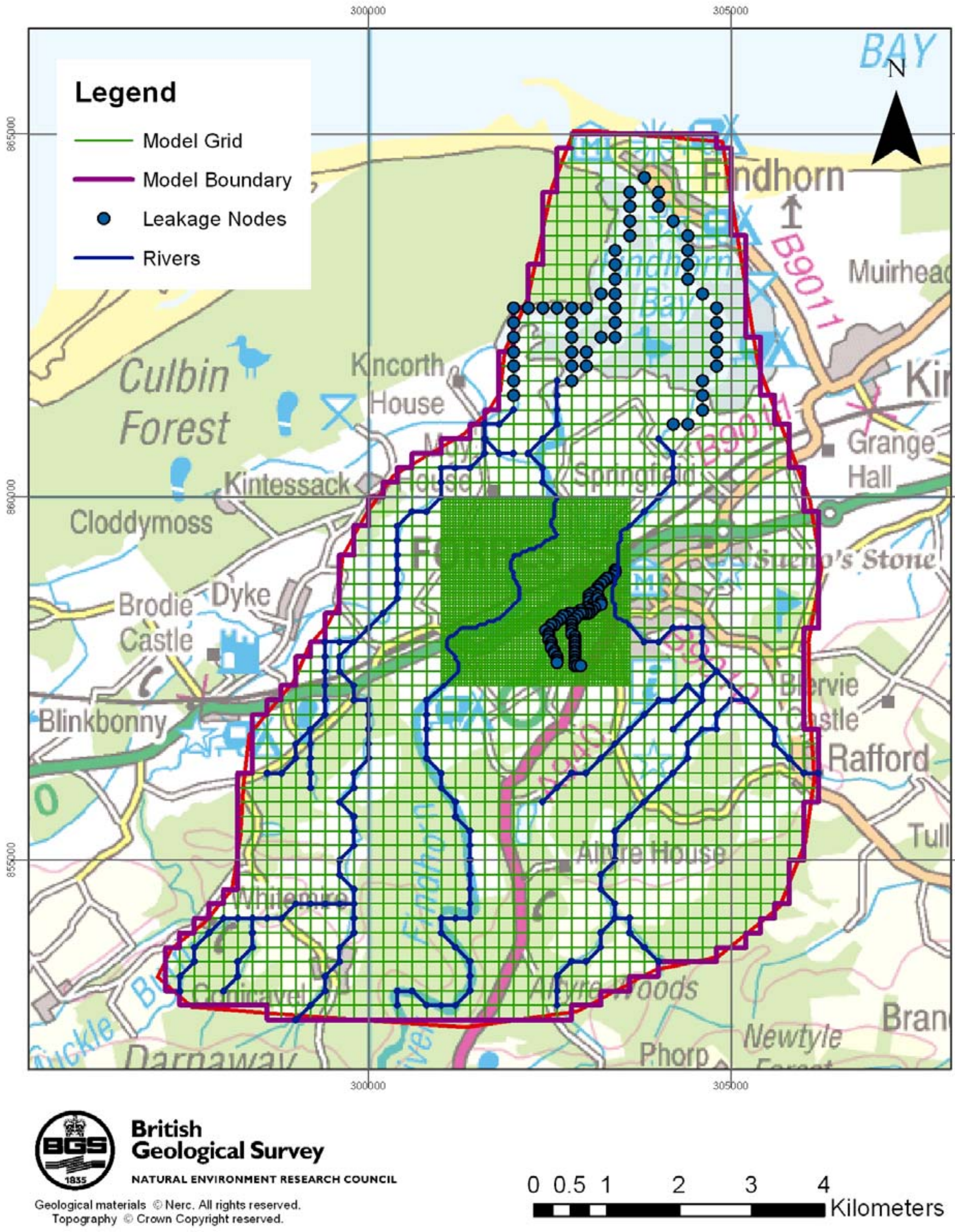


Figure A2. Model grid and boundary conditions.

Model refinement

INTRODUCTION

To aid the development of understanding of the system, and to provide a basis for the flood prediction runs, a steady state model of the groundwater system was developed. The use of a steady state model enabled the rapid assessment of whether the choice of boundary conditions, hydraulic parameters, etc resulted in the correct representation of the system, especially the flow in the drain and culverted stream (known as the existing drain) around the area of groundwater flooding.

DEVELOPMENT OF T DISTRIBUTION

One of the key controlling factors of groundwater flow is the distribution of transmissivity in the superficial deposits. Using the recent re-mapping of the sediments around Forres and a more regional appreciation of the nature and thickness of the superficial deposits, a transmissivity map was developed (Figures A3 and A4). This was translated into the input file for the model layer representing the superficial deposits (Layer 1). The pumping test analysis from the Phase 2 fieldwork was used to inform the T distribution for the superficial deposits underlying Forres and to the south of Pilmuir.

The transmissivity for the sandstone was set at 50 m^2/d.

ENHANCEMENTS OF THE CONCEPTUAL MODEL FROM THE MODEL REFINEMENT PROCESS

As the model was developed and the simulation of the groundwater system improved, so the conceptual model of groundwater flow south of Forres was refined. The impact of the rivers on the groundwater system, especially the River Findhorn, was found to be importantas the river has a “steppy” profile with drops of 4 – 5m in the river stage in a relatively short distance. The River Findhorn also cuts down into the sandstone in the upper part of the catchment and so is connected to the sandstone layer in the model.

Other important features of the system that needed to be included were the nature and geometry of superficial deposits and the resulting T distribution. A ridge of sandstone was identified to the south-west of Forres and when this was put into the model it improved the distribution of steady-state heads considerably. Additionally, the connection between the sandstone and the superficial deposits was found to be poor in the southern part of the model due to till deposits overlying the sandstone.

Adding the recharge from the SUDS scheme also improved the correlation between the simulated groundwater head contours and site measurements.

When all these refinements were put into the model, the simulated groundwater head contours and the flows were much closer to observations than the initial simulation.

BEST STEADY-STATE MODEL

The results from the best steady-state model is presented below (Figures A5 and A6). Generally, the groundwater flow is to the north, with outflow in the upper reaches of the River Findhorn and the Burn of Mosset and the Findhorn Estuary. The River Findhorn, generally, loses in the downstream part of the river and gains in the upstream section. However, there are local subtleties, such as the change between gaining and losing sections in the bend in the River Findhorn close to RFB02. The modelled flow in the existing drain is 1880 m^3/d (22 l/s), which is comparable to the observed flow of 20 – 30 l/s.

Comparison with observed heads is generally good. Figures A7 and A8 show that immediately south of Forres, the 10 m and 12 m modelled contours fit generally well with observed data.

The water balance for the steady-state model is presented below (Table A1). The main inflow and outflow is the River Findhorn. However, in terms of groundwater input the main inflow is rainfall recharge and the main outflow is leakage to the Estuary.

Table A1. Water balance for the best steady-state model

Inflow (m^3/d)		Outflow (m^3/d)	
Recharge	18,076	Leakage to Estuary	17,615
Flow in River Findhorn	756,000	Flow in River Findhorn	755,406
Flow in Muckle Burn	0	Flow in Muckle Burn	832
Flow in Burn of Mosset	0	Flow in Burn of Mosset	223
TOTAL	774,076	TOTAL	774,076

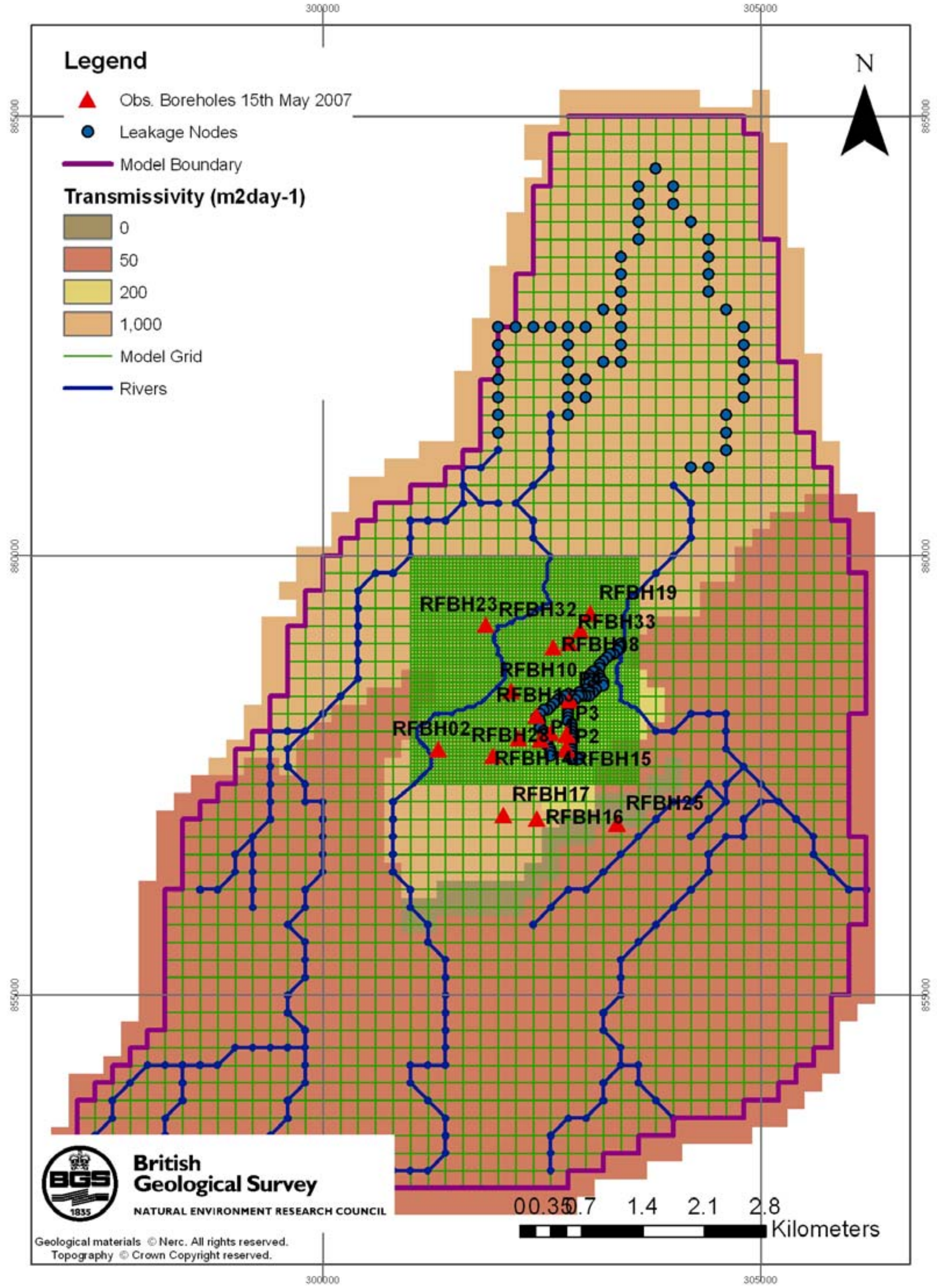


Figure A3. Transmissivity distribution for the best model.

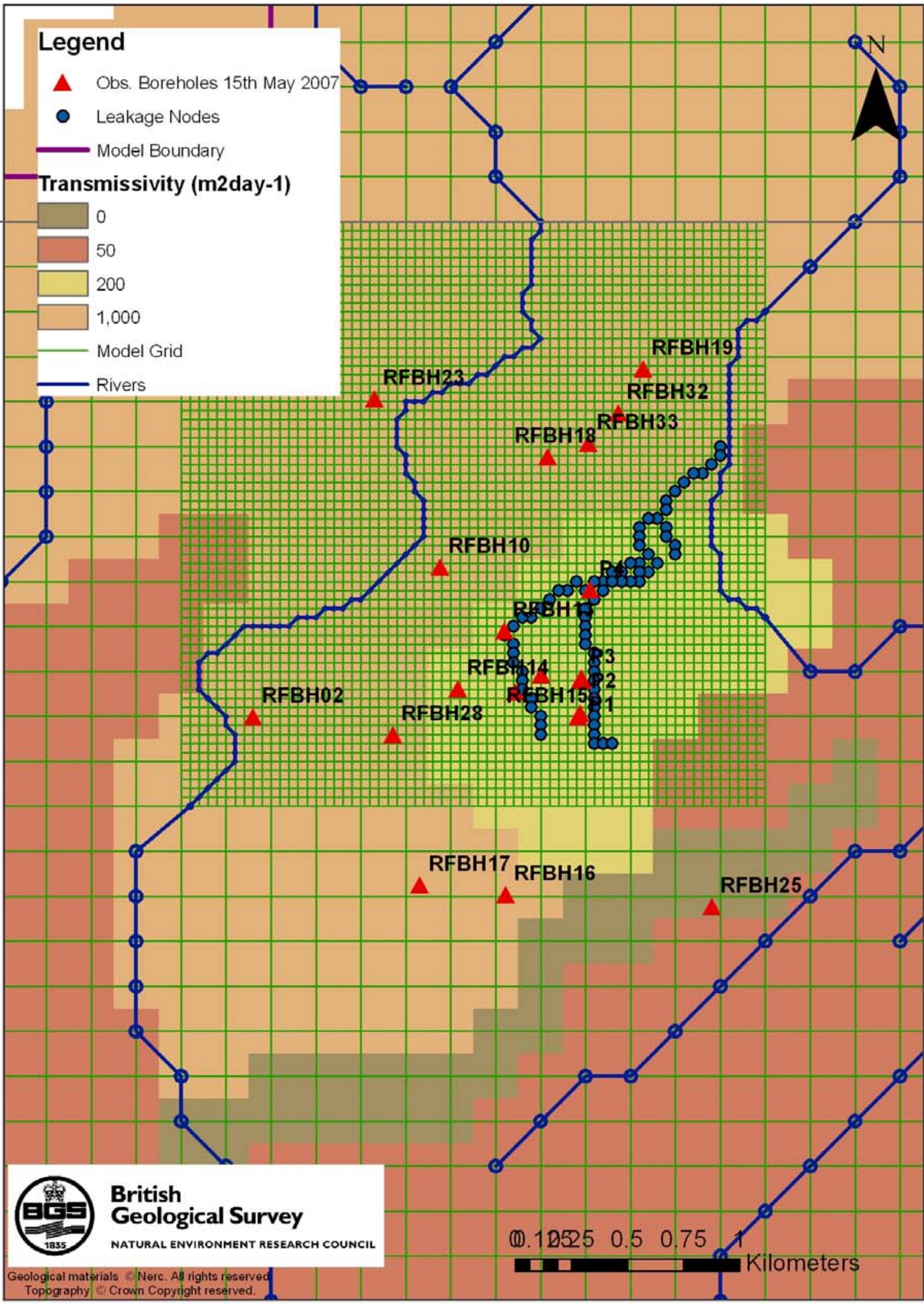


Figure A4. Detail of transmissivity distribution for the best model.

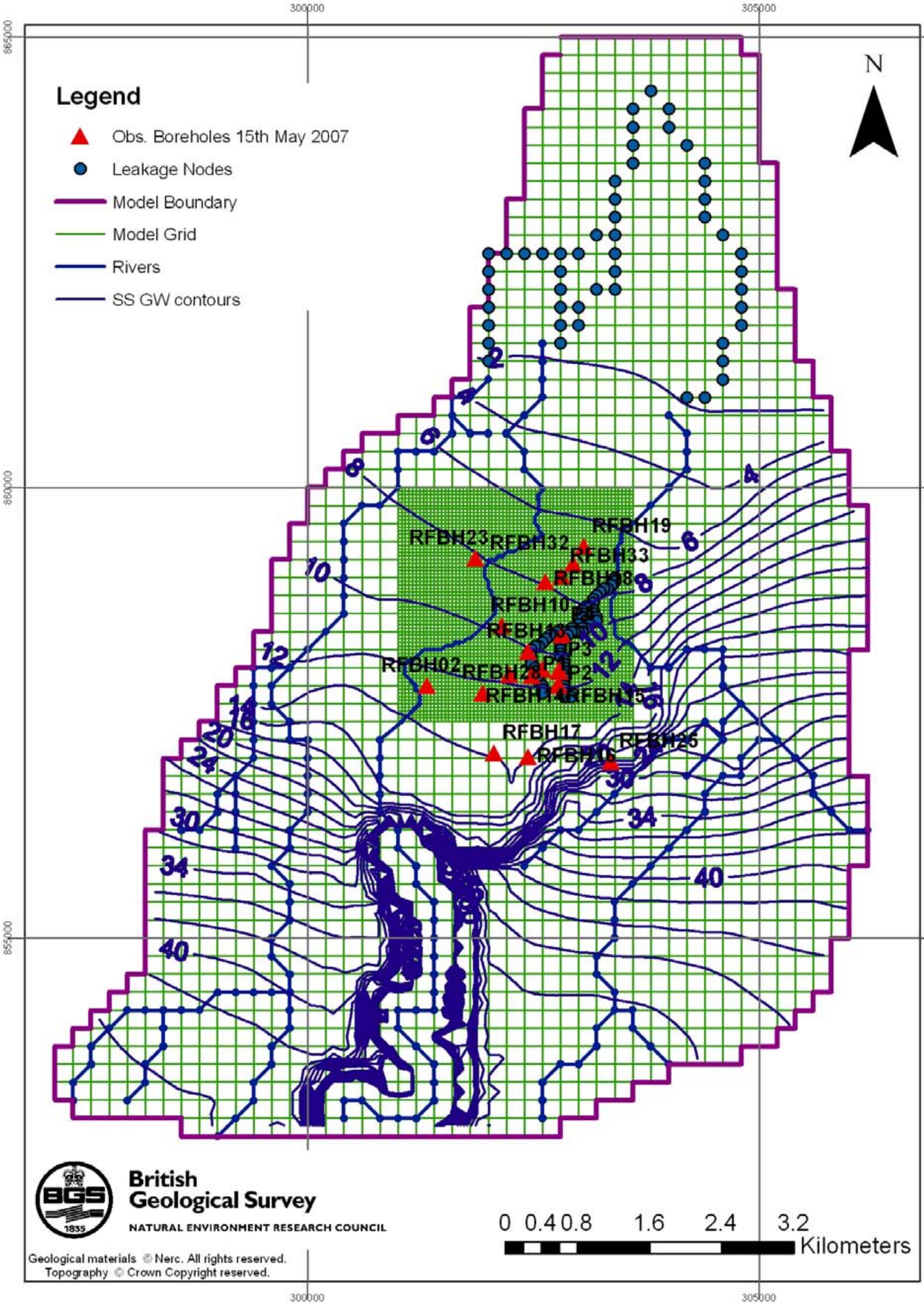


Figure A5. Steady-state head contours for best model.

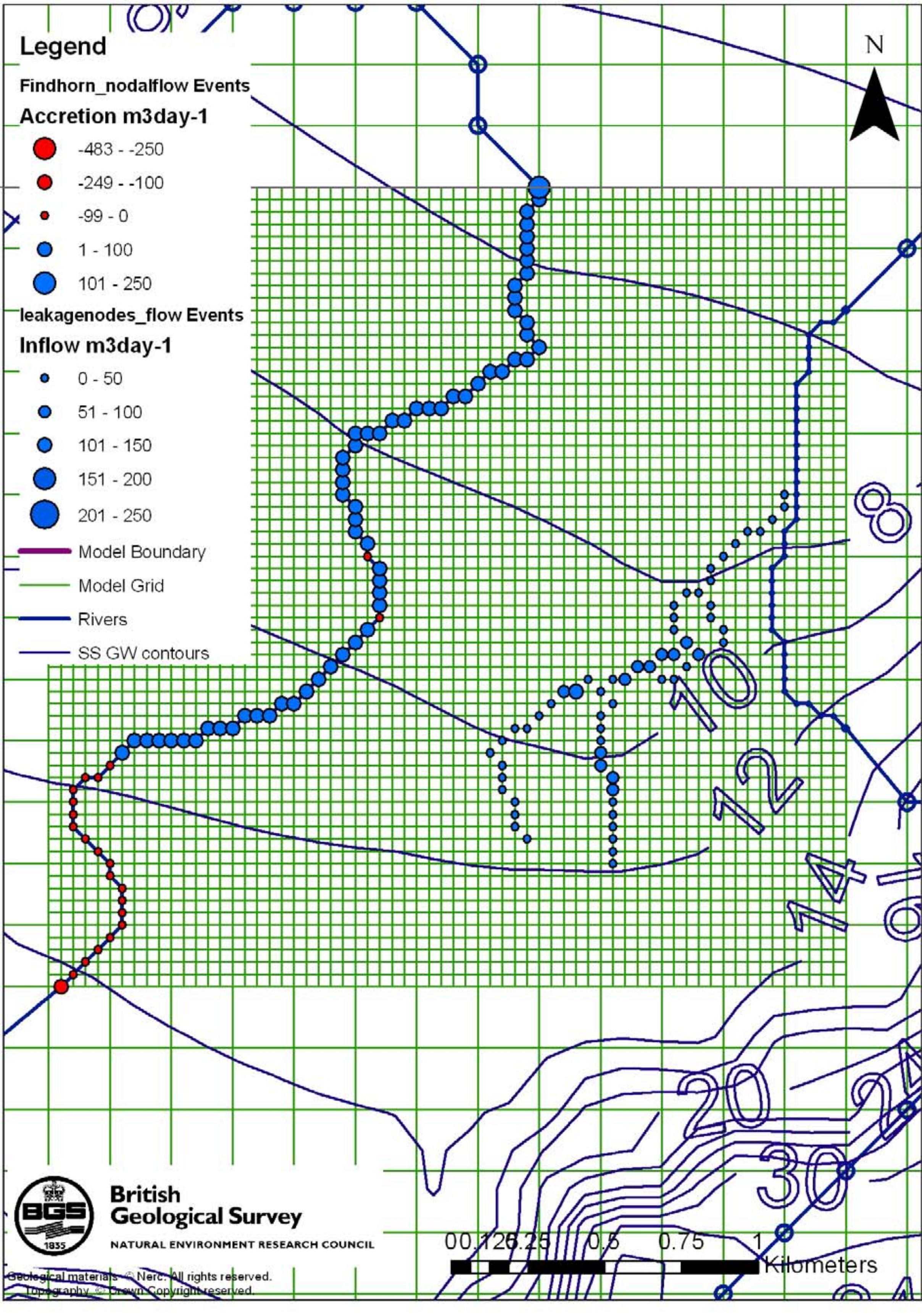


Figure A6. Detail of steady-state head contours and flows for best model.

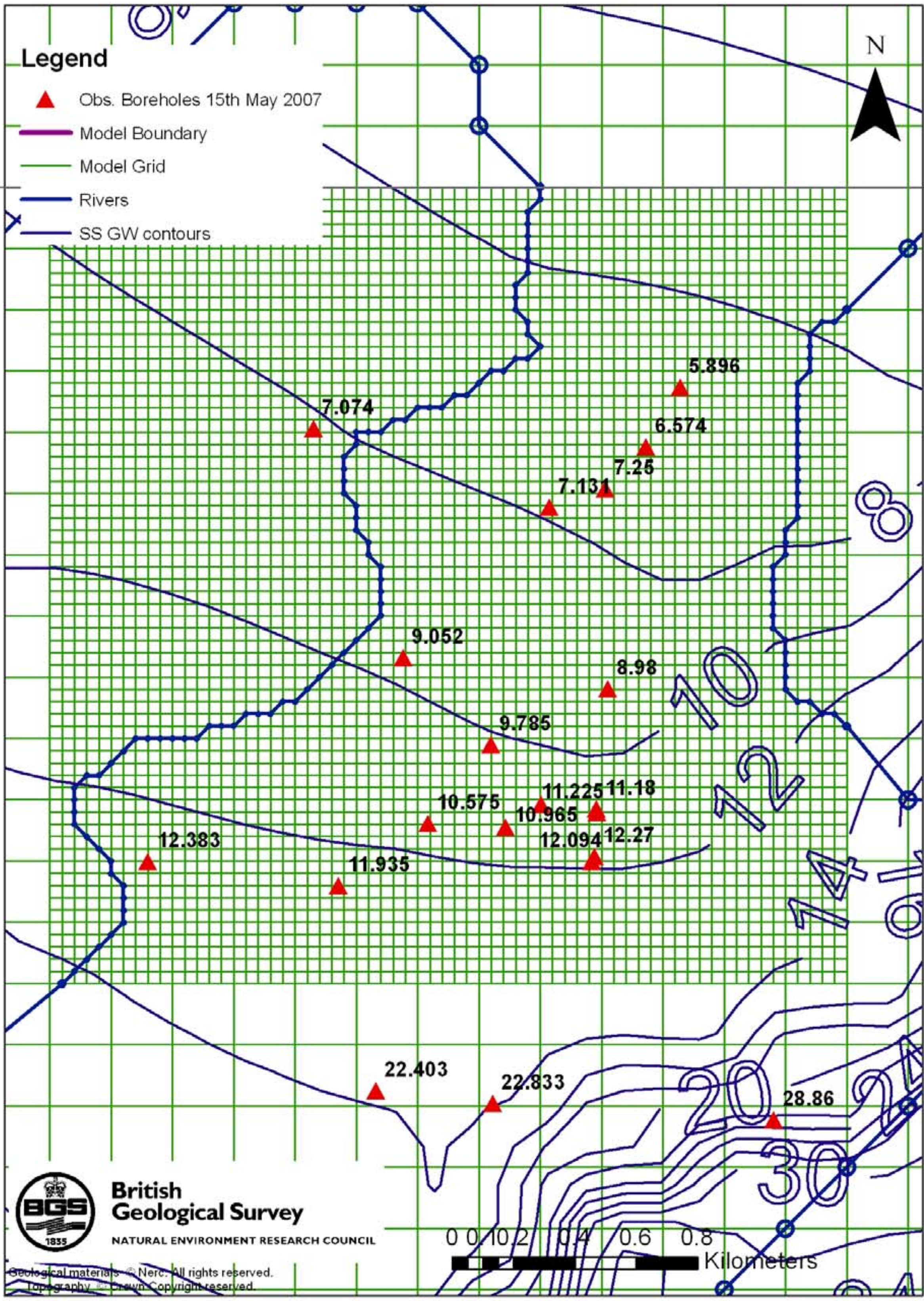


Figure A7. Detail of steady-state head contours for best model and comparison with observed data (15th May 2007).

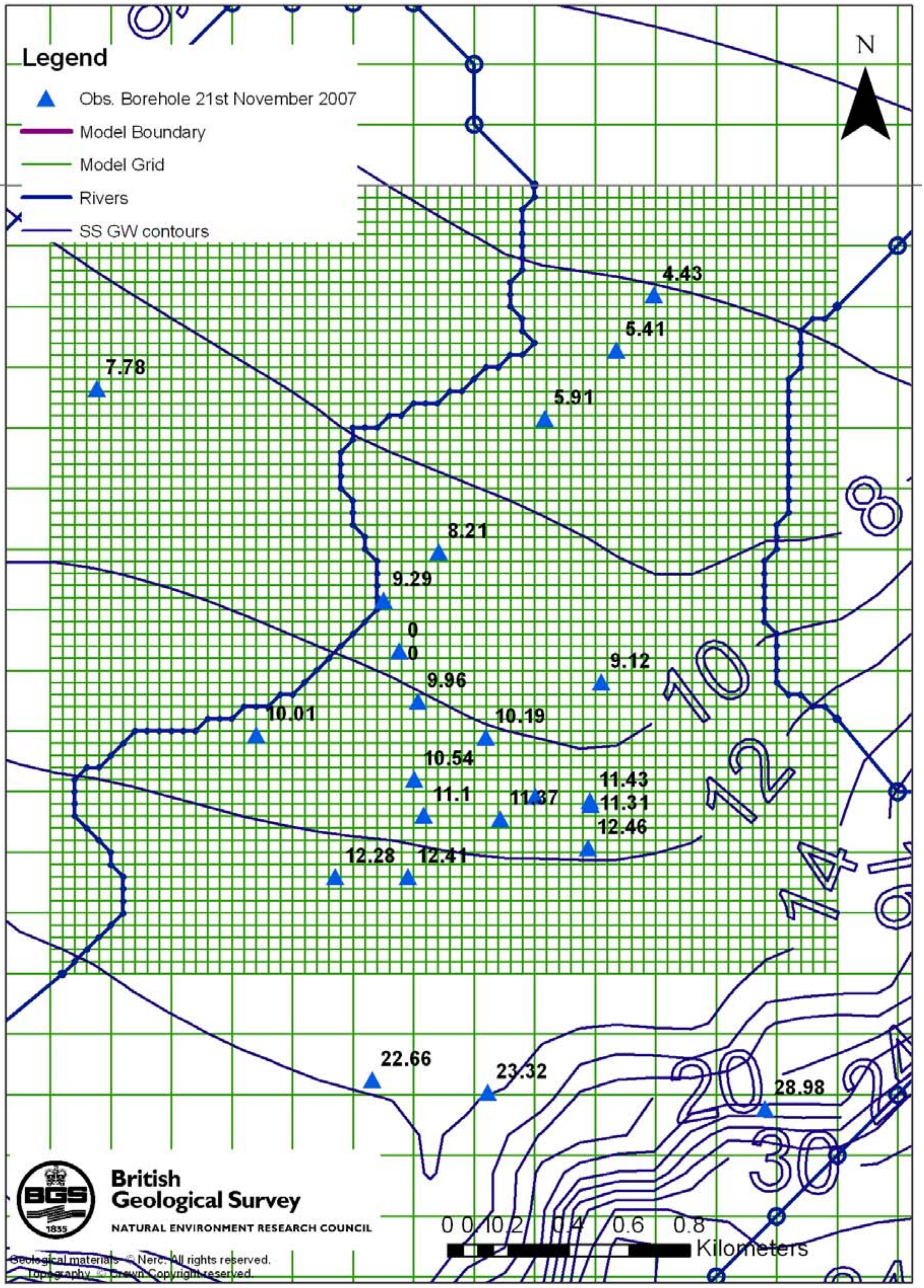


Figure A8. Detail of steady-state head contours for best model and comparison with observed data (21st November 2007).

Dynamic Balance

Introduction

To understand how the groundwater system responds to seasonal pattern of recharge, a dynamic balance was undertaken. A dynamic balance simulation is a model run using a repeated series of monthly average recharge. The model is run until the groundwater heads and outflows in any particular month are identical from one year to the next. For this project, the use of dynamic balance run serves two purposes: (1) to get the model operating time variantly to determine if the model reproduces seasonal responses; and (2) to see if the "expected" pattern of flooding on the Pilmuir area is reproduced.

Results

The recharge time series used for the dynamic balance is presented in Figure A9. The use of this recharge time series produces groundwater hydrographs which can be compared with measured data. One of these hydrographs are presented in Figure A10. This shows that the range in heads is about 0.1 m, which is similar to that observed in the field.

Flood maps were developed for the project to enable the spatial extent of groundwater flooding to be predicted. The model groundwater flood maps were produced by calculating the difference between groundwater head and ground surface at a model node. Therefore, if the modelled groundwater head is close to or above ground surface, then groundwater flooding is likely to occur. The flood map for the dynamic balance runs were produced for the same times as for those produced for the prediction runs, namely 1 day, 10 days and 100 days after the flood event on the 1st June (Figure A11). These diagrams show that the flooding routinely observed in the catchment is reproduced.

The flooding to the north of the area shown in Figure A11 is due to the modelled groundwater heads being too high in this area. This is due to the network of field drains in this area not being mapped and added to the model.

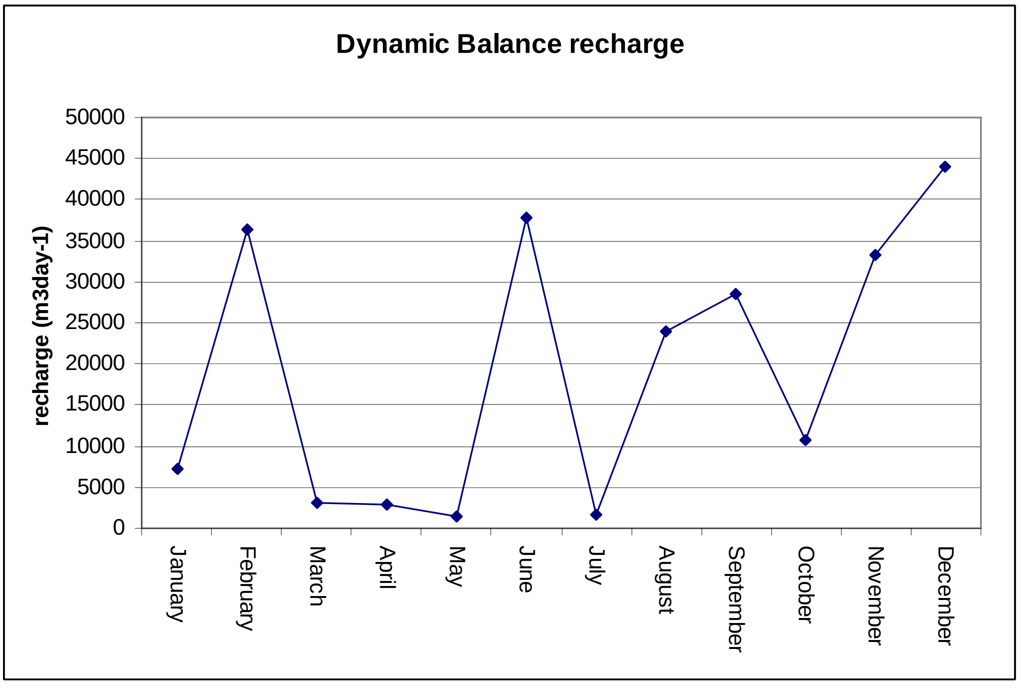


Figure A9. Monthly recharge used for the dynamic balance run.

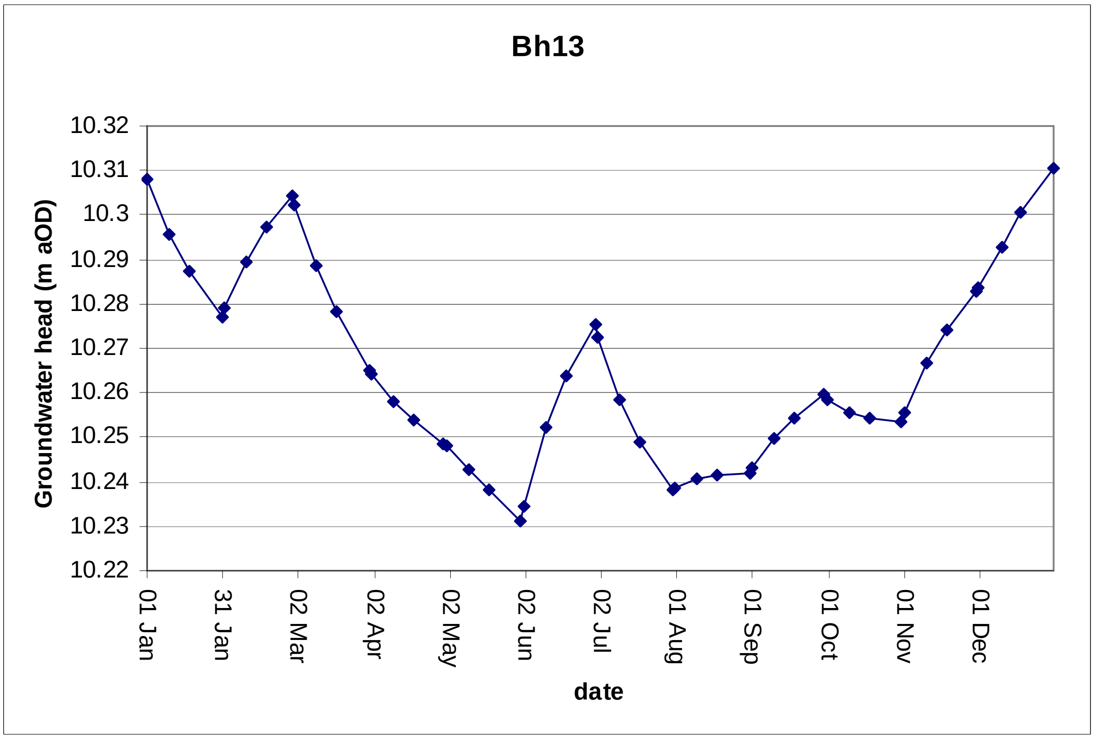


Figure A10. Typical annual hydrograph for BH13 from the dynamic balance run.

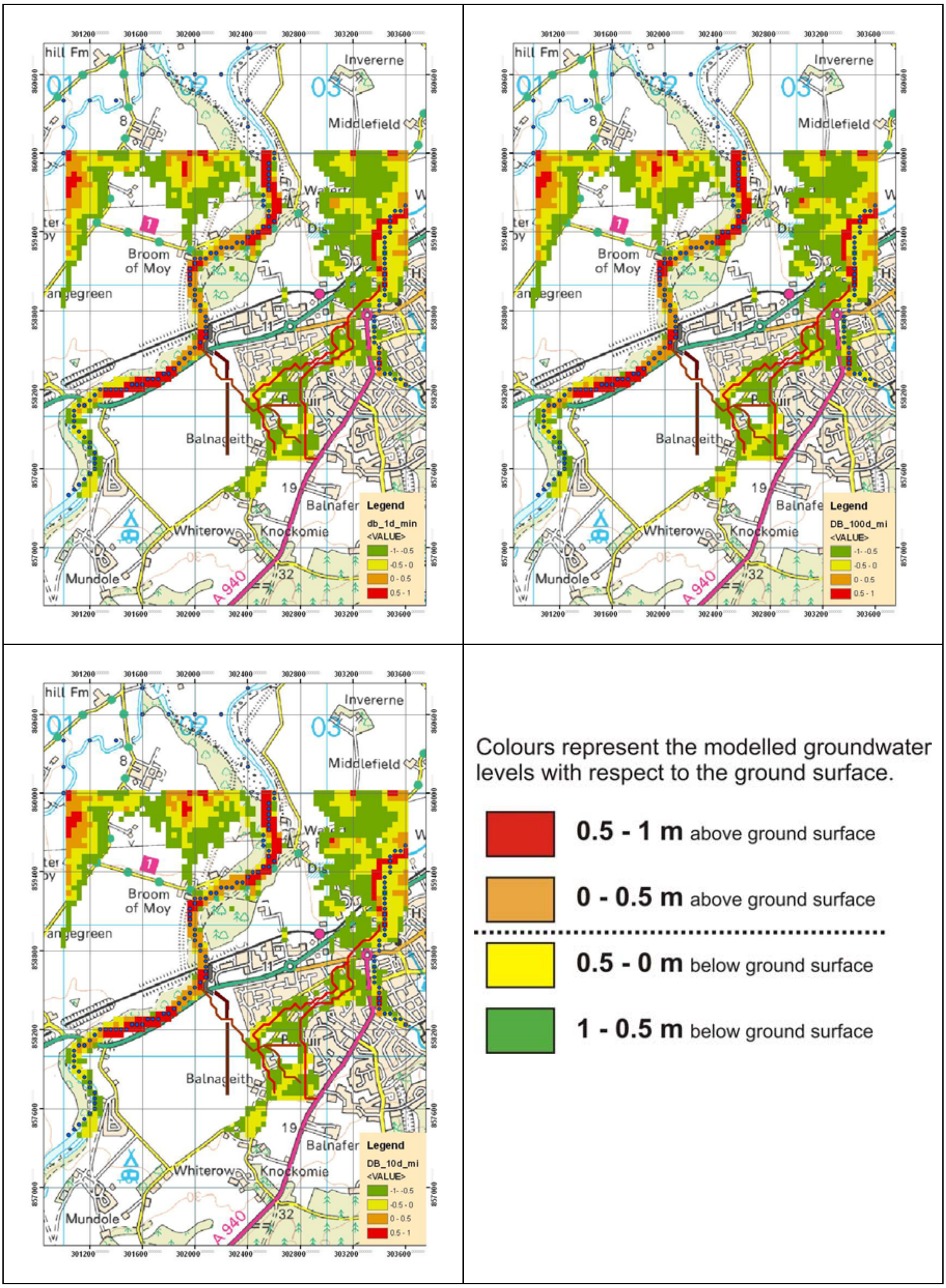


Figure A11. Flooding predicted by average conditions in for 1days, 10 days and 100 days after 1st June.

4. PREDICTION RUNS

Introduction

In this section, the results for the prediction runs are presented and discussed. These runs consider the impact of four main engineering solutions to the flooding south of Forres, in Pilmuir, under different rainfall conditions:

1. Drain to convey groundwater to the River Findhorn.
2. Bund to impound flood waters from the River Findhorn.
3. Toe drains to control seepage through/under the bund.
4. Cut-off barrier to prevent groundwater flooding of the industrial estate, where there is no room to construct a wide embankment to mitigate seepage.

These features are illustrated by Figure A12.

Processes likely to be occurring during flooding

The likely sequence of events during the flooding and the impoundment of water behind the bunds are as follows:

1. Heavy rain in the upper catchment leads to an increase in stage in the River Findhorn and flooding of the floodplain
2. The floodplain on the riverside of the embankment (known as inundated area) is flooded to a depth of ~2m.
3. The water table rises as a result of combined effect of river stage and increased recharge.
4. Water from the inundated area saturates the soil and a "wetting front" moves downwards to meet the rising water table.
5. Once the unsaturated zone is fully saturated then the water from the inundated area can flow vertically down to the aquifer and laterally away from the area (e.g. towards Forres).

The modelling simplifies the situation by using a grid of river nodes to simulate the inundated area. This is an improvement on the Phase 1 work (MacDonald et al. 2007) which used a very high (1000 mm/d) recharge value to represent the recharge from the flooded areas. Using river nodes allows the flow into the groundwater system to vary, based on the head difference between the stage in the water on the floodplain and the water table below.

Modelling flooding and the impact of the Engineering Schemes

The series of runs reported are represented in Table A2. This shows that there are three types of runs undertaken:

1. Simulations to examine of the impacts of "natural" conditions on the system – a single dynamic balance run (Table A2; Runs 0 and 1a).
2. Simulations to examine the impacts of inundation on the system – a linked series of dynamic balance runs (Table A2; Runs 1b, 2, 3, and 4).
3. Simulation to determine the "worst case" – a linked series of dynamic balance runs with high recharge (Table A2; Run 5).

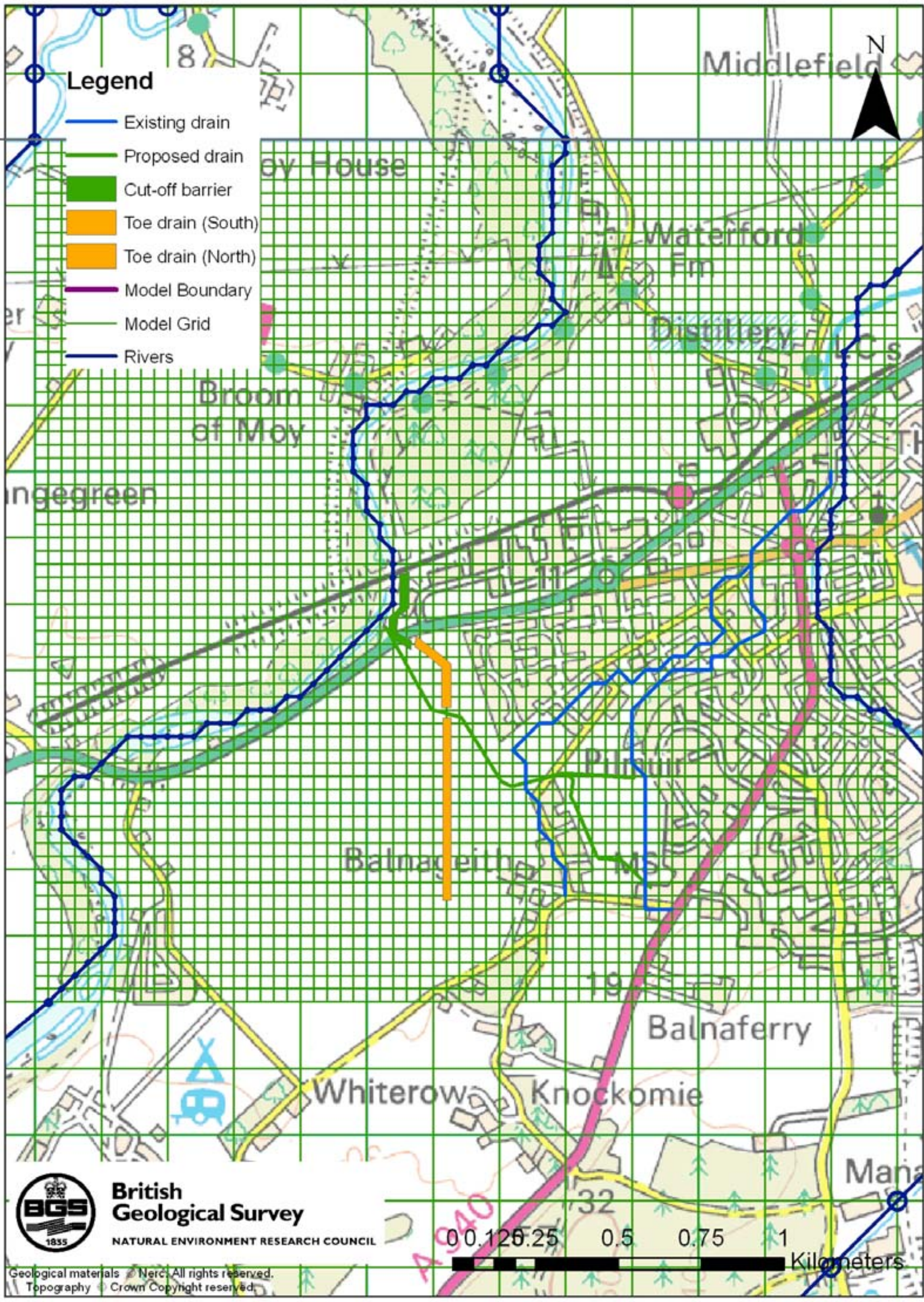


Figure A12. Features of the FAS used for prediction runs.

The runs to examine the impact of inundation are undertaken by a linked series of runs of the groundwater flow model; Run A, Run B and Run C. Run A is a dynamic balance which included the features of the flood scheme which can impact the groundwater system all the time. These features are the new Pilmuir drain, the embankment toe drains and the cut-off barrier by the garden centre. Run B is to simulate the flooding and is one day long. All the changes to the system during flooding are included in this run. These changes include the representation of the inundated area and rise in the stage of the River Findhorn. Run C is a dynamic balance run which uses the same monthly recharge input as Run A and allows the system to return to "normal" conditions. During this run, heads and flows can be monitored to asses the impact of the flooding on the groundwater system.

To examine the "worst case" in Run 5 an extra run is undertaken after the initial dynamic balance run. This run (Run D) is series of monthly values of high recharge and is designed to represent to extreme climatic conditions leading to high groundwater levels preceding the flooding.

Table A2. Summary of model runs undertaken

Run	Description	Purpose	Details of runs undertaken
0	Basecase no engineering measures	To provide a basecase with which to compare all subsequent runs	Dynamic balance (Run A)
1a	Eng. Measures no flood	To see how engineering measures (drains, cutoff wall, etc) reacts to “natural” groundwater system	Dynamic balance (Run A)
1b	Eng. Measures 60 mm/d Rf	To determine how system responds to catchment wide 60 mm/d recharge	Dynamic balance (Run A), followed by one day recharge at 60 mm/d (Run B), followed by dynamic balance (Run C)
2	1 in 50 year flood	To determine how system responds to inundated area for a 1 in 50 year event	Dynamic balance (Run A), followed by one day of inundation and elevated river stage (Run B), followed by dynamic balance (Run C)
3	1 in 200 year flood	To determine how system responds to inundated area for a 1 in 200 year event	Dynamic balance (Run A), followed by one day of inundation and elevated river stage (Run B), followed by dynamic balance (Run C)
4	1 in 200 year flood AND 60 mm/d Rf	To determine how system responds to inundated area for a 1 in 200 year event combined with catchment wide recharge	Dynamic balance (Run A), followed by one day of inundation, elevated river stage and recharge of 60 mm/d (Run B), followed by dynamic balance (Run C)
5	1 in 200 year flood AND 60 mm/d Rf AND antecedent conditions	Worst case scenario: To determine how system responds to inundated area for a 1 in 200 year event combined with catchment wide recharge and high recharge antecedent conditions	Dynamic balance (Run A), then 6 months of maximum recharge for each month (Run D), followed by one day of inundation, elevated river stage and recharge of 60 mm/d (Run B), followed by dynamic balance (Run C)

The impact of groundwater flooding of each different aspect of the flooding is examined by the prediction runs.

1. *Inundated area riverward of the proposed embankment*. This is represented as a combination of river nodes and additional recharge. The 1 in 50 year flood and the 1 in 200 year flood extents in the areas behind the bund and to the east of the Broom of Moy (see Figure A12) are represented. The former is represented by a combination of river nodes and additional recharge, whilst the latter uses only river nodes. The bund itself is not represented implicitly, but through the positioning of the boundary conditions representing the flooding

2. *Rise in the stage of the River Findhorn.* For the 1 in 50 year and 1 in 200 year flood event, the stage of the River Findhorn is raised by 4.2 m and 5 m respectively (river stage data taken from Mike Flood numerical model of the River Findhorn). The river stage is raised to simulate flood conditions in the River Findhorn and to prevent recharge reaching the groundwater system flowing out to the River Findhorn. River stage is returned to previous conditions (1 m) after one day.

3. *Recharge to the catchment as a whole*. A recharge value of 60 mmday^{-1} is applied over the whole model area for one day. This is to simulate an intense local rainfall event, similar to that which occurred during Summer 1997.

4. *High recharge antecedent conditions.* To determine the worst case of a flood occurring on already high groundwater levels, high recharge conditions are applied for the preceding 6 months before the flood (December to May). The rainfall for these months is determined from the maximum monthly rainfall observed for the rainfall record for the Forres rain gauge (January 1977 to December 1999) (see Table A3). An extra model run is undertaken between Run A and Run B with higher rainfall which raises the groundwater heads before the start of the flooding.

The inflows to or the outflows from the groundwater system from each of these parts of the engineering solution, are detailed in Table A4.

Table A3. Years used to represent highest rainfall for the 6 months prior to the June flood run.

Month	**Year**	**Rainfall mm)**
December	1999	96.7
January	1988	102.8
February	1990	98.2
March	1992	79.6
April	2000	141.2
May	1997	124.9

To investigate how the proposed works will mitigate the flooding, various simulations were undertaken as presented in Table A4. The flows for the time variant runs are the maximum flow as the model returns to a dynamic balance.

The results are presented below. The 1 in 200 year run is analysed in detail, followed by a brief summary for the other runs. The 1 in 200 year run is used for comparison purposes with the other simulations.

Table A4. Summary of prediction runs.

Run	Description	Outflow from groundwater system (l/s)			Flow into model due to flooding (l/s)	Maximum groundwater head (m OD)				
		Estuary	Existing Drain	Proposed Pilmuir Drain		RFBH02	RFBH101	RFBH14	RFBH104	P4
0	Basescase no Engineering measures	206.40	24.01	n/a	n/a	12.75	11.05	11.60	10.21	8.94
1a	Eng. Measures no flood	206.34	23.65	0.09	n/a	12.76	11.07	11.61	10.22	8.94
1b	Eng. Measures 60 mm/d Rf	548.94	45.97	0.86	n/a	12.98	11.31	11.84	10.45	9.14
2	1 in 50 year flood	206.53	25.96	5.18	1271.90	12.79	11.17	11.67	10.46	8.95
3	1 in 200 year flood	206.59	27.46	18.27	2761.21	13.22	12.27	11.94	11.50	8.96
4	1 in 200 year flood AND 60 mm/d Rf	549.24	45.99	20.87	3200.59	13.51	12.44	12.09	11.58	9.14
5	1 in 200 year flood AND 60 mm/d Rf AND antecedent conditions	749.07	79.53	32.00	2309.87	14.23	13.05	12.68	12.01	9.31

*Note that the groundwater model does not predict any water in the embankment toe drains, since the groundwater passes below them.

1 IN 200 YEAR RUN

It is worth discussing the results for the 1 in 200 year prediction run in detail. This run can then be used as the basecase to which changes for the other runs can be compared. The maximum flows for the main outflows from the system represented in the model are summarised in Table A4. The following plots are produced for the run:

- Groundwater hydrographs for five selected locations (Figure A13)
- River flow hydrograph for the River Findhorn immediately upstream and downstream of the inundated area (Figure A14)
- Flood maps for 1day, 10 days and 100 days after the flood event (Figure A15)
- Difference plots for 1 day, 10 days, 30 days, 60 days and 100 days after the flood event (Figure A16)

Each aspect of the results are discussed below.

The maximum outflow to the estuary is 207 l/s, which is comparable with the dynamic balance (Table A4). The flow to the existing drain (pipe) is increased by around 2 l/s compared to the dynamic balance. The main change in the flows is the proposed drain, which has a maximum flow due to groundwater of 18 l/s for the 1 in 200 year event. This is a significant increase on the dynamic balance model run which has less than 1 l/s. The extra recharge from the flood event is calculated at 2762 l/s.

The hydrograph responses for the run are plotted in Figure A13. The locations (Figure 3) were chosen to examine the impact of flooding around the inundated area, roughly North (BH101), South (BH14), East (BH02) and West (BH104), as well as one hydrograph in the Pilmuir area (P4). Boreholes 101, 02 and 104 show a rapid response, followed by a slow recession. These boreholes are directly under the inundated area and respond very rapidly to the flooding. The response in Borehole 14 is less rapid, with the peak being 30 days after the flood event. This is due to the recharge from flood waters migrating away from the inundated area and causing groundwater level rises outside of the inundated area. The progression of the groundwater rise after the flood event can be seen on the difference plots (Figure A16). The hydrograph for Borehole P4 shows a more “natural” response. Again examining the difference maps (Figure A16) for the 1 in 200 year event shows that groundwater level rise does not reach P4 as the groundwater level is controlled by the existing drain.

The river hydrograph shows how baseflow in the River Findhorn increases before and after the flood event (Figure A14). The important aspect of the hydrograph is the increase in flow immediately after the flood event (1 day). This is due to the reduction in stage from 5.2 m above the river bed elevation during the flood event to 1 m above the elevation after the flood event. This reduction in stage allows more groundwater to flow into the River Findhorn after the flood event. Baseflow to the rivers is the main way that recharge from the flood waters leaves the system.

Examining the flood maps (Figure A15) shows how the flooding affects groundwater heads for 1 day, 10 days and 100 days after the flood water have subsided. The green and yellow area show groundwater close to the ground surface (1 m below and 0.5 m below respectively). The orange and red areas show where groundwater is predicted to be above ground level (0.5 m above and 1 m above respectively). In all cases groundwater is close to the ground surface in the Pilmuir area and to the north-east and north-west of Forres. The former is due to the low-lying ground around Pilmuir and is presumably the reason why the existing drain has been installed. The latter is due to the model not adequately simulating groundwater heads in this area (as discussed earlier for the basecase), presumably because existing drains and ditches have not been mapped and included in the model for this area.

The flood map for day 1 shows the inundated areas to the east of the Broom of Moy persisting. Even after 10 days the flooding is still evident. Away from the inundated areas, flooding appears to increase as the groundwater moves outward from the inundated areas. This is also suggested by the difference maps (Figure A16).

The difference plots (Figure A16) show the increase in groundwater head in the runs compared to the “normal” conditions in the dynamic balance. This is necessary due to the seasonality in the dynamic balance response. By subtracting the groundwater head at any model node for the flood runs from the head in the dynamic balance run it is possible to see the impact of the flooding without the complication of changes in groundwater head due to recharge. Plots of groundwater head difference are presented for 1 day, 10 days, 30 days, 60 days and 100 days after the end of flooding. Generally the plots shows that the impact of flooding declines over time, but as it declines, it spreads out from the areas of inundation. The recharge from the inundated areas can be seen in the high groundwater heads (1 – 2 m zone) adjacent to the River Findhorn. These zones persist until day 30. The impact of the existing drain can be seen on the progression of the recharge form the flood waters. For example, in the 30 day, 60 day and 100 day plots a “kink” in the 0.05 – 0.1 m zone can be seen around the south of Pilmuir. This area corresponds to the existing drains and is likely to be caused by the existing drains controlling groundwater heads.

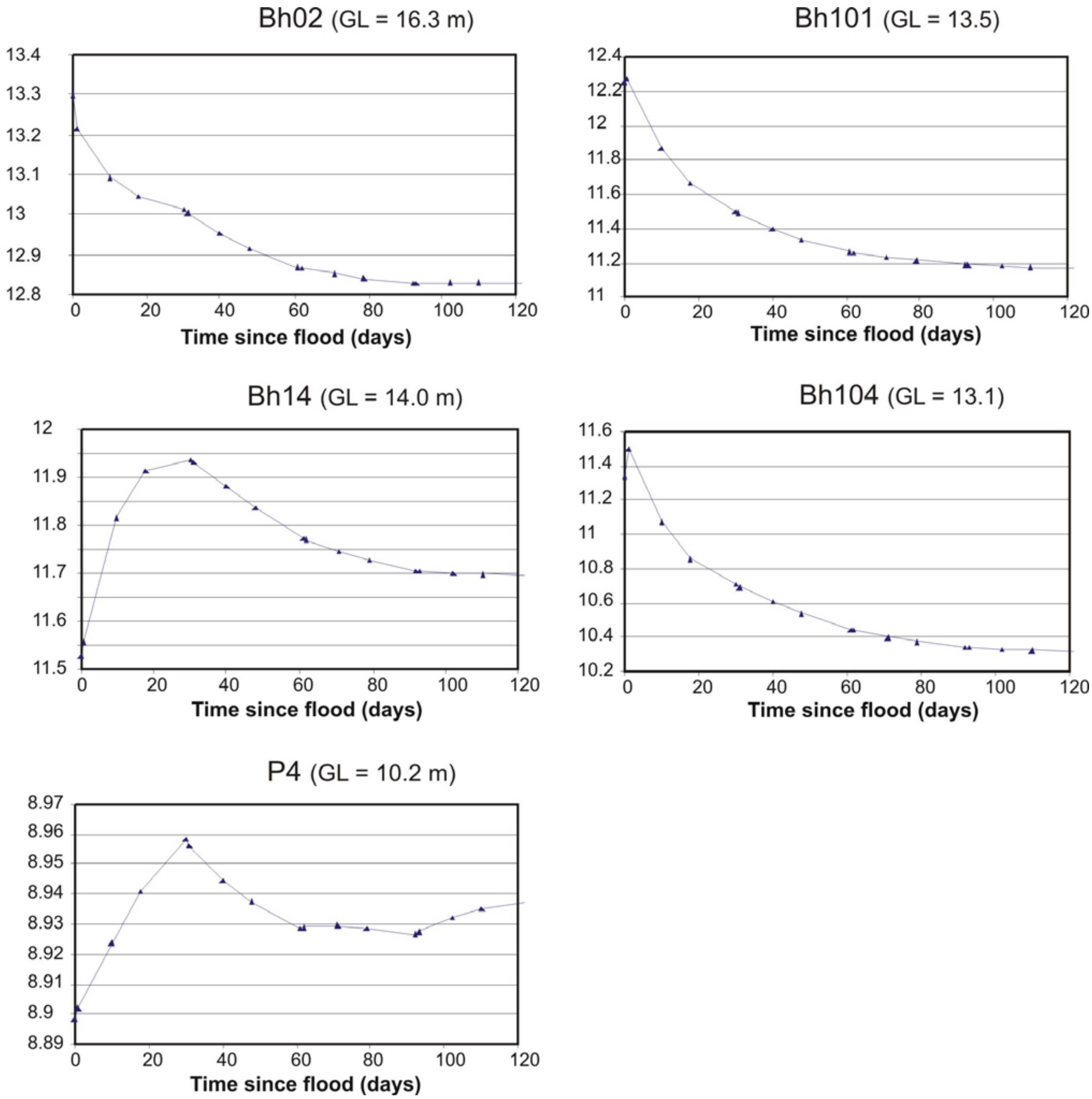


Figure A13. Hydrograph response during the 1 in 200 year run.

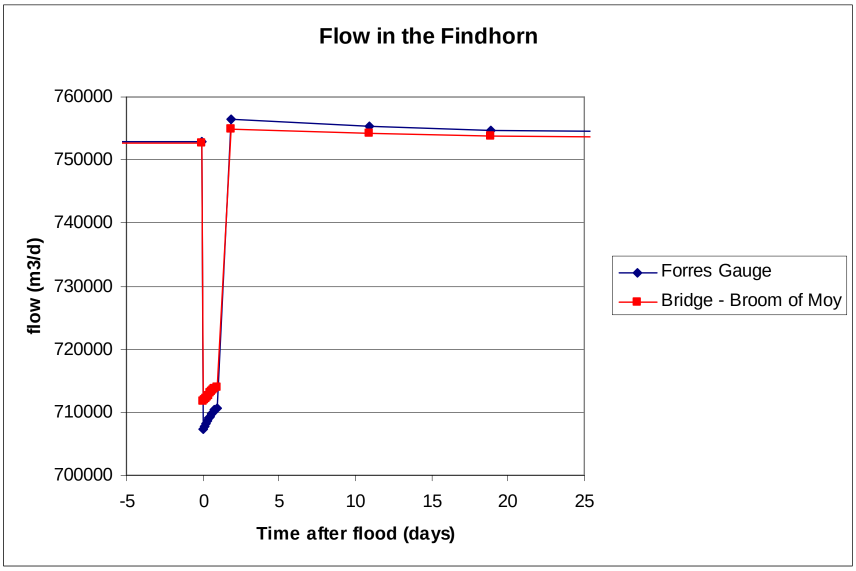


Figure A14. Groundwater influence on the River Findhorn during the 1 in 200 year run. During the flood event, the groundwater contribution reduces since the heads in the river are higher; after the flood, groundwater contribution increases as the excess water in the aquifer flows back to the river. Note that the *absolute* flows are arbitrary and do not relate to the river flows during a flood event.

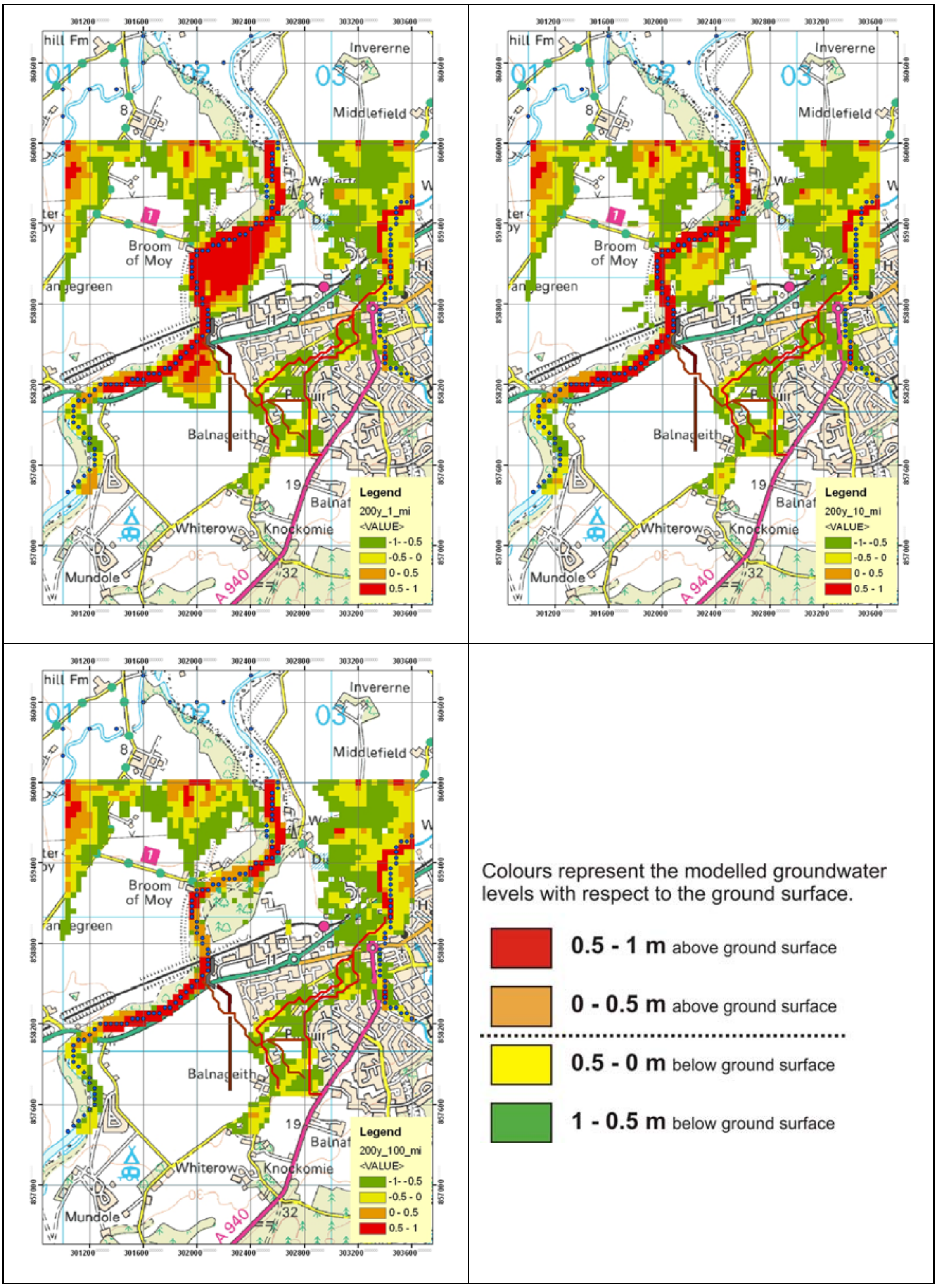


Figure A15. Flood maps for the 1 in 200 yr event (1 day, 10 days and 100 days after flooding).

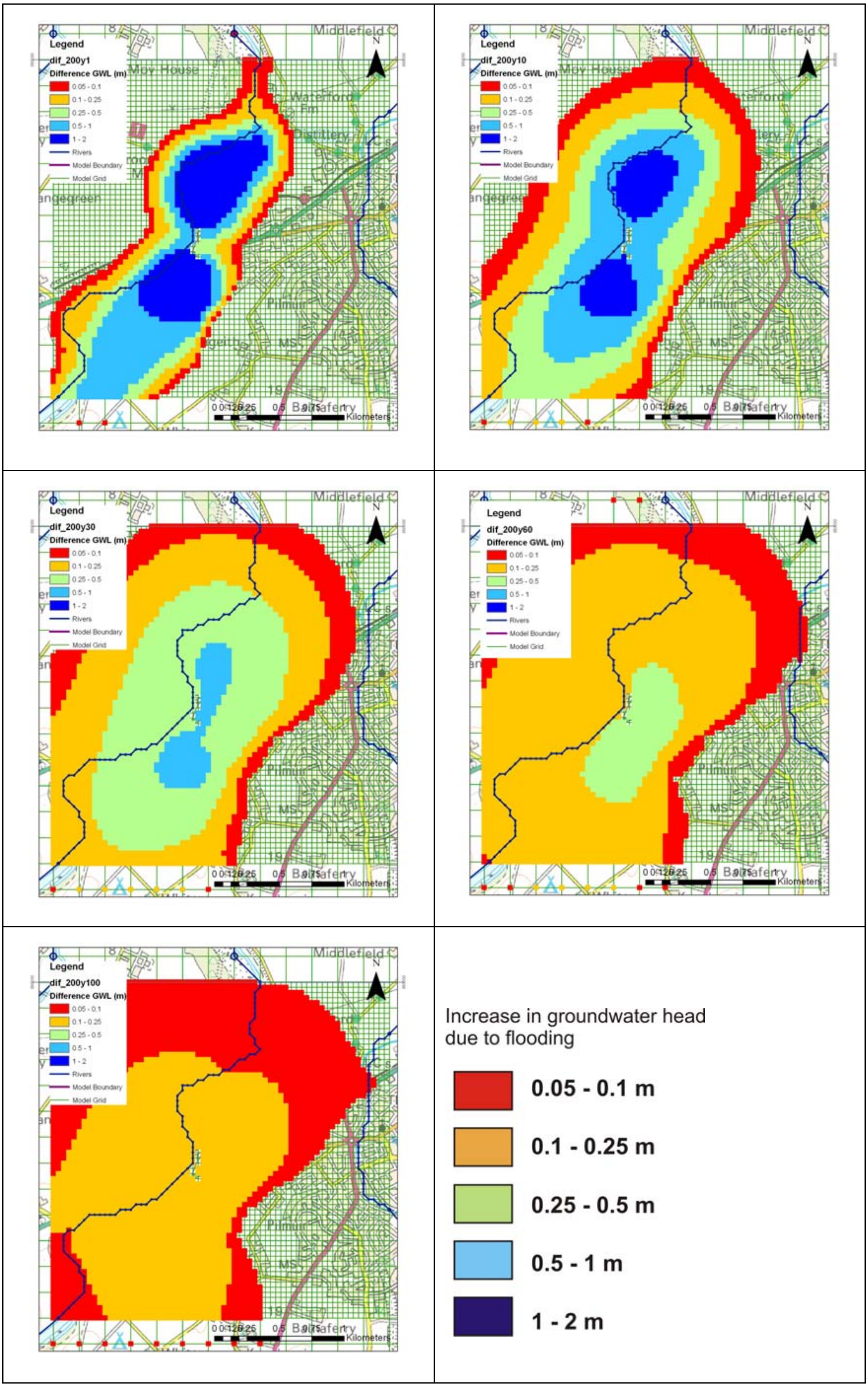


Figure A16. Difference plots of 1 in 200 yr after 1 day, 10 days, 30 days, 60 days and 100days.

Building on the preceding discussion, The following runs are discussed:

- 60 mm recharge event
- 1 in 50 year event
- 1 in 200 year with 60 mm/d recharge
- 1 in 200 year event with 60 mm/d recharge and high recharge antecedent conditions

The flood maps (1 day, 10 day and 100 day) and the difference plots (1 day, 10 days, 30 days, 60 days and 100 days) are presented for each run and compared with the 1 in 200 year event run. The maximum flows presented in Table A4 are also used for comparison.

60 MM RECHARGE EVENT

The flow into the existing drain is more than in the 1 in 200 year event run (46 l/s), while it is much less in the proposed Pilmuir drain (1 l/s). Flooding behind the bund is less pronounced under this run, while an increase in flooding can be observed to the north of the area (Figure A17). This is caused by the general raised heads due to recharge. The difference plots (Figure A18) show in this case that there is an increase in groundwater head ranging between 0.25 to 0.5 m in the whole area. However, the difference is smaller in the Pilmuir area, since the existing drain (pipe) constrains the groundwater levels.

1 IN 50 YEAR EVENT

Flow into proposed drain is less thanin the 1 in 200 year event run (~ 5 l/s). The total recharge due to flood waters entering the groundwater system is around half of the 1 in 200 year flood (~1272 l/s). Less flooding is observed behind the bund (Figure A19), but comparable flooding is observed elsewhere. The difference plots (Figure A20) clearly show the reduced impact of flooding on groundwater behind the bunds.

1 IN 200 YEAR WITH 60 MM/D RECHARGE

This addition of recharge results is much more flow into the existing drain (~ 46 l/s) than the 1 in 200 year flood event alone. Slightly more flow occurs into the proposed drain (~21 l/s). Flow is markedly increased to the estuary, but this is understandable given the 60 mm/d recharge is applied on a catchment-wide basis and has to find an outlet. Flood maps show increased flooding to the north of the area (Figure A21). This is caused by the raised heads due to recharge. The difference plots (Figure A22) show a marked change from the 1 in 200 year run. Increases of between 0.25 and 0.5 m are observed over the whole area. The exception being the existing drains which control heads. The impact of the inundated areas on groundwater heads are very similar to that for the 1 in 200 year runs.

1 IN 200 YEAR EVENT WITH 60 MM/D AND INCREASED RECHARGE FOR ANTECEDENT CONDITIONS

This is the worst case run and as would be expected the outflows from the system are the largest (Table A4). A flow of nearly 80 l/s occurs into the existing drain and 32 l/s into the proposed Pilmuir drain. There is less water entering the system from the inundated areas. This is due to higher groundwater heads resulting from the increased recharge in the six months leading up to the flood. The increased head reduces the outflow from the inundated areas. The flooding is more extensive than the 1 in 200 year runs (Figure A23). Again, the most noticeable change is in the difference plots (Figure A24) which show an increase of head between 1 – 2 m over most of the area. The existing drains controls rises in groundwater heads and drain the system.

ADDITIONAL RECHARGE CALCULATION FOR 1 IN 200 YEAR EVENT "DO NOTHING" SCENARIO

An estimate was required of the volume of floodwater that might enter the groundwater system in the Forres area from a 1 in 200 year river flood event if there were no engineering works and the flood waters were allowed to flow through Forres (see Figure 1 in main report for rough extent). The approach taken was to use the results from Run 3 and extrapolate over the area estimated by Moray Flood Alleviation to be flooded by a 1 in 200 year flood event with no engineering works.

The calculation was made for the area between the River Findhorn and the Burn of Mosset south of 859400. In this area approximately 1.2 Mm^2 would be inundated to an average depth of 1 m for approximately 1 day, and 1.1 Mm^2 for a depth of 0.2 m for approximately 1 day. Using the soil permeability of 0.3 m/d and the recharge calculated from Run 3 for similar depth of flood water, the estimated recharge is approximately 700,000 m^3.

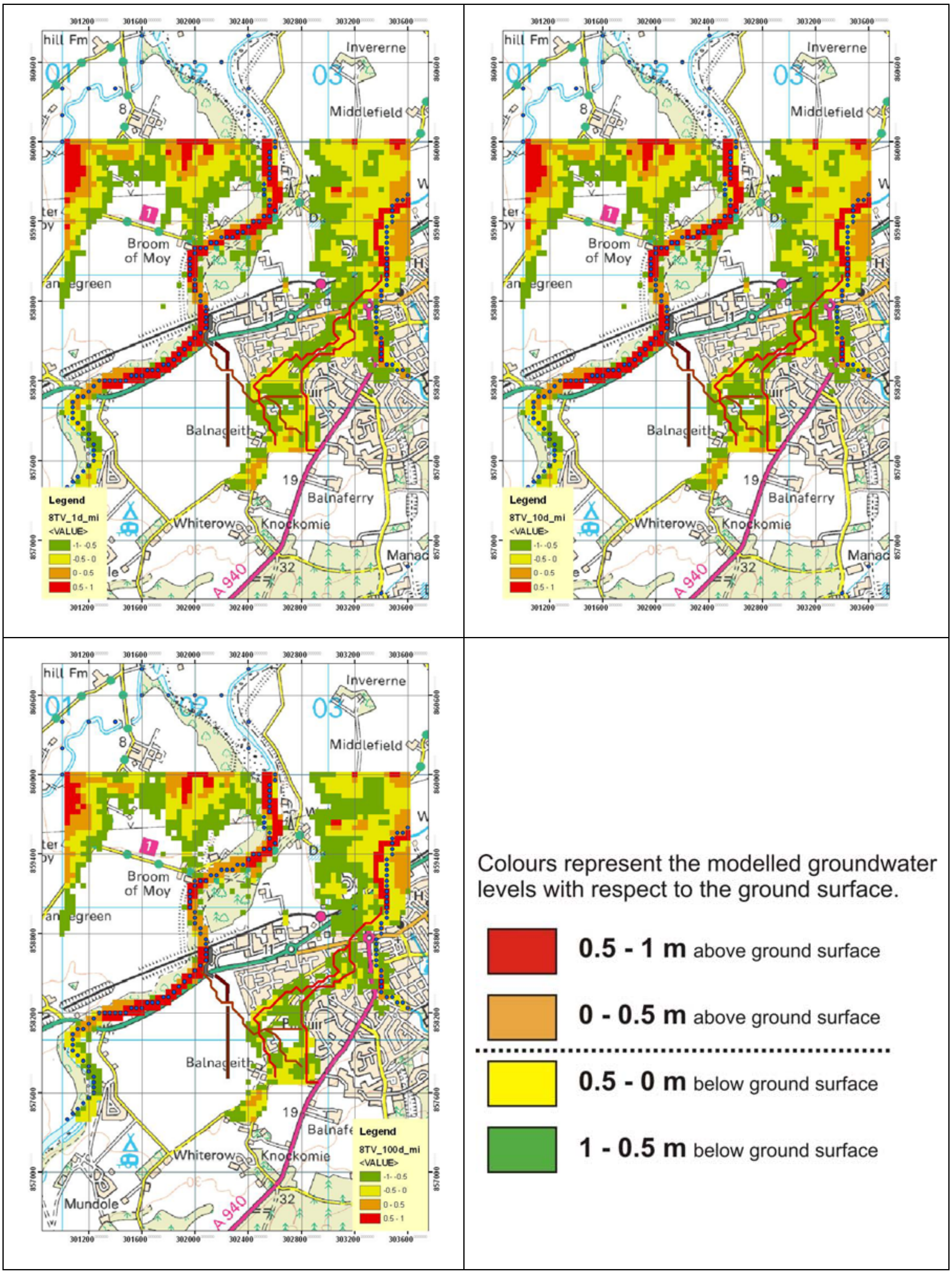
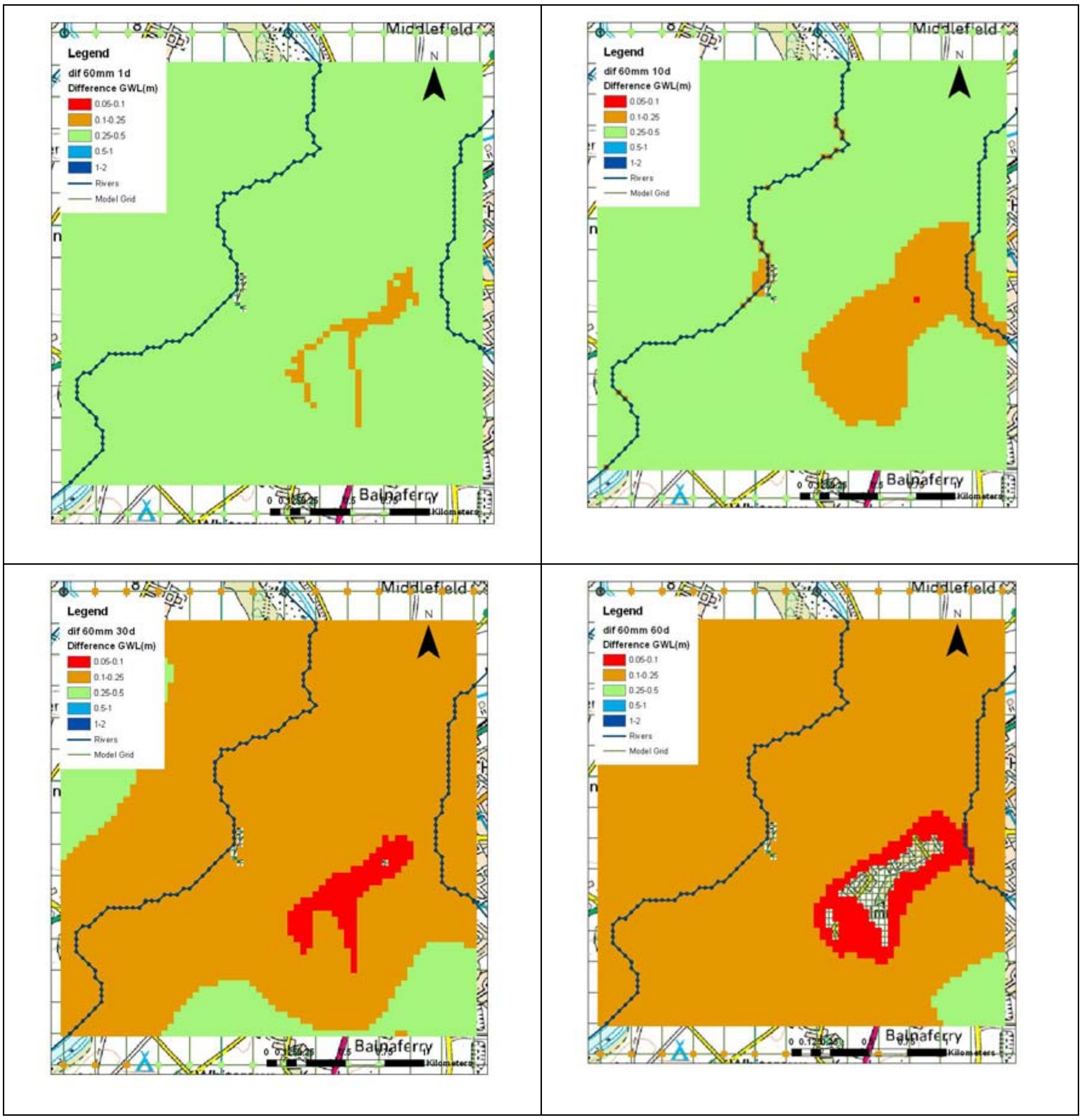


Figure A17. Flood maps for the 60 mm recharge event (1 day, 10 days and 100 days after flooding).


Legend
dif 60mm 1d
Difference GWL(m)
0.05-0.1
0.1-0.25
0.25-0.5
0.5-1
1-2
Rivers
Model Grid
N
Balnaferry
Kilometers
Legend
dif 60mm 10d
Difference GWL(m)
0.05-0.1
0.1-0.25
0.25-0.5
0.5-1
1-2
Rivers
Model Grid
N
Balnaferry
Kilometers
Legend
dif 60mm 30d
Difference GWL(m)
0.05-0.1
0.1-0.25
0.25-0.5
0.5-1
1-2
Rivers
Model Grid
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Balnaferry
Kilometers
Legend
dif 60mm 60d
Difference GWL(m)
0.05-0.1
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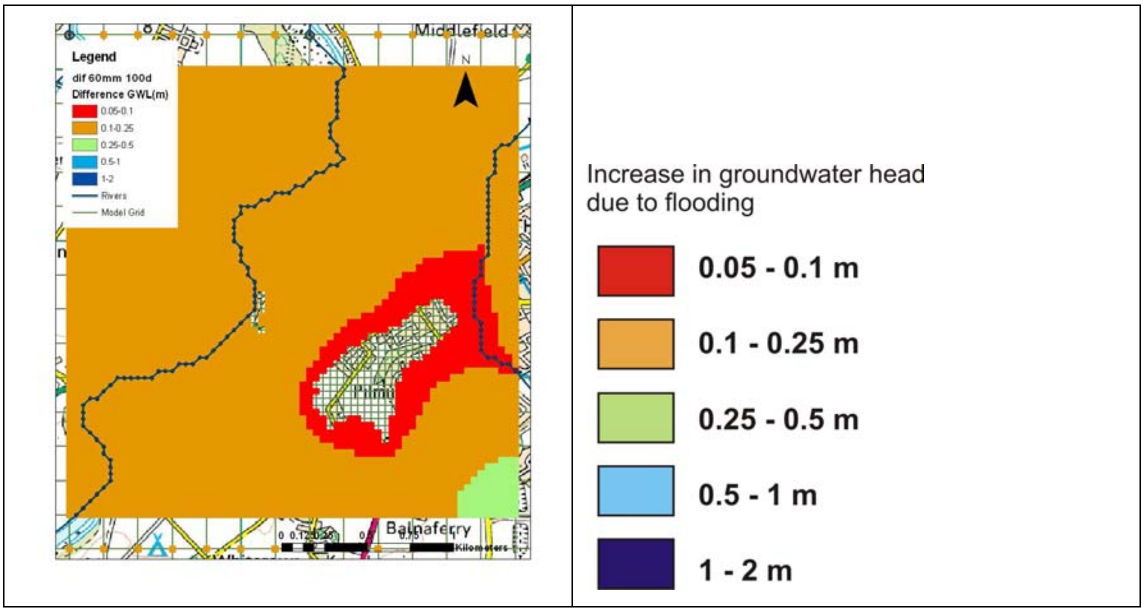
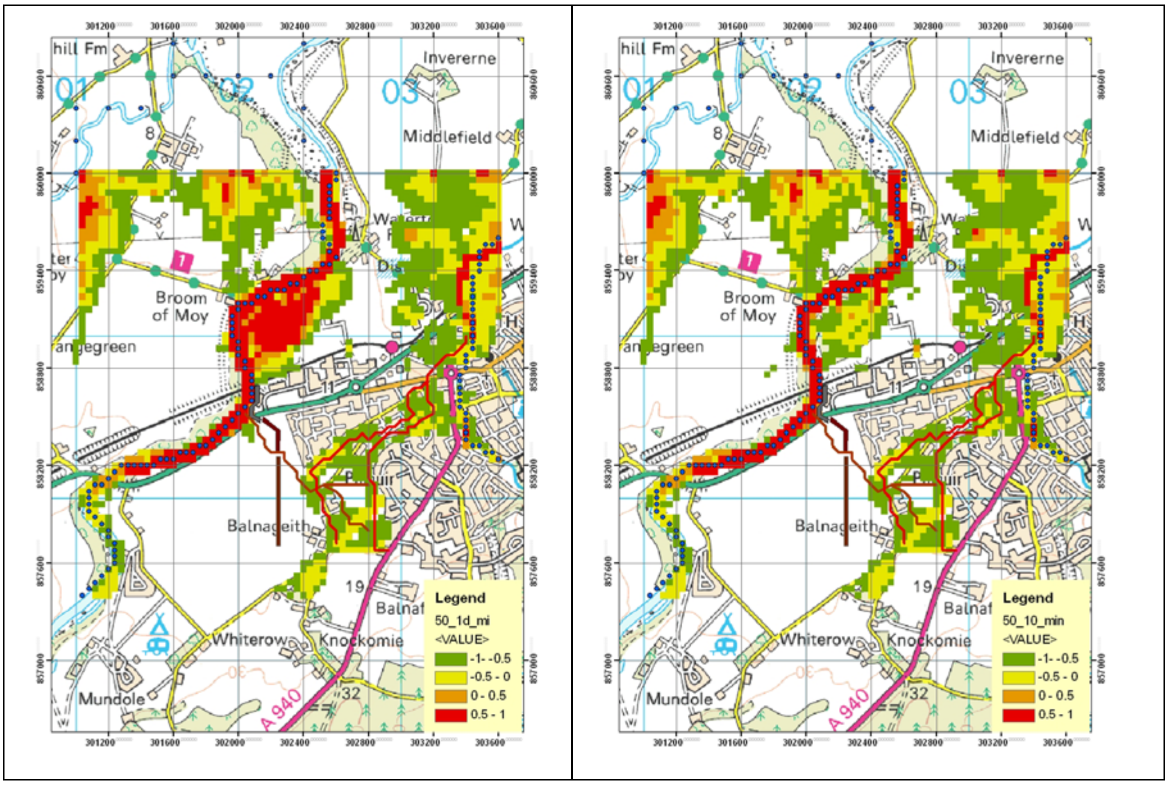


Figure A18. Difference plots of 60 mm recharge after 1 day, 10 days, 30 days, 60 days and 100 days.



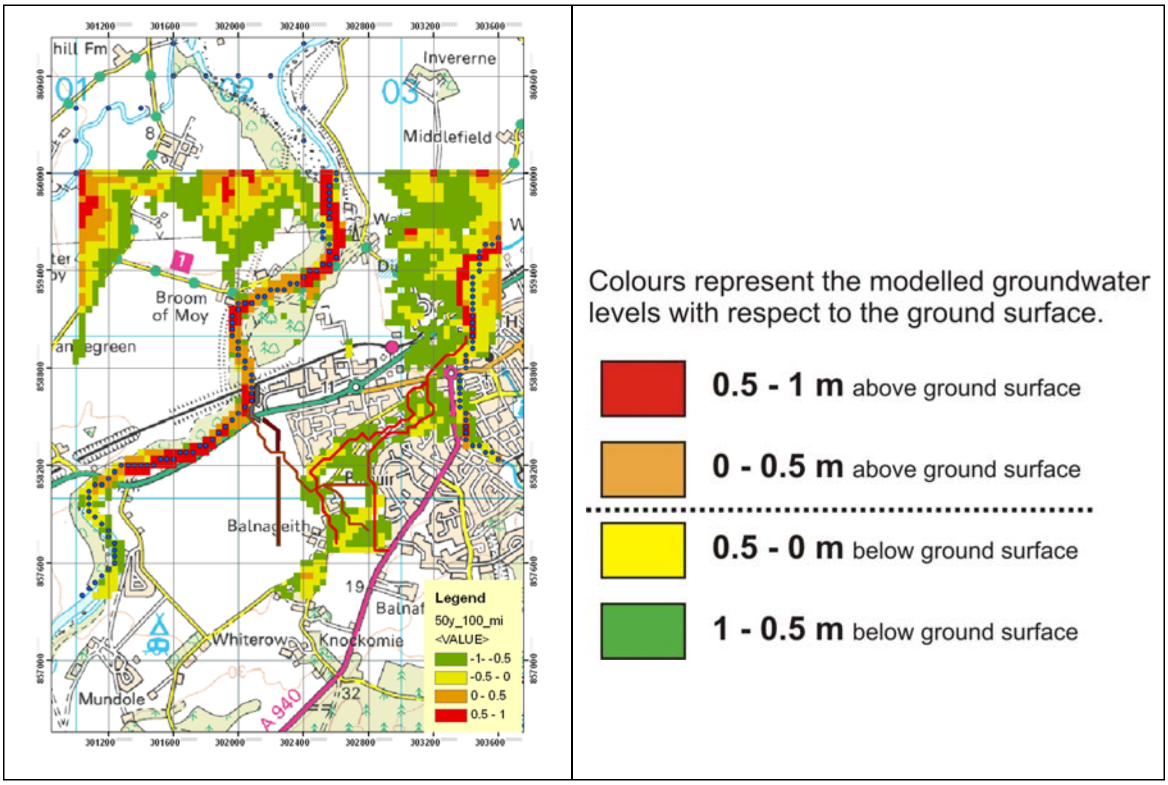
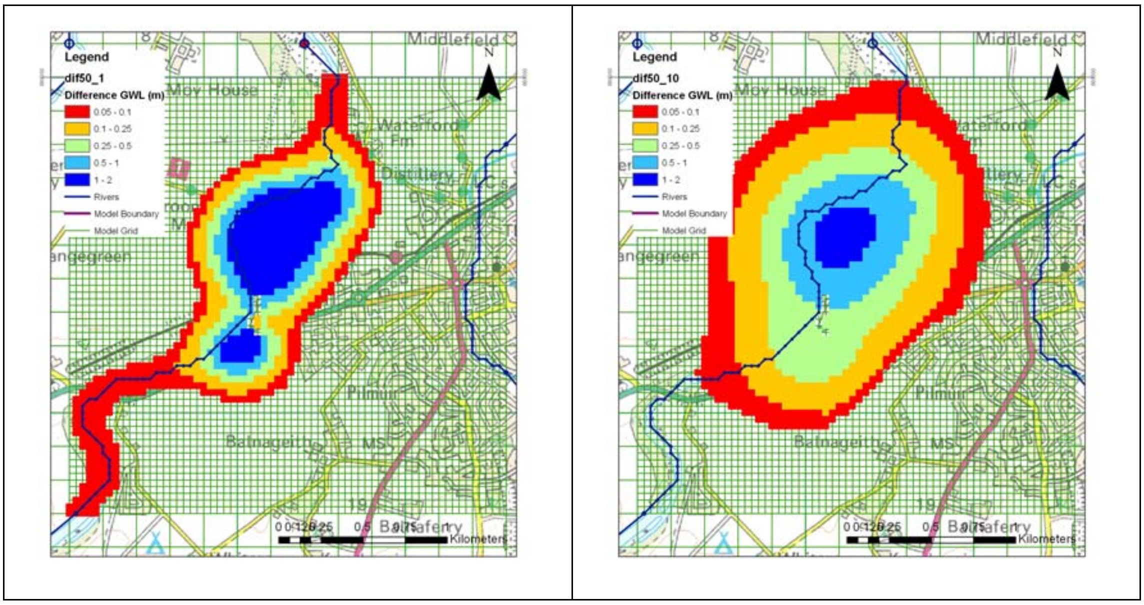


Figure A19. Flood maps for the 1 in 50 yr event (1 day, 10 days and 100 days after flooding).



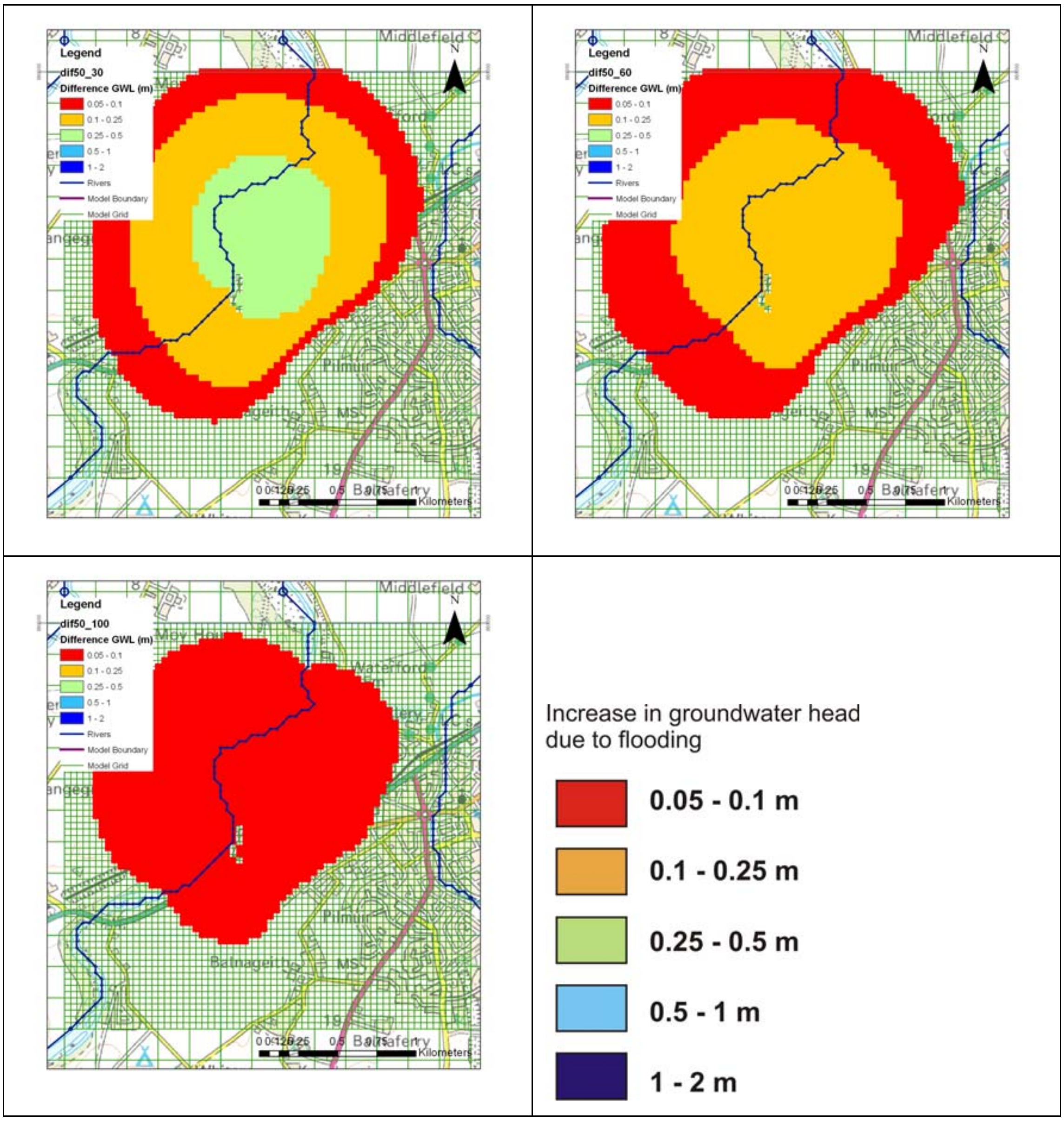


Figure A20. Difference plots of 1 in 50 yr after 1 day, 10 days, 30 days, 60 days and 100days.

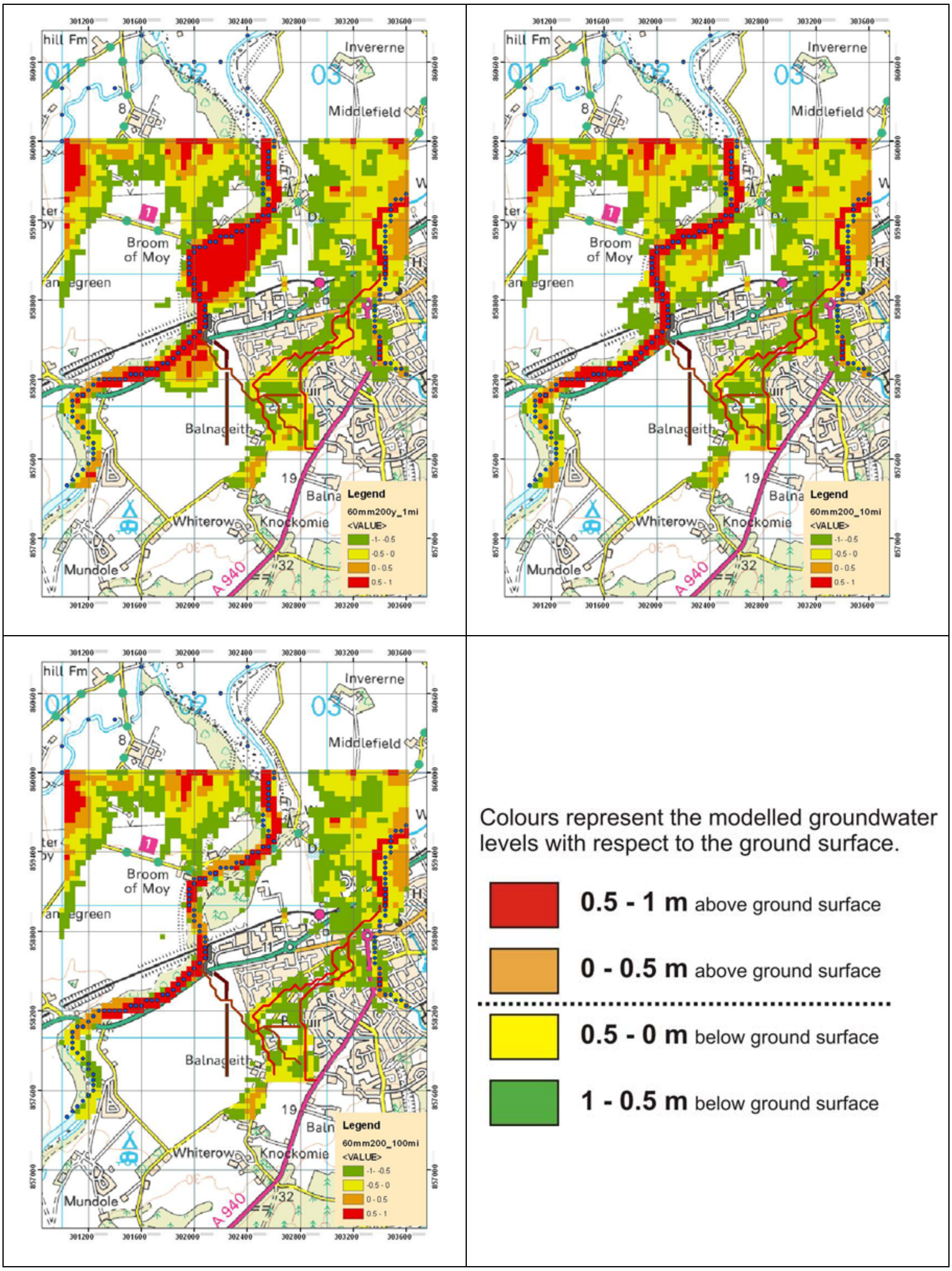


Figure A21. Flood maps for the 1 in 200 yr event with 60 $mmday^{-1}$ recharge (1 day, 10 days and 100 days after flooding).

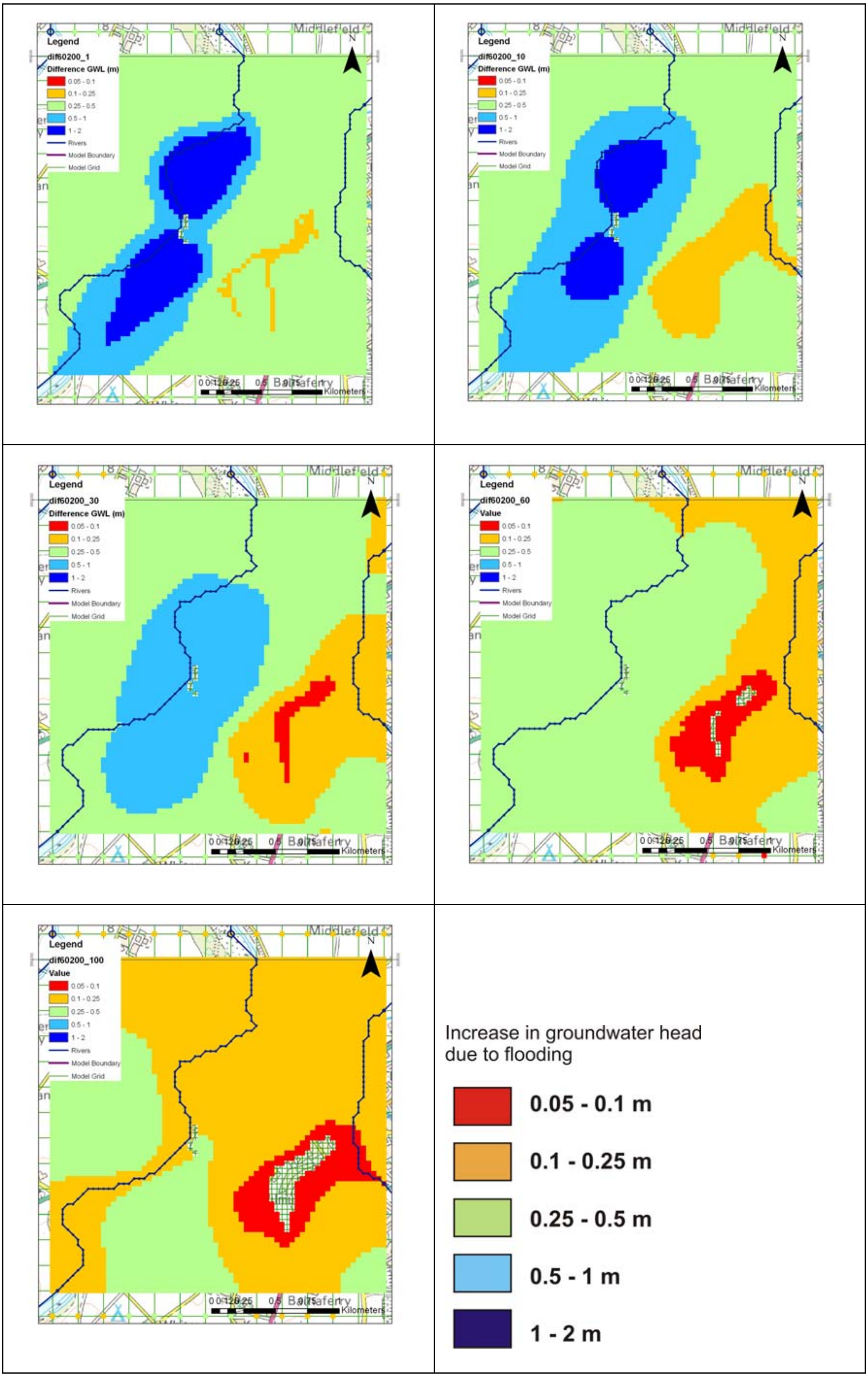


Figure A22. Difference plots of 1 in 200 yr with 60 mm/d

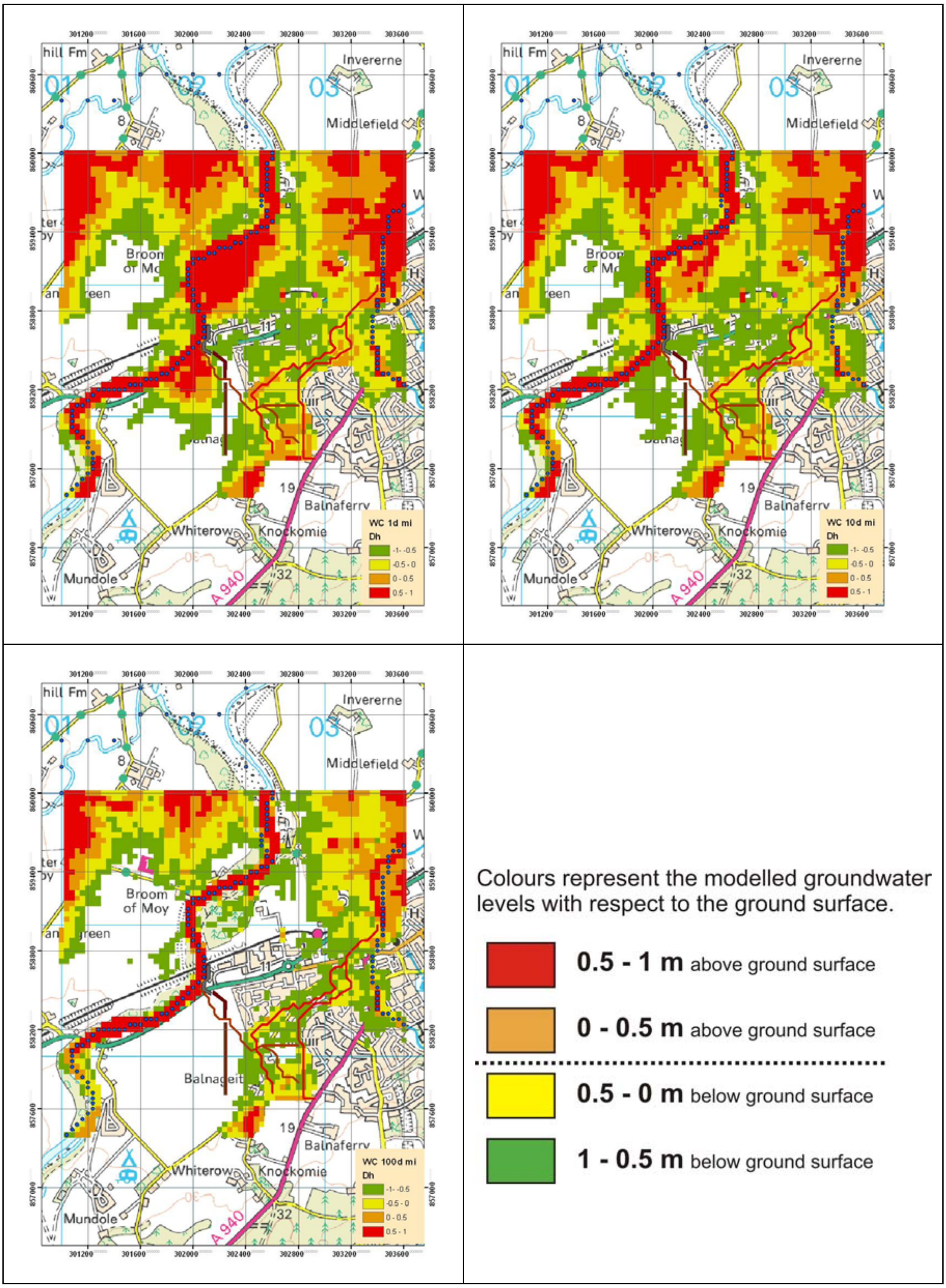


Figure A23. Flood maps for the 1 in 200 yr event with 60 mmday^{-1} recharge and antecedent conditions (1 day, 10 days and 100 days after flooding).

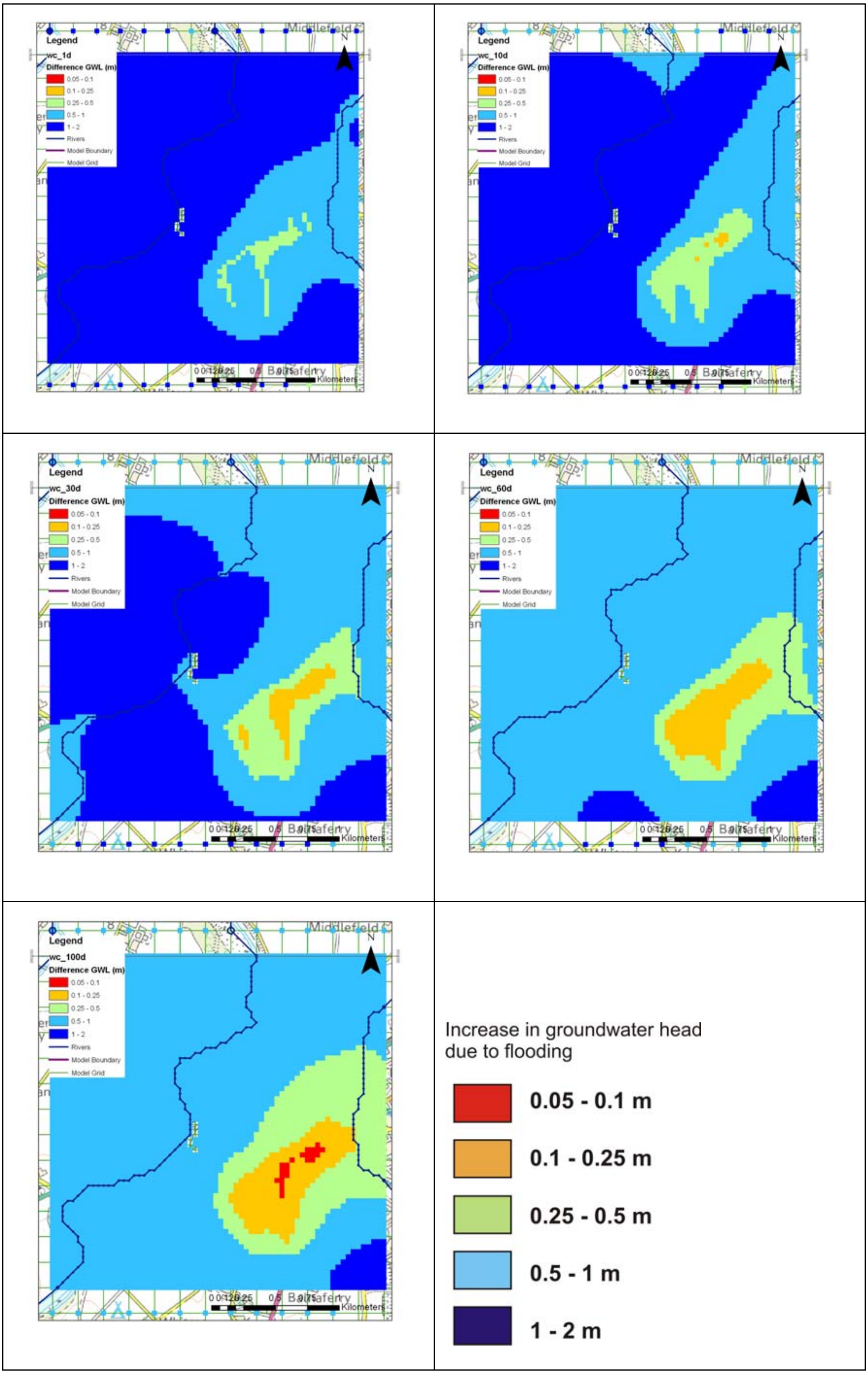


Figure A24. Difference plots of 1 in 200 yr with 60 mmday^{-1} recharge and antecedent conditions.

CONCLUSION AND RECOMMENDATIONS

Introduction

This appendix has described the application of groundwater modelling to both enhance the understanding of the groundwater system around Pilmuir and to determine the impacts of flood alleviation schemes on groundwater flooding. To this end a steady-state groundwater flow model was developed and compared with existing data. This steady-sate model was enhanced to simulate a dynamic balance to determine how well the seasonal changes in the system could be simulated. Finally, the model was used to determine the impact of the flood alleviation scheme on groundwater flooding in the Pilmuir area.

Improved conceptual understanding

The following are the main advances in conceptual understanding made during this phase of the groundwater modelling:

- Transmissivity distribution derived from the pumping test analysis was confirmed by the modelling.
- The importance of the role of SUDS in controlling groundwater heads locally was identified.
- Losing and gaining stretches of the River Findhorn were identified.
- The connection of the River Findhorn to the sandstone bedrock in the south of the area was proposed and appears plausible.
- The new model allowed the role of compartmentalisation of the system to be studied.
- The recharge modelling demonstrates that recharge occurs in the summer months, with the maximum occurring in June, with significant values in August and September.
- The high groundwater levels modelled to the north-west and north-east of Pilmuir suggest that the drains in this area (not included in the model) are effective at discharging groundwater and reducing groundwater levels in this area.

Simulation of groundwater flooding

The simulation of the flooding for this work represented an improvement over the Phase 1 work. Inundated areas were represented by river nodes (head dependant leakage nodes) and the volume of water added to these areas was realistic. The stage in the River Findhorn was also varied to reproduce a larger volume of water flowing down the river during a flood event. Finally recharge was used to represent a high rainfall event over the whole catchment.

To examine the impacts of the flood alleviation scheme on groundwater flooding, two spatial methods of data analysis were developed. The first was a flood extent map which determined the difference between the modelled groundwater head and the ground surface. The second was difference plots to enable groundwater head at the same location to be compared with those under different conditions. Since the runs were based on a dynamic balance it was necessary to determine differences in head at the same time in the seasonal cycle.

The general conclusions from the simulation of the flooding are as follows;

- Flooding persists in the inundated areas for between 30 and 60 days after flooding.
- Simulations using catchment wide recharge (as opposed to river flooding alone) produced impacts over a wider area that persist for longer.

- The main outflows to the system of flood waters were the existing and planned drains, and the River Findhorn. The existing drains controlled the level of flooding during catchment wide events.
- The worst flood impact was caused by the combination of 1 in 200 year inundation, local catchment recharge and high recharge antecedent conditions.

The main conclusion from the work is that the engineering schemes are highly unlikely to exacerbate the groundwater flooding situation across Forres, and may alleviate some of the groundwater flooding issues.

Recommendations for further work

The main conceptual issues that could be followed up are the role of bedrock topography in "compartmentalisation" of groundwater flow in the superficial deposits and collecting evidence for high groundwater levels to the north-west and north-east of Pilmuir. Based on the experience of simulating groundwater flooding, the following technical advances could be pursued:

- Developing an object in the ZOOM model to represent lakes.
- Undertaking a model water balance on a defined area (rectangle) during the flood events.
- Investigate statistical methods for defining return periods for recharge events.

As a longer term aim, the development of a more appropriate simulation of the unsaturated zone, especially where surface water overlies an unsaturated zone, would be useful.