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Preliminary numerical modelling of groundwater flow in the Dumfries basin

Groundwater Systems and Water Quality

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INTERNAL REPORT IR/04/053

Preliminary numerical modelling of groundwater flow in the Dumfries basin

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Front cover

River Nith at Holywood

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Summary

The Dumfries Basin occupies the lower part of the River Nith catchment in south-west Scotland. The basin is a deep, partly fault bounded, outlier of Permian sandstone and breccia, with a partial superficial cover comprising a variety of lithologies which range from gravel to sandy clay. There is a complex interaction between the River Nith and the aquifer as the river and its various tributaries cross the basin.

Piecemeal investigation of the aquifer had taken place since the first public supply borehole was commissioned in the late 1970s. The main driver of these studies was groundwater development and latterly also pollution protection. The purpose of the current study was to bring these findings together, to identify gaps in data and to develop and test a conceptual flow model for the basin. The key objective of the study was to determine the total renewable resource available in the Dumfries Basin Aquifer as a part of the overall Nith catchment, by:

- Defining the groundwater flow system, its principal recharge and discharge zones.
- Developing a catchment scale water balance.
- Identifying data gaps.

The conceptual flow model of the aquifer was developed and this work drew on new drilling, monitoring, and analytical activities, which together allowed the new conceptualisation to be developed. The conceptual model has now been tested with the development of a distributed recharge model for the basin, which depends partly on surface water accretion data, an overall basin-wide water balance and a steady state groundwater flow model. This report describes the modelling and water balance studies.

Annual precipitation totals vary from approximately 1000 mm in coastal areas to more than 2000 mm over the high ground near the western watershed. Average potential evaporation is typically in the range 450 to 550 mm a^{-1}.

The bedrock aquifer sequence of the Dumfries Basin comprises the Doweel Breccia and Locharbriggs Sandstone formations that are Permian in age. The Doweel Breccia comprises predominantly sedimentary breccia interbedded with sandstone and underlies the western part of the basin. The formation extends eastward toward the centre of the basin where it interfingers with the Locharbriggs Sandstone that underlies the eastern and northern parts of the basin. The superficial geology of the Dumfries Basin is dominated by an extensive development of glacigenic deposits, including lodgement tills and sand and gravel deposits, with marine clays towards and at the coast. Whereas the Locharbriggs Sandstone has high storage and low permeability, fractures control the hydraulics of the Doweel Breccia which has the opposite characteristics.

The effective depth of the aquifer is variable, but evidence from boreholes in the Terregles area and elsewhere indicates that active fracture flow occurs to depths in excess of 100 m. The piezometry of the aquifer, for which data are concentrated in the central and western parts of the basin, suggests that the main rivers are the principal discharge areas for groundwater in both the Permian and superficial aquifers. It was also accepted that the low permeability fluvio-marine silts and clays in the south of the basin, both onshore and offshore, allowed little groundwater flow directly to the sea, whilst also acting as a barrier to sea water intrusion. The conceptual model has the following features:

- The basin edge is effectively a no flow boundary given the comparatively limited hydraulic properties of the surrounding Palaeozoic rocks.

- Rainfall recharge occurs to the bedrock aquifer via superficial sands and gravels which principally occur in the north-western and central part of the basin. Rainfall recharge is greatly inhibited in areas underlain by clay or silt grade superficial material and peat.
- The Quaternary and bedrock aquifers are not always in hydraulic contact.
- Some surface water indirectly recharges the aquifer, probably in the upper or northernmost part of the basin.
- Piezometry indicates both lateral flow towards the River Nith and a groundwater sink in the western central part of the basin which is intensively pumped.
- Marine and alluvial silts inhibit discharge from the basin directly to the sea.

The approach adopted was to develop a time variant water balance alongside a steady-state model of groundwater flow. To enable both these tasks to be carried out a distributed recharge model was required. Both the recharge model and the subsequent water balance are based on a simulation period of January 1970 to October 2003. This period was chosen to enable the longest reliable record of data to be used and to provide different climatic conditions.

A distributed recharge model has been developed for the Dumfries basin using the Penman-Grindley soil moisture balance method. Recharge is calculated on a grid of 500 m, to be compatible with the groundwater flow model. Using a combination of rainfall, potential evaporation, landuse and geology, recharge was calculated on a daily time step from January 1970 to October 2003. The daily recharge was aggregrated to a monthly values to be compatible with both the water balance and the groundwater flow model.

Characterisation of the Quaternary deposits showed that the majority of the superficial deposits are permeable. Where low permeability deposits are identified (marine clays and peats), the runoff is increased at the expense of vertical recharge

The distributed recharge for the Dumfries basin was summarised for the catchment of the River Nith and the Lochar Water. The long term average recharge (1970 to 2003) for the River Nith catchment is 434 mm a^{-1} and for the Lochar Water catchement is 200 mm a^{-1}. The discrepancy in the estimate of recharge between the two catchments is due to the higher rainfall in the River Nith catchment and to the peat deposits limiting vertical recharge in the Lochar Water catchment. To build confidence in the results of the recharge model, a time series of monthly recharge is compared to adjacent groundwater hydrographs. This comparison showed that groundwater heads rise when recharge is calculated by the model. There was little or no delay between recharge leaving the soil zone and arriving at the water table.

A time variant water balance was constructed running from January 1970 to October 2003 using a monthly time step. A combined surface water-groundwater balance was necessary due to the dominance of river flows on the system. The water balance was undertaken to test the conceptual model and to provide an indication of available groundwater resource in the Dumfries basin. As for the recharge model, the water balance was summarised for two areas, the River Nith catchment and the Lochar Water catchments. The main inflows were identified as being river flows, especially the River Nith and rainfall recharge. The main outflows were identified as river flows, groundwater abstraction and springs. A flow balance was achieved, but to do this an estimate of flow at the bottom of the River Nith catchment was required. The error in the estimate of flow in the River Nith is more than the other components of the water balance combined. To enable a more accurate water balance, the flows at the tidal limit of the River Nith need to be obtained.

A groundwater flow model has been developed for the Dumfries basin, the boundaries of the model being defined by the edge of the basin in the north, east and west as no-flow boundaries. To the south, the sandstone aquifer extends under the sea and the southern boundary is defined by the Waterbeck fault, around 5 km from the coast. The southern boundary is defined as no-flow, but leakage is allowed from the sandstone to the sea or vice versa. The superficial deposits and the sandstone are represented by separate layers in the model. The extensive river network of the River Nith and the Lochar Water and their tributaries are fully represented in the model. There is a relatively simple distribution of transmissivity in the sandstone, with three main zones; Locharbriggs Sandstone (100 m^2day^{-1}), Doweel Breccia (600 m^2day^{-1}) and the southern part of the basin under the marine clays 50 m^2day^{-1}. The hydraulic properties of the superficial deposits are defined by the mapping of the Quaternary domain.

In the water balance, the main inflows to the model are baseflow from the rivers flowing onto the basin and rainfall recharge. Numerous rivers and streams flow onto the basin and the baseflow was determined from field data or estimated and applied to the appropriate river node. Rainfall recharge was taken directly from the calculation of distributed recharge described above. The main outflows from the model are baseflow to rivers, abstractions, springs around the Larchfield-Caelaverlock ridge and leakage to the sea.

A series of simulations were undertaken with the model; steady state, dynamic balance and historical simulation from January 1970 to October 2003. The steady state simulations were used to test the conceptual model on a spatial basis and to provide initial conditions for the time variant runs. The dynamic balance and historical simulation were undertaken to build confidence in the model and to identify issues in data on a time varying basis.

The output from the steady state simulation includes groundwater head contours, sections of groundwater heads through the groundwater system and sections down the rivers of both groundwater head and river baseflows. Comparing the modelled results with field data for the steady state simulation shows that the model reproduces the patterns of groundwater flow reasonably well. However there are differences and these occurred in the north of the basin, where groundwater head data are limited, around the estuary of the River Nith and in the east of the basin. The sections of groundwater heads show good agreement between modelled and field data, except around the Terregles Fish Farm and Dupont boreholes. This is thought to be due to the influence of abstraction on measured groundwater heads.

It is difficult to compare the modelled baseflow in the River Nith as few river flow data exist close the tidal limit of the River Nith. However, the modelled baseflows show a gain in river flows along the River Nith, which is consistent with the few data available. Modelled baseflows underestimate the observed baseflows in the Lochar Water. This is thought likely to be due to the impact of the mosses in the Lochar Water catchment. The peats in the mosses have been extensively drained and could provide a baseflow-like response in the Lochar Water and its tributaries. The drainage water is currently unaccounted for in the groundwater flow model.

The time variant simulations have similar issues as for the steady state simulation. Patterns of groundwater flow are broadly acceptable, but the detailed picture cannot be obtained due to lack of data. Again the baseflow in the River Nith cannot be verified due to lack of data. The baseflow in the Lochar Water is underestimated by the model, again due to the impact of the peat drainage.

However, comparison can be made between modelled and field data for the hydrographs of groundwater head for the three observation boreholes with a long record; Holywood, Newbridge and Redbridge. The timing and magnitude of the groundwater head hydrograph at Redbank can be reasonably simulated. The amplitude of the modelled variation at Holywood and Newbridge is too small. This may be due to the influence of the river in the model. The baseflow hydrographs at Friars Carse and Fiddlers Ford match reasonably well, although both river gauges are close to the edge of the basin. The baseflow at Kirkblane, on the Lochar Water is underestimated by the model and there are no data with which to compare the baseflow at the bottom end of the River Nith catchment.

To help quantify the uncertainty in the groundwater flow modelling, a limited sensitivity analysis was undertaken on the steady state model. In all, seven runs were undertaken, varying recharge, transmissivity and river leakage coefficients. The sensitivity runs demonstrated that changing recharge caused the most significant changes in groundwater heads and baseflows. Varying the transmissivity and river leakage coefficients caused changes in heads, especially in the interfluves, but had a limited impact on river baseflows. The conclusion from the sensitivity is that a good estimate of recharge is important.

The numerical modelling of groundwater flow in the Dumfries Basin has allowed the conceptual model of groundwater flow to be tested. The modelling has confirmed that the main groundwater outflow is to the rivers. Outflow to the rivers obviously controls groundwater flow directions. The conceptual model was also developed during the modelling process. The role of the mosses, drained peats, in limiting vertical recharge and enhancing flow to the Lochar Water was established. The limiting of leakage between the River Nith and the sandstone aquifer was also identified. Springs issuing from the Larchfield-Caerlaverlock ridge were also recognised as being important.

In terms of the water balance of the system, river flow was confirmed as being the most important inflow and outflow. Rainfall recharge is also a significant input, with the highest recharge occurring in the River Nith catchment. However, a method of measuring flow close to the tidal limit of the River Nith is required to enable an accurate water balance to be obtained.

The modelling also enabled gaps in data to be identified. The main data deficiencies being groundwater heads in the north of the basin, under the Larchfield-Caelaverlock ridge and in the east of the Lochar Water. It is extremely important that a method of measuring river flows close to the tidal limit of the River Nith is established. However, despite these deficiencies in data it is evident that further groundwater abstraction could be undertaken from the Dumfries Basin. Further work is required to enable this conclusion to be verified.

The main recommendations from the work are further data collection. A better spatial distribution of groundwater heads is required. The understanding of groundwater flow would be enhanced by observation boreholes drilled in the north of the basin, around High Kilroy (292000, 582000), in the south along the Larchfield-Caerlaverlock ridge and in the east of the basin, around Locharbriggs (300000, 578000). More time variant head measurements are required. For example, loggers should be placed in observation boreholes at Carnation No. 1, Locharbrigss, Dundas Chemicals and Greenmerse. Measurement of surface water flow at the bottom end of the River Nith catchment is essential. Producing a rating curve would enable the flood level data at Greensands to be used to create a flow record. Other areas that require investigation include the springs and streams that drain the Larchfield-Caerlaverlock ridge, the drainage of the peats to the Lochar Water and the surface water system around Longbridge Muir.

Once these data have been collected and analysed, then further time variant modelling can be undertaken. The aim of this modelling will be to determine the groundwater resources available in the Dumfries Basin.

1 Introduction

The Dumfries Basin is located in the lower part of the catchment of the River Nith in south-west Scotland (Figures 1 and 2). The basin is a deep, partly fault bounded, outlier of Permian sandstone and breccia, with a partial superficial cover comprising a variety of lithologies which range from gravel to clay. These strata form the Dumfries Basin Aquifer, a regionally significant aquifer which provides water for public supply, industry, and agriculture as well as a small number of private domestic supplies. There is a complex interaction between the River Nith and the aquifer as the river and its various tributaries cross the basin.

The hydrogeology of the Dumfries Basin Aquifer is of interest to all groundwater users in the catchment. Understanding the hydraulics of the basin is of key significance to the Scottish Environment Protection Agency (SEPA). SEPA is the responsible body for the implementation of integrated catchment management through the implementation of the Water Framework Directive (European Union, 2000). SEPA will also be responsible for issuing defensible groundwater abstraction licenses in selected catchments which, by definition will undertake to safeguard licensed sources from derogation. Understanding the Dumfries Basin Aquifer is also of key significance to Scottish Water (SW) who need to safeguard their existing groundwater assets and to optimise future use of the groundwater resource. Other interested parties include the fish farms at Terregles and Holywood, groundwater bottlers at Crichton Royal and Du Pont at Drungans. Protection of the resource from potentially polluting surface activities is, of course, paramount to all.

With these interests in mind, a major programme of study has been undertaken to identify and address knowledge gaps and to develop a sound groundwater flow model for the basin aquifer. The key objective of the study was to determine the total renewable resource available in the Dumfries Basin Aquifer as a part of the overall Nith catchment. Further aims included:

- Defining the groundwater flow system, its principal recharge and discharge zones.
- Developing a catchment scale water balance.
- Identifying those parts of the aquifer that are under stress, and those parts which are available for further additional exploitation.

The project design included four key tasks: drilling and monitoring, analytical activities, conceptualisation, and numerical modelling.

This report details the work undertaken for the numerical modelling of groundwater flow in the Dumfries basin. It summarises the hydrogeology of the basin, presents a summary conceptual model and details the time-variant water balance incorporating the calculation of recharge. The work is synthesised into a preliminary groundwater flow model. The main output of the numerical modelling is the development of a steady-state groundwater flow model, which is used to test the validity of the conceptual model. Time-variant modelling is also undertaken and both a dynamic balance and a historical simulation are performed. Whilst the data do not justify a fully time-variant model, the time-variant modelling was nevertheless undertaken to further test the conceptual model.

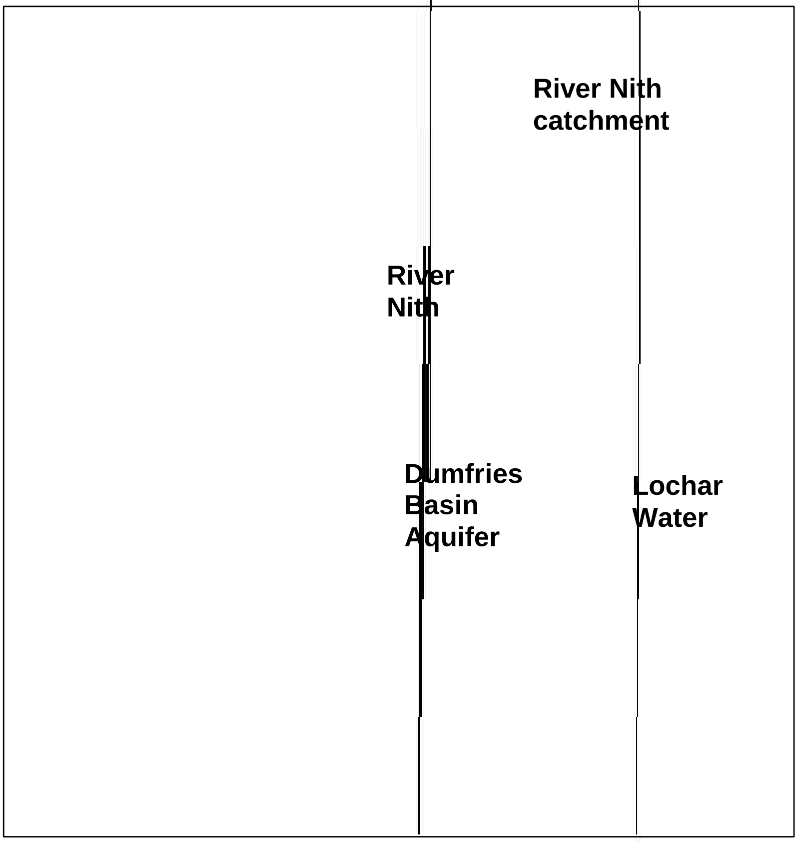

Figure 1 Location of Dumfries Basin within River Nith catchment

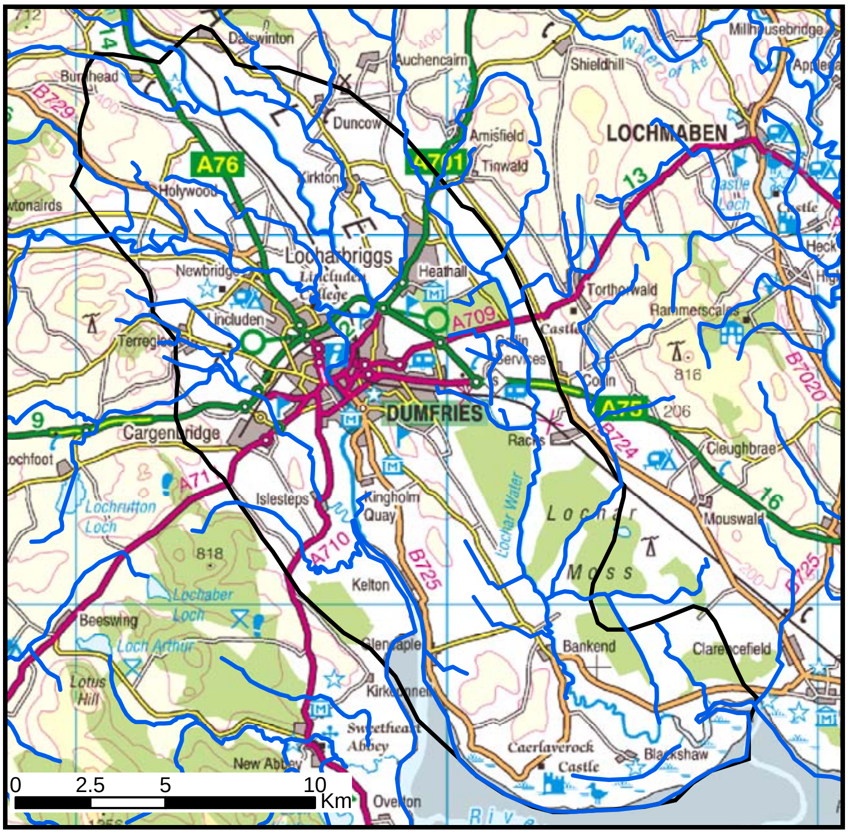

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Figure 2 Dumfries Basin location map

2 Summary of the hydrogeology of the Dumfries Basin

2.1 GEOLOGY

2.1.1 Solid geology

The bedrock aquifer sequence of the Dumfries Basin comprises the Doweel Breccia and Locharbriggs Sandstone formations that are Permian in age (Figure 3). The Doweel Breccia comprises predominantly sedimentary breccia interbedded with sandstone and underlies the western part of the basin (British Geological Survey, 1996; McMillan 2002). The formation extends eastward toward the centre of the basin where it interfingers with the Locharbriggs Sandstone that underlies the eastern and northern parts of the basin. The Locharbriggs Sandstone comprises two facies: distinctive orange-red, cross-bedded sandstones, that are interpreted to have accumulated as a migrating dune field in arid desert conditions; and thin bedded and laminated, orange-red, silty sandstone containing pebbles of local derivation generated by fluvial reworking of breccia and sandstone (McMillan, 2002).

The Permian basin-fill sequence unconformably overlies a steeply dipping succession of grey, fine-grained, wacke sandstone and mudstone of Silurian age that is intruded by the Criffel-Dalbeattie granodiorite to the south-west of the basin. Carboniferous strata, continuous with the sequence in the adjacent Annan Basin, unconformably underlie the south-eastern part of the Dumfries Basin (British Geological Survey, 1998; Holliday et al., 2001).

The Permian basin-fill sequence is inferred to have a maximum thickness of between 1.1 and 1.4 km, from modelling of air-born gravity data, with the centre of the basin lying immediately to the north of Dumfries. The basin is interpreted from Bouger gravity anomaly data to be fault-bounded by a series of en echelon faults along its western margin and fault bounded also to the north-east.

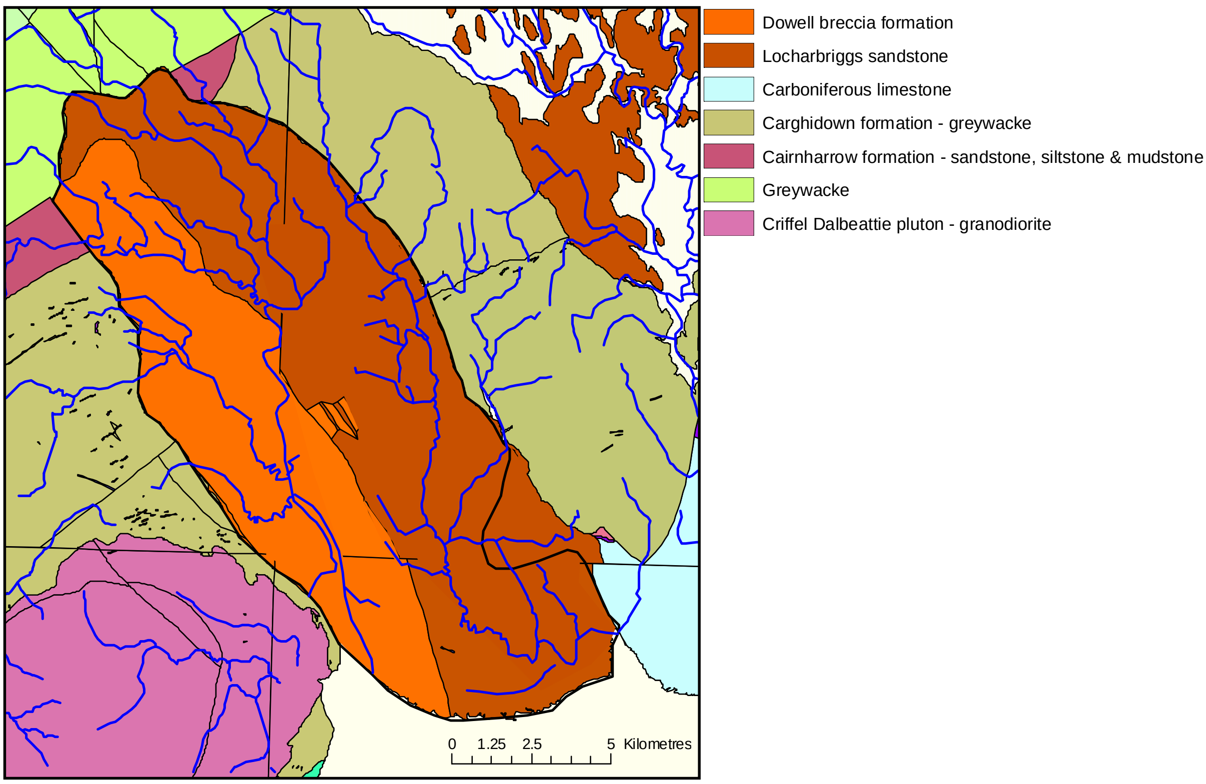


Figure 3 Solid geology map

2.1.2 Quaternary geology

The superficial geology of the Dumfries Basin is dominated by an extensive development of glacial deposits, both granular and cohesive, formed during the Dimlington (Late Devensian) glaciation (Figure 4). To the south-east of Dumfries, ice, originating in the Southern Uplands, moulded a streamlined topography of rock ridges aligned south-east. During deglaciation, active retreat of the Nith glacier took place in a north-westerly direction to pinning points (bedrock highs) at Cargenbridge, Maxwelltown and Locharbriggs. To the north-west of Dumfries, the basal deposit resting on the Permian strata is a lodgement till of the Dimlington ice sheet. On the lower lying ground the till is overlain by extensive discontinuous spreads of cobble gravel which form a distinctive morphology of mounds (kames), 15 m high, kame terraces and ridges (eskers), the crests of which trend north-west to south-east. These deposits exhibit normal faulting characteristic of an ice-contact origin. They are commonly overlain by a discontinuous thin (usually 1m or less) gravelly flow till.

To the south-east of Locharbriggs fine sand, silt and clay, with dropstones, was deposited in ephemeral glacial lakes. These glaciolacustrine deposits are overlain by tabular spreads of cross-bedded sand and pebbly gravel. The Nith glacier readvanced resulting in the formation of a moraine, characterised by moundy topography that extends in an arc between Locharbriggs and Cargenbridge. The deposits of the moraine comprise folded and sheared glaciolacustrine sand and silt, which locally exceed 30 m in thickness.

Following deglaciation, a rise in relative sea level resulted in the deposition of extensive deposits of bedded sand, clay and silt to the south of Dumfries. Owing to isostatic rebound, these deposits now form dissected terraces which generally lie at an elevation of 10 to 15 m aOD (McMillan, 2002). Marine clays, once worked for brick-making, are overlain by bedded sands of littoral origin south of Cargenholm. During the Holocene, there was renewed estuarine and tidal flat sedimentation associated with the main Post-glacial transgression which laid down fine-grained sediments which form flat-lying ground up to 10m aOD backing the coast. Extensive peat basins, such as those at Lochar Moss and Kirkconnell Flow, have developed locally on top of the Holocene alluvial, estuarine and tidal flat deposits. The most recent alluvial sediments of the Dumfries Basin occupy the valley floor floodplain and lowest terraces of the River Nith and its tributaries. These comprise gravel, sand and silt reworked from the glacial sediments.

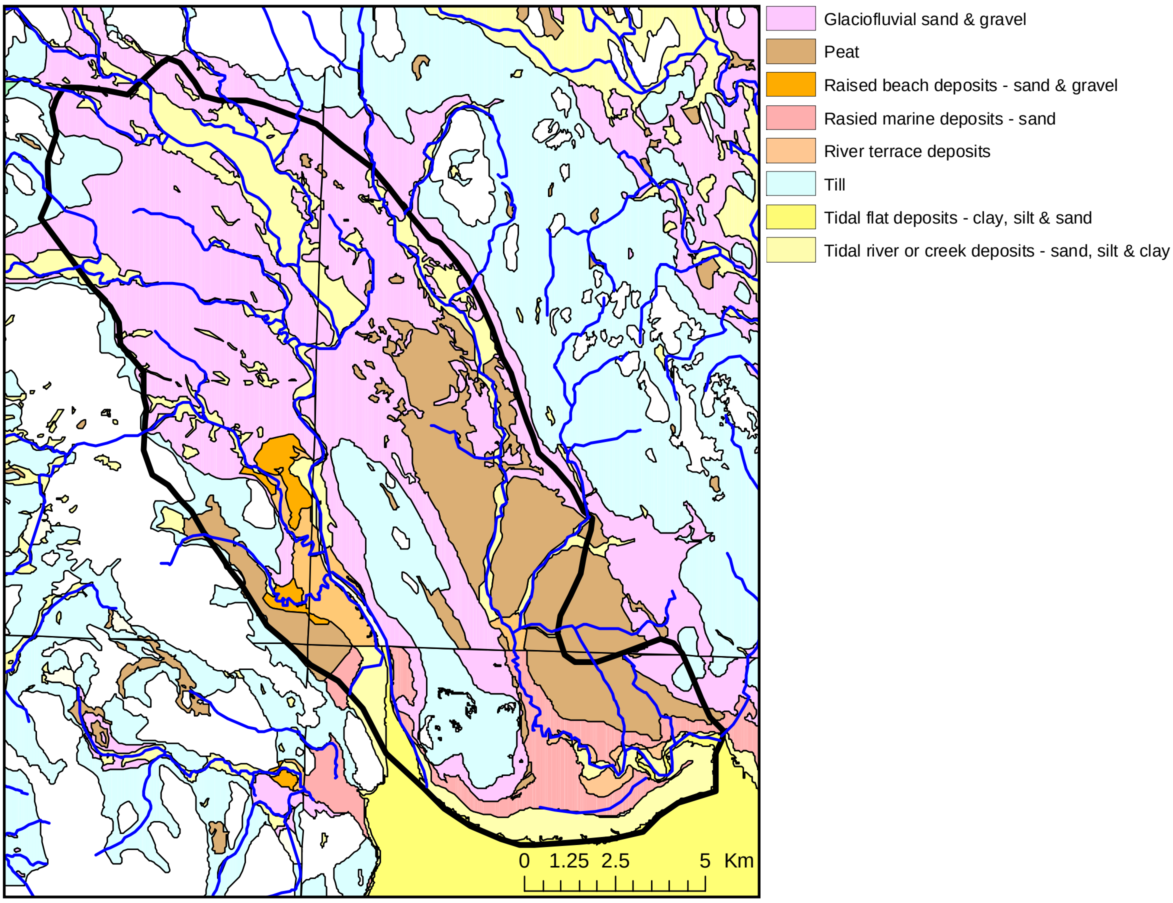


Figure 4 Quaternary geology map

2.2 HYDROGEOLOGY

2.2.1 Quaternary domains

The UK may be divided into large scale provinces or terrains based on predominant Quaternary characteristics that cover the full range of Quaternary processes and deposits. In each province, the main Quaternary issues including generic processes can be identified. Within each province are smaller scale catchments each characterised by similar processes such as till thinning on the interfluves with valley alluvium in northern England. Each catchment may be further subdivided into domains each of which represents a specific sequence of deposits which in turn can be related to vertical flowpath for infiltrating water passing down to a bedrock water table.

Data with which to evaluate the role of superficial sequences on recharge processes and aquifer vulnerability are, for the most part, sufficient to develop GIS format compilations of Quaternary domain types and hydrogeological pathway types at least to catchment scale. Quaternary hydrogeology domains maps, however, consider the Quaternary as a 3-D sequence in which each domain class has a discrete set of defined pathway processes.

The latest Quaternary mapping undertaken in the Dumfries basin was developed further in to Quaternary domains (Figure 5). In all thirteen domains (Table 1) were identified based on the origin of the material, the sequence and layering of the Quaternary deposits and the permeability of the deposits. The aim was to characterize the Quaternary so that the potential for recharge could evaluated. Thin, permeable Quaternary deposits will transmit water vertically more readily than thick, low permeability materials. The main conclusion of the Quaternary domain mapping is that the majority of the Quaternary deposits are relatively permeable. The main exceptions being the marine clays in the south of the basin and the peat deposits in the east of the Lochar Water catchment. In these areas, it is likely that the Quaternary deposits will inhibit recharge.

In developing the Quaternary domains, the thickness of the quaternary deposits was taken into account (Figure 6). The thickest sequence of Quaternary deposits are found under the peat deposits in the east of the Lochar Water catchment, where a thickness of over 30 m occurs. Other regions of thick Quaternary deposits occur in the marine clays in the Nith estuary, where a sequence of Quaternary deposits over 30 m is found.

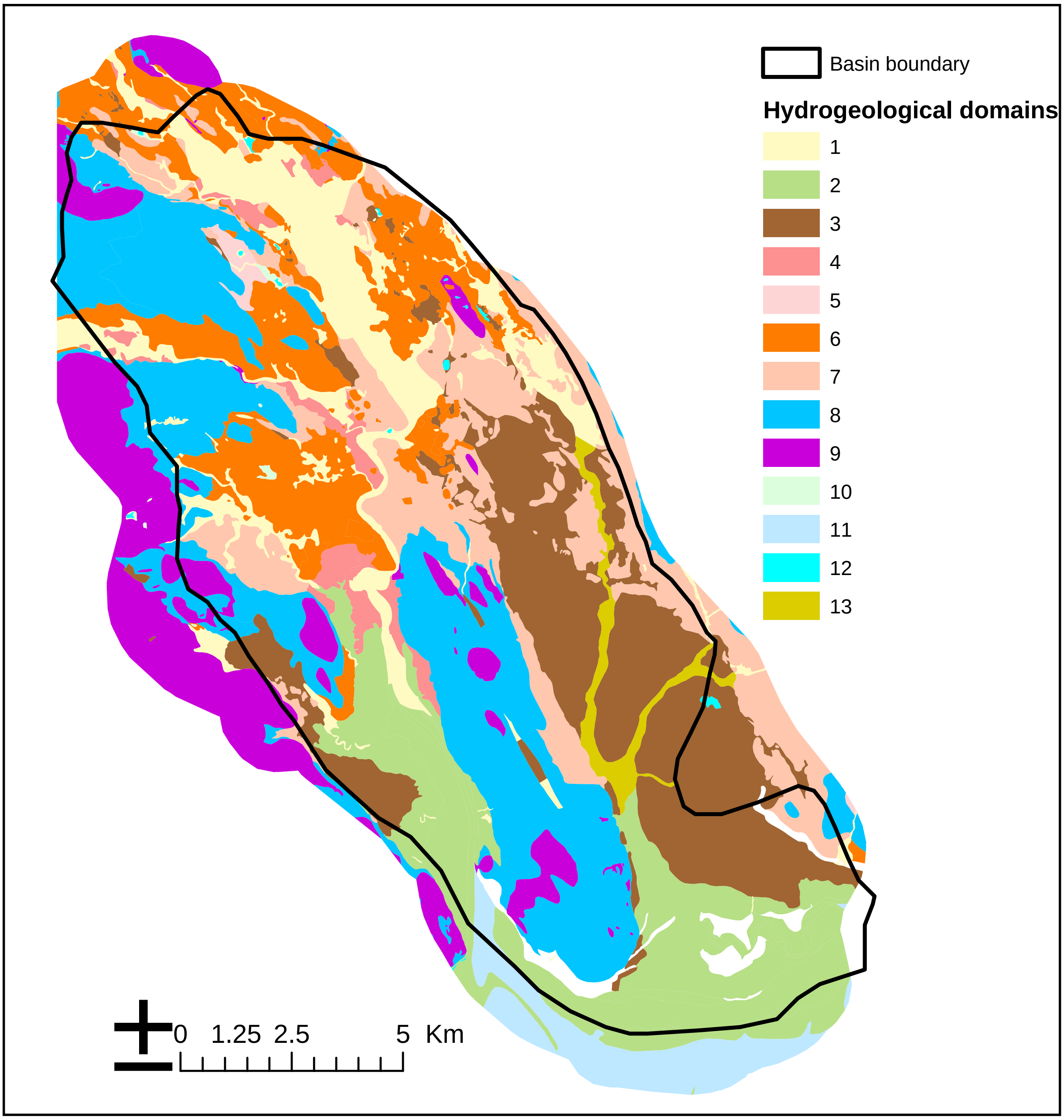


Figure 5 Hydrogeological domains interpreted from Quaternary geology (refer to Table 1)

Table 1 Quaternary domains identified within in the Dumfries basin

DOMAIN	**MATERIALS & MORPHOLOGY**	**QUATERNARY THICKNESS**	**AREA**
1. Alluvial and river terrace deposits on till	Floodplain sand and gravel, 2-3 m on sand and gravel and/or till	River Nith S of Dalswinton: thick underlying sands and gravels, 17m at Holywood	N of Dumfries, River Nith and tributaries
2. Modern and Flandrian tidal flat, raised tidal flat, saltmarsh and warp deposits on till or rock	Clay, silt and fine sand with interbedded peat on laterally discontinous till; clay and silt overlain by peat in Lochar Gulf area		S of Dumfries: River Nith and Lochar Gulf: Craigs Moss, Racks Moss (centre), Ironhirst Moss
3. Peat on raised tidal flat deposits on glaciofluvial sand and gravel and till	Peat, 2-3 m on clay, silt and fine sand on ? discontinuous till (possibly on gravel)	Lochar Moss, E of Dumfries: thick sands below peat	Lochar Moss Racks Moss (flanks) Kirkconnel Flow
4. Flandrian and Late Devensian raised beach, shoreface and deltaic deposits on till or rock	Sand and gravel (possibly silt) on till or rock	New Abbey Pow BH 4m gravel on sand; South Carse BH 8m sand on ?till	Ingleston, Carsethorn, Southerness
5. Glaciolacustrine deposits	Laminated clay and silt with dropstones on till	?	Small patch at Holywood; possible concealed
6. Glaciofluvial ice contact and morainic deposits on till or rock	Mounds and ridges of sand, gravel and silt; laterally discontinuous - hollows may be occupied by peat on till; moraines S of Locharbriggs glacitectonised sands and silts	10m+ N of Locharbriggs	Dalswinton, Locharbriggs flanking Nith valley and tributaries; W of Dumfries, Kirkbean
7. Glaciofluvial Sheet deposits on till or rock	Sheets and terraces of sand, gravel and silt	?10m around Locharbriggs	Locharbriggs, flanking Lochar Gulf, Kirkbean, Cargenbridge
8. Till on rock	Sandy diamictons, jointed, sandy interbeds	< 5m	Ridges S of Cargenbridge and SSE of Dumfries; NW of Dumfries
9. Rock at or near surface	Locharbriggs Sandstone Doweel Breccia Lower Palaeozoic wackes and siltstones		
10. Lacustrine deposits			
11. Intertidal sandflat deposits			
12. Superficial deposits not mapped			
13. Alluvial deposits on peat (domain 3)			

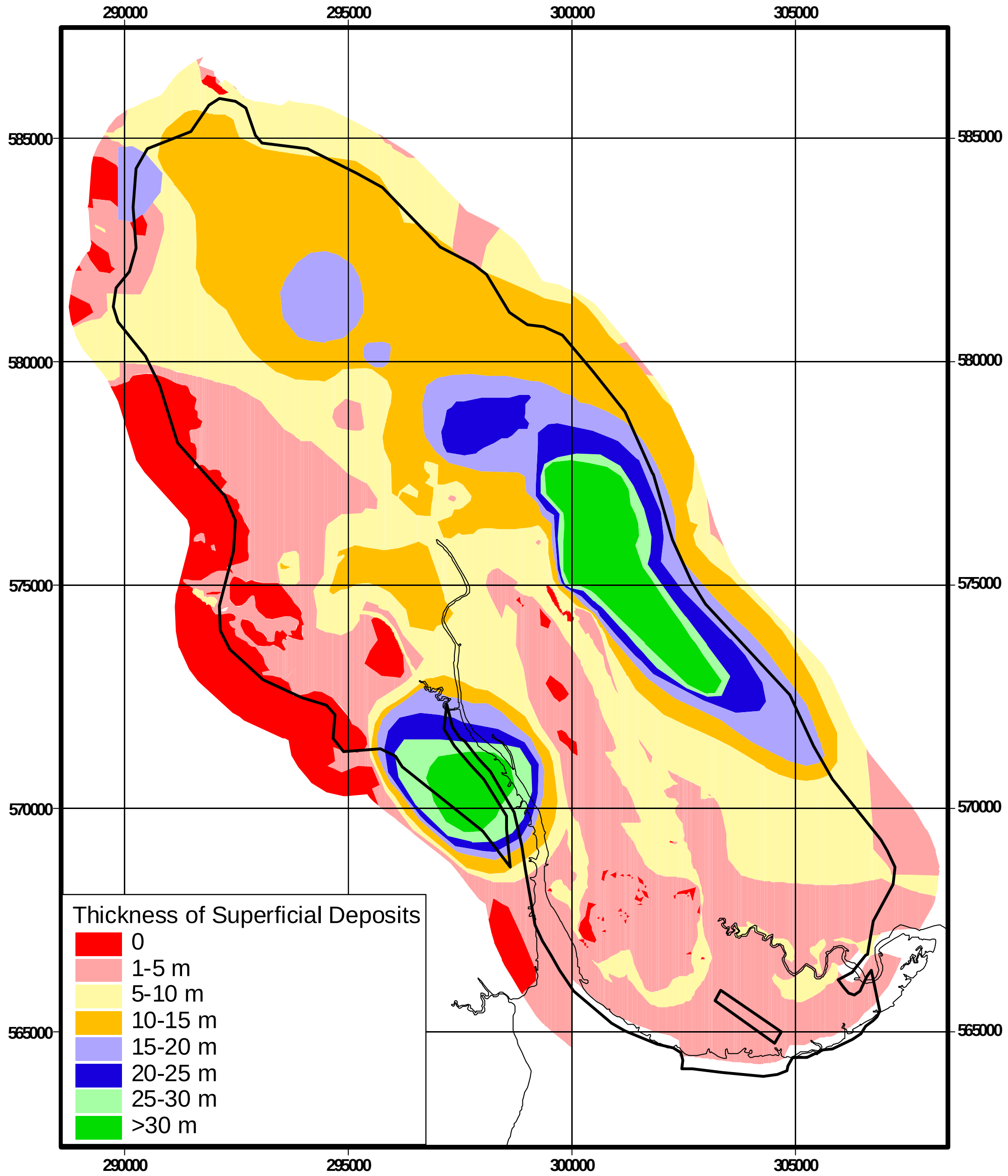


Figure 6 Estimated Quaternary thickness (m)

Characterisation of the Quaternary deposits shows that the majority of the superficial deposits are permeable. Where low permeability deposits are identified (marine clays and peats), it is assumed that runoff is increased at the expense of vertical recharge. The recharge potential of the superficial deposits are summarised in Figure 7. The Quaternary domain mapping is interpreted to provide three levels of recharge potential; high for the sands and gravels, moderate for materials with some silt and low for clayey deposits.

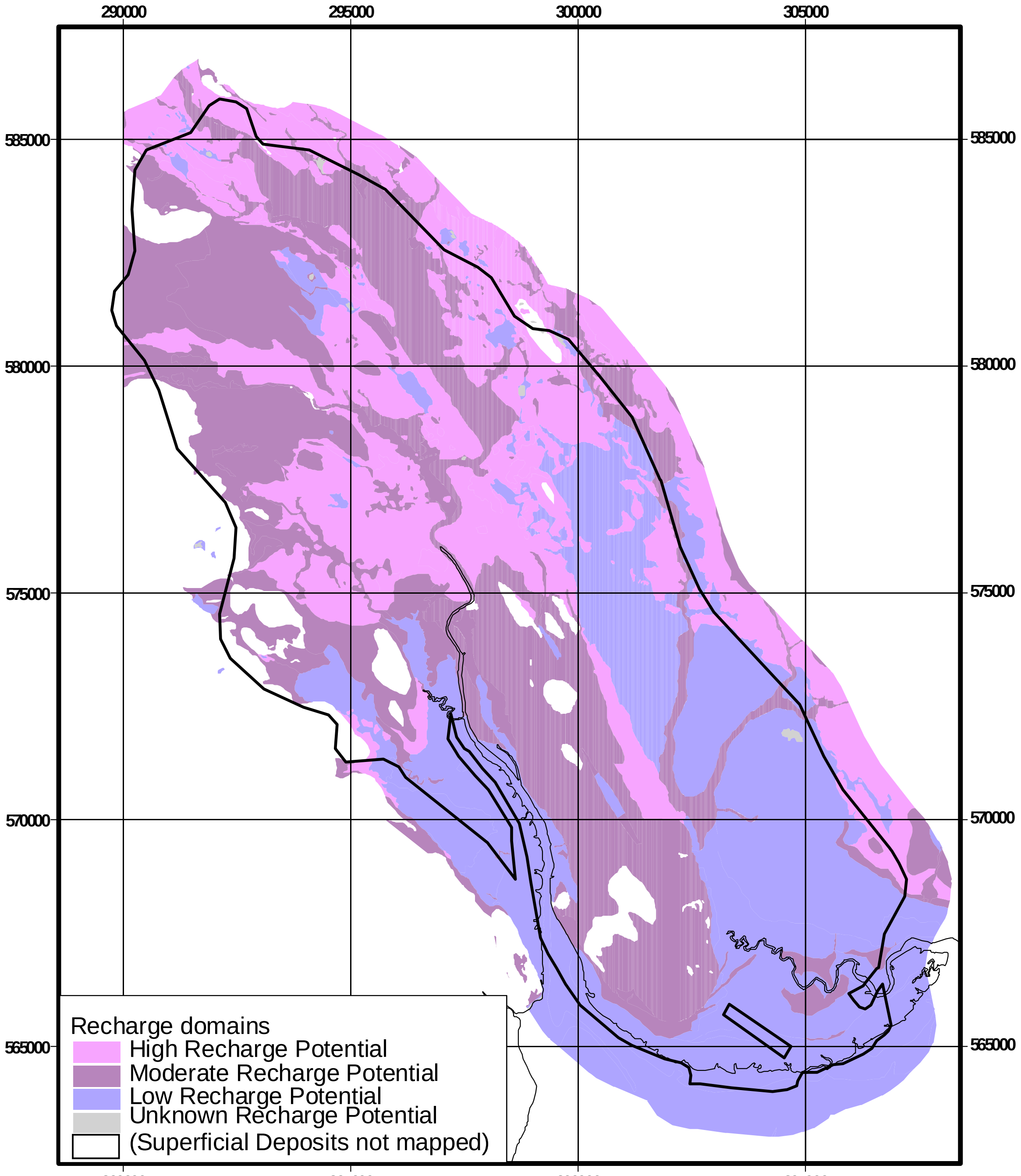


Figure 7 Potential recharge distribution derived from Quaternary domains

2.2.2 Aquifer properties

Transmissivity estimates obtained from pumping test analysis have been collated and these are listed in Table 2 and plotted in Figure 8. Higher transmissivity values have been obtained from the analysis of the Terregles boreholes, which exhibit active fracture flow to depths in excess of 100 m. These high transmissivities are in contrast to those estimated at the ICI boreholes, the highest of which is 94 m^2 day^{-1}. The low calculated transmissivities at this site may be due the limited depths of the boreholes; four of the boreholes are less than 40 m deep. However, ICI borehole No.2 is 216 m deep and has an estimated transmissivity of only 94 m^2 day^{-1}. Consequently, it could be stated that it is justifiable to include a zone of lower transmissivity in the conceptual model of the aquifer in this area. Transmissivity estimates in the south west of the basin at the Racks Moss and Longbridgemuir boreholes are only 10 $m^2 day^{-1}$. The sandstone aquifer thins towards the south-east and this may result in lower aquifer transmissivities.

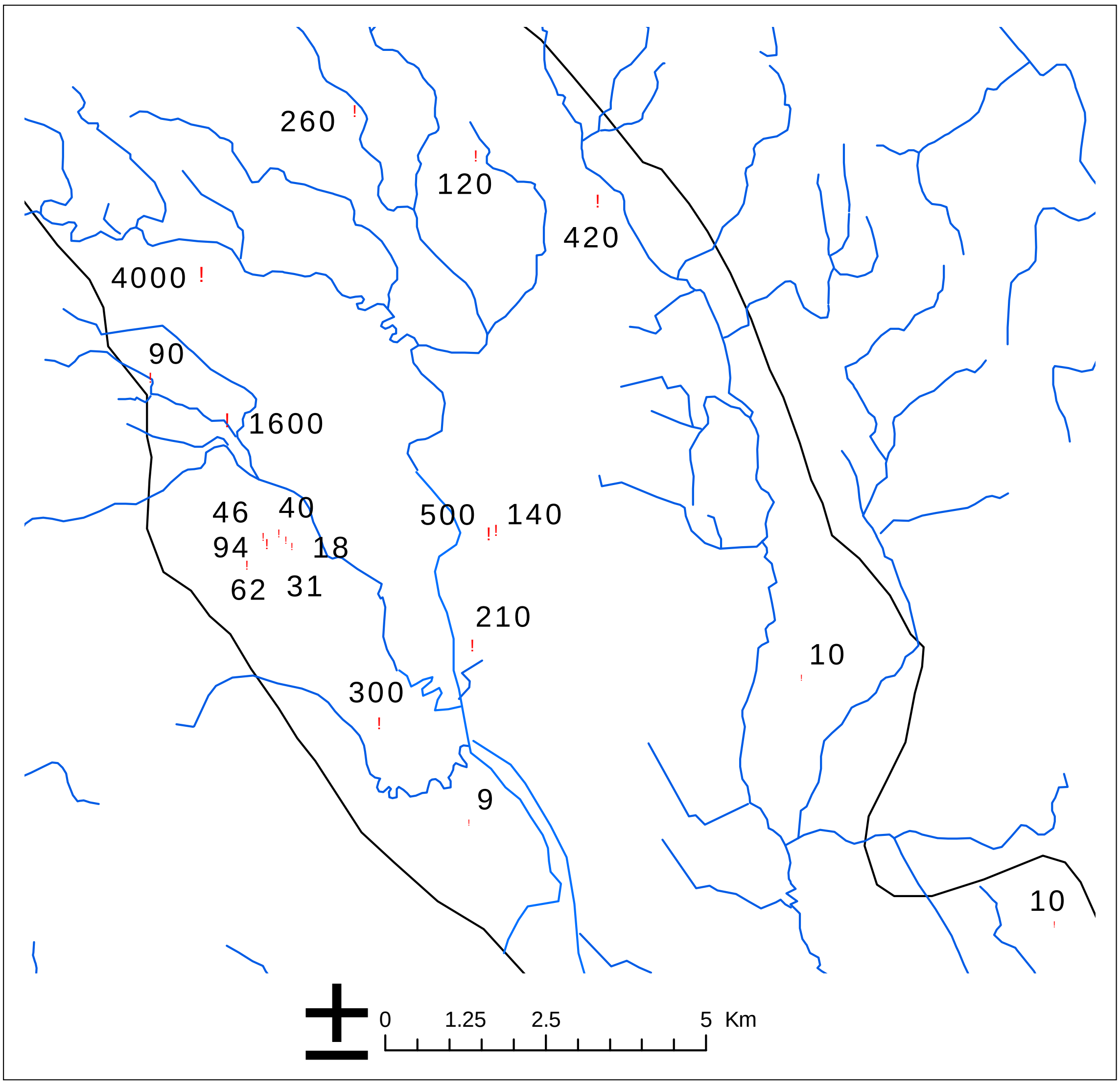


Figure 8 Transmissivity estimates from borehole tests

Table 2 Transmissivity estimates derived from analysis

Borehole	Transmissivity ($m^2\ d^{-1}$)	Depth (m)
Cargen	300	112
Crichton Hospital	210	?
Greenmerse	9	75
Holywood Fish Farm	120	?
Holywood Production BH	260	75
ICI BH 401	18	35
ICI BH 402	40	40
ICI BH 403	31	37
ICI BH 404	46	38
ICI BH 501	62	71
ICI BH No 2	94	216
Larchfield	140	61
Larchfield Production BH	500	95
Locharbriggs	420	77
Terregles Fish Farm	90	122
Terregles No 1	4000	103
Terregles Production BH	1600	112
Racks Moss	10	100
Longbridgemuir Farm	10	80

2.2.3 Groundwater Heads

The groundwater contours for the basin are presented in Figures 9 and 10. These contours are based on the hydrogeological map (British Geological Survey, 1990; Figure 9) those presented by MacDonald et al. (2003). Data are mostly found in the centre of the basin (Figure 11). Table 3 presents the most complete collection of groundwater heads in the Dumfries basin. The contours in Figures 9 and 10, whilst based on limited data, show the overall pattern of groundwater flow in the basin. The groundwater flow direction is towards the south-east in the northern part of the basin. Groundwater flow can be observed towards the River Nith and the Lochar Water in the central part of the basin. In the southern part of the basin, then the groundwater flow direction is away from the Larchfield-Caerlaverock ridge. However, due to the sparse nature of the groundwater head data, groundwater flow directions in the north of the basin and in the south-east is inferred rather than measured.

Water levels in the Permian are above the rock/superficial strata interface across much of the basin. Higher ridges of bedrock occur in some places, such as around Larchfield south of Dumfries, and there may be up to 15 m of unsaturated rock beneath some of these. In general, surface topography is reflected by the depth to the piezometric surface. Confined conditions occur under low-lying areas south of Dumfries across the floodplain of the River Nith. Artesian flow occurs wherever the surface level is at or below 10 m aOD and laminated silty clay overlies the main aquifer. Elsewhere, individual fractures, and sandstone horizons separated by breccia, may be at different heads, as observed in a number of geophysical flow logs that have been measured in boreholes in the western part of the basin (Buckley, 2000).

Groundwater heads have been measured over time for a number of boreholes in the Dumfries basin. The longest record is at Redbank, where groundwater heads have been measured since 1981. The observation boreholes at Newbridge and Holywood have been monitored since 1993. For the recently drilled boreholes on the east of the basin, Racks Moss, Ironhurst Moss and Longbridge Muir (Figure 11), groundwater head has been measured for the last two years.

The longest period of time with contemporaneous records of groundwater head is June 1993 to October 2003 (Figure 12).

Examining the groundwater head hydrographs for observation boreholes at Newbridge, Redband and Holywood shows that all three observed groundwater data exhibit a defined seasonality. There is no long-term decline in groundwater levels observed in head at any of the three boreholes. Of the three boreholes, the groundwater head variation at Holywood appears to reflect more complex temporal patterns. These could be due to abstraction or the influence of the river Nith. Similar temporal complexities are also observed in the groundwater head variation at Redbank. The groundwater head variation at Newbridge, in contrast, appears smoother, with a more well-defined seasonality. The range of groundwater head fluctuations is consistent for all three boreholes. An amplitude of 2 m is observed for the groundwater head variation at Newbridge and Redbank, whereas an amplitude of 3 m is observed for Holywood.

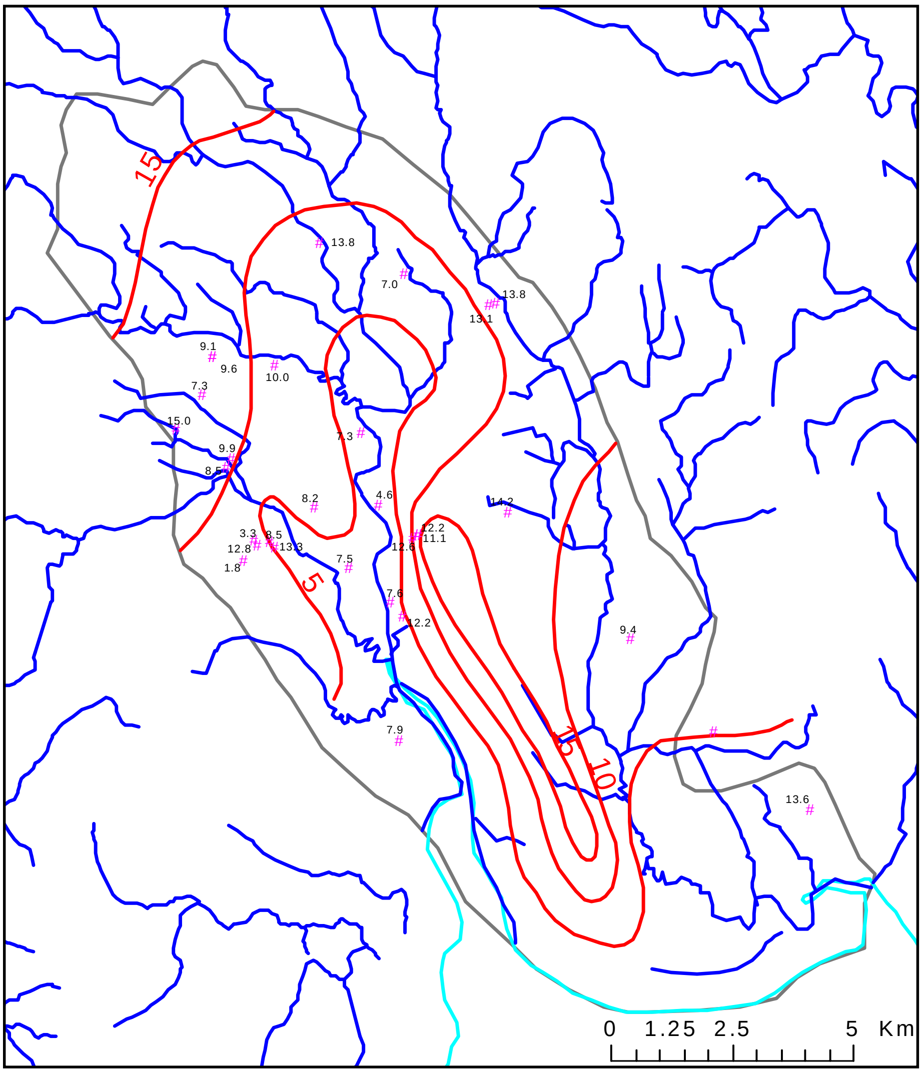


Figure 9 Observed groundwater levels and contours taken from the Eastern Dumfries and Galloway hydrogeological map (British Geological Survey, 1990)

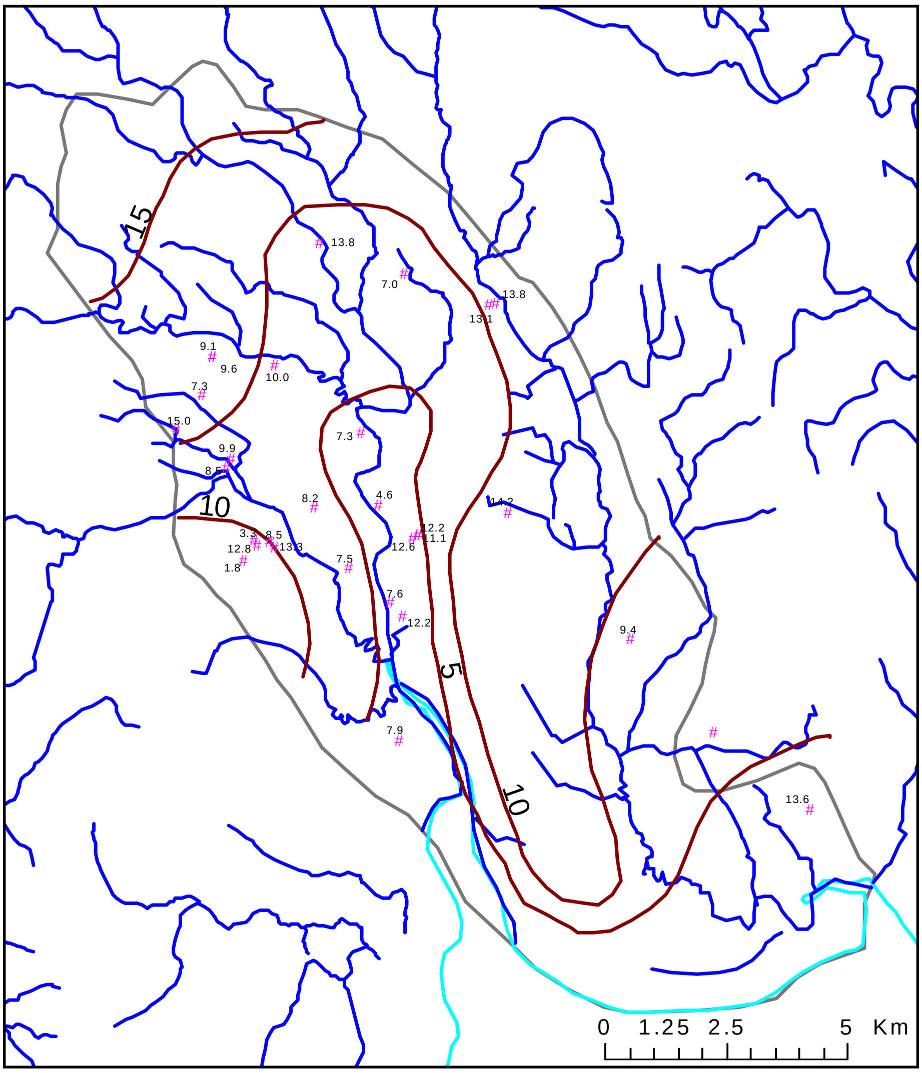


Figure 10 Observed groundwater levels and contours after MacDonald et al. (2003)

Table 3 Estimated groundwater levels from collated data

(NB. Levels are recorded on different dates and some are affected by pumping. Others are taken as the mean for the period of their record.)

Location	Easting	Northing	Observed m aOD
Carnation No 1	296910	577330	7.3
Dundas Chemicals	300230	575580	14.2
Golf Course	295890	575670	8.2
Greenmerse	297760	570480	7.9
Holywood Fish Fm	297890	580900	7.0
Holywood Pro BH	296000	581600	13.8
ICI BH 401	294900	574900	8.5
ICI BH 403	295000	574800	13.3
ICI BH 404	294550	574950	3.3
ICI BH 501	294300	574500	1.8
ICI BH No 2	294620	574830	12.8
Kingholm Mill	297580	573570	7.6
Larchfield Expl BH	298200	575050	11.1
Larchfield Obs BH	298200	575050	12.2
Larchfield Pro BH	298100	575000	12.6
Locharbriggs	299800	580200	13.1
Locharbriggs	299950	580250	13.8
Newbridge	294990	578850	10.0
Redbank Obs BH	296670	574320	7.5
Terregles FF House B	292800	577430	15.0
Terregles No 1	293620	579050	9.1
Terregles Obs 1	293620	579050	9.6
Terregles Obs 2	293390	578180	7.3
Terregles Pro BH	294020	576770	9.9
The Manse	293930	576590	8.5
Well Cottage	297840	573250	12.2
Workington Brewery	297320	575730	4.6
Racks Moss	302970	572730	9.4
Longbridgemuir	306990	568910	13.6
Ironhirst Moss	304800	570650	9.7

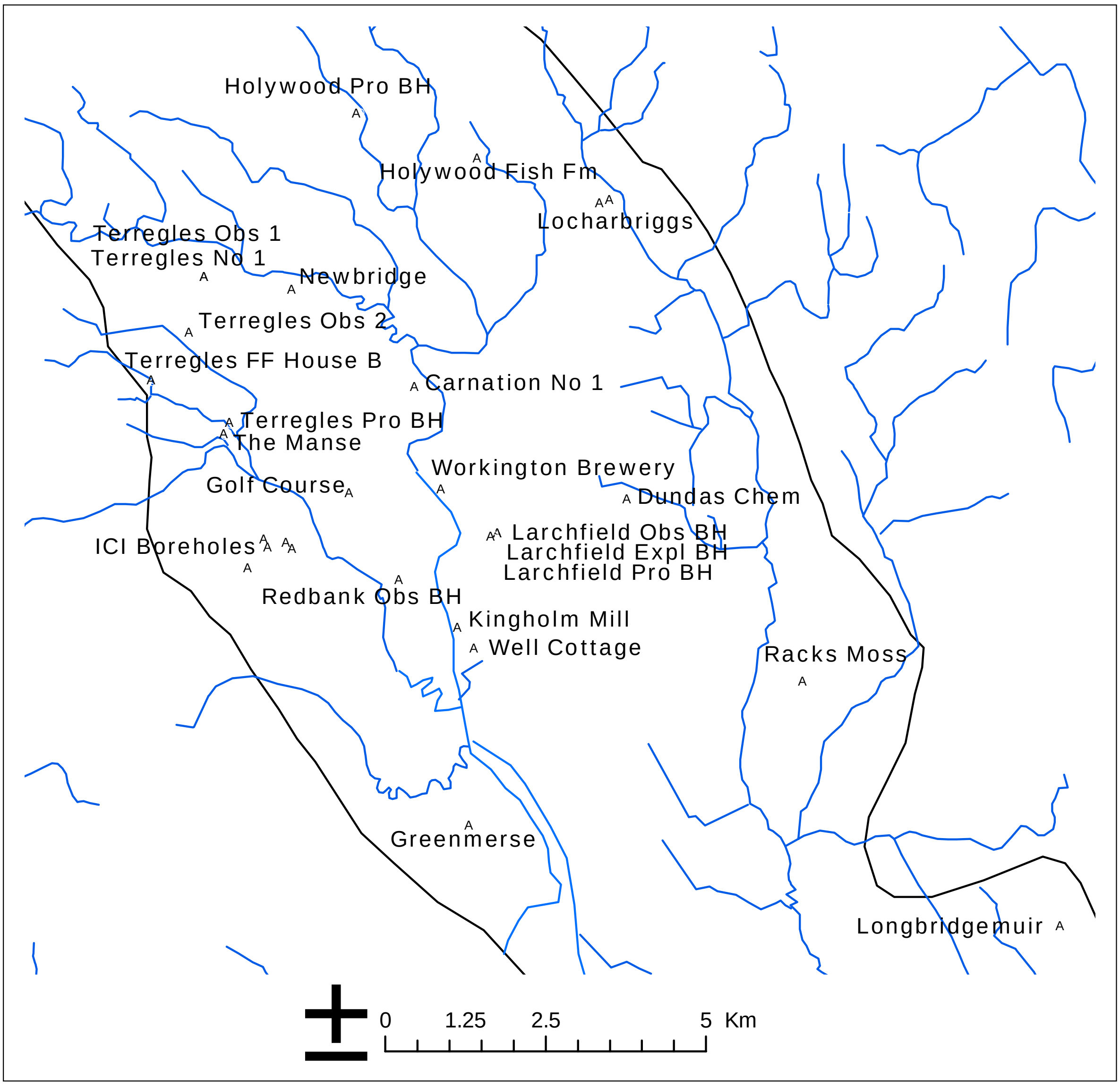
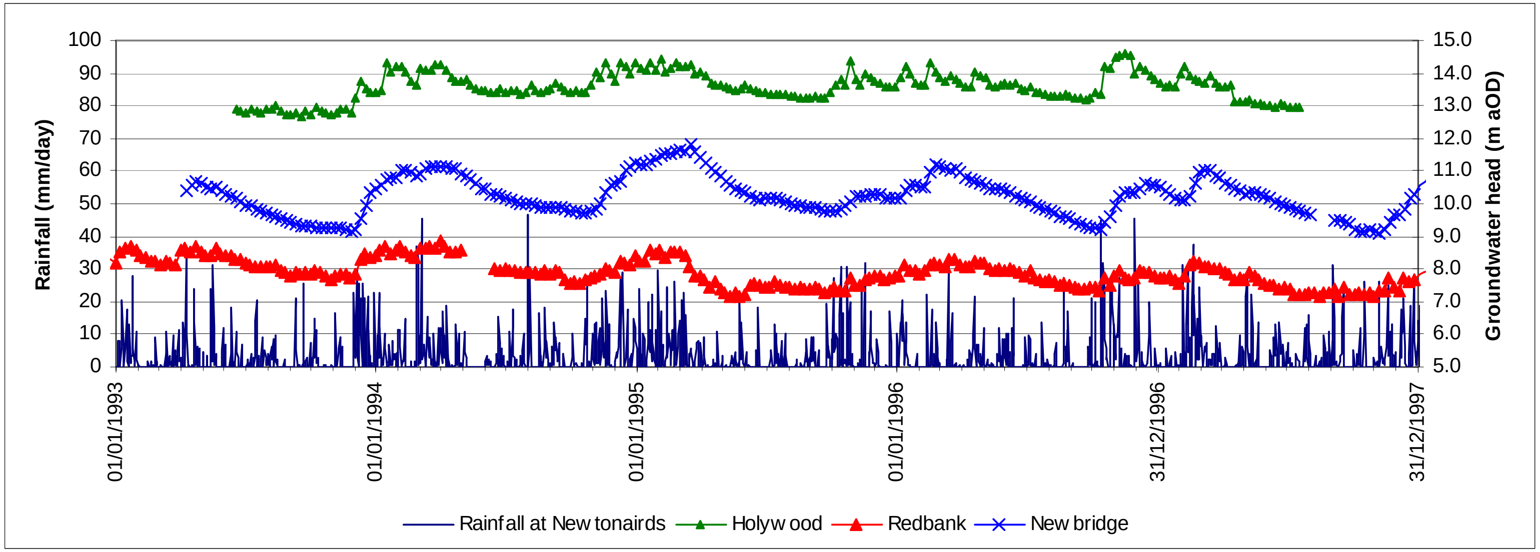


Figure 11 Location of observation boreholes



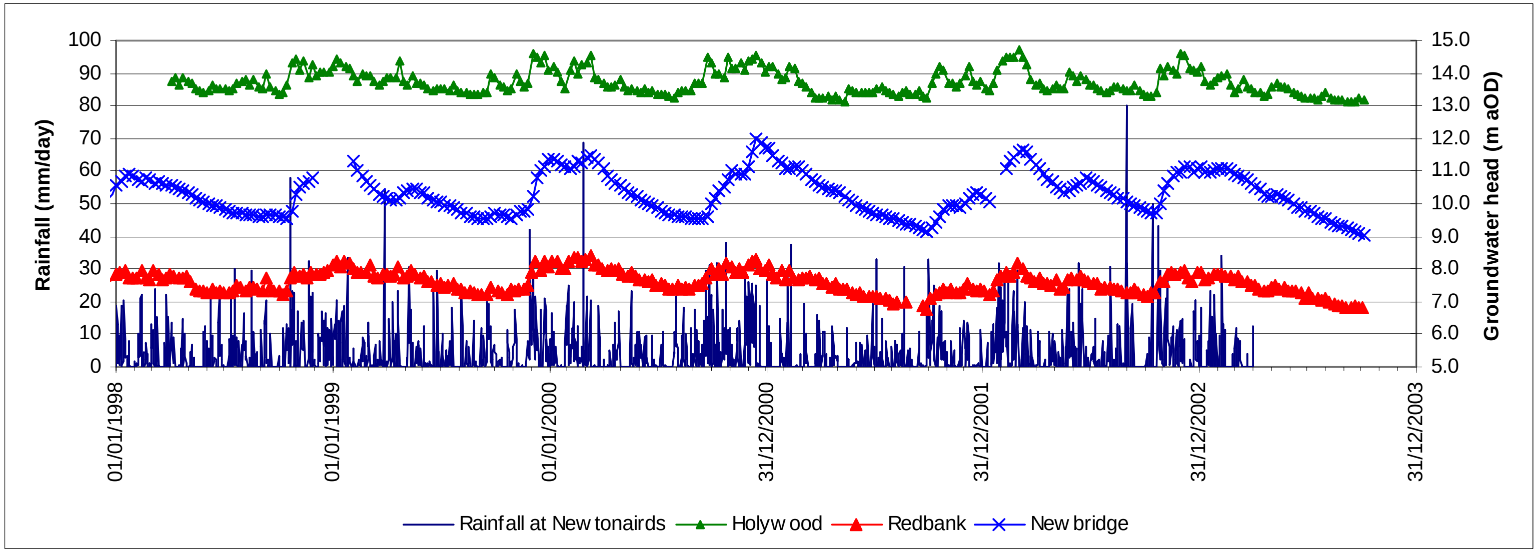


Figure 12 Groundwater head hydrographs at Newbridge, Redbank and Holywood

2.2.4 Hydrochemistry

Until recently, the hydrochemistry of the Dumfries basin was not well characterised. As part of the Dumfries project, all the available boreholes were sampled and analysed MacDonald et al. (2003). The sampling was carried out in November 1999 and water samples were taken from 22 boreholes and analysed for major and minor ions and residence time indicators; CFCs and SF_6.

The study showed that the groundwater in the Dumfries basin was of the Ca-Mg-HCO_3 type, is moderately mineralised and of neutral pH. The hydrochemistry is due to recharge dissolving carbonate material in the breccia, sandstone and superficial deposits.

The residence time indicators show that groundwater in the Dumfries basin is a mixture of older (pre-1950) and modern (< 10 years) water. In the Dowell Breccia, in the west of the basin, groundwaters have a large component of modern water. In the Locharbriggs Sandstone, groundwater is older, with less than 10% modern water. The variation between the ages of groundwater in the east and west of the basin are due to the different nature of groundwater flow. Within the Dowell Breccia groundwater flow is rapid and storage is limited, whereas in the Locharbriggs Sandstone Formation, groundwater flow is slower and storage higher.

The study also showed that pumped boreholes close to rivers did not have a high proportion of modern waters. The percentage of modern water in the boreholes at the Holywood Fish Farm boreholes, which abstract over 8 Ml day^{-1}, is under 40%, which is below the median for the basin. This suggests that the source of water for the boreholes is not predominately river water.

Agriculture is widespread in the basin and so pollution from fertilizer and pesticides could occur. One of the aims of the geochemical study reported in MacDonald et al. (2004) was the examination of trends in Nitrate concentrations in boreholes. Nitrate concentrations in the basin vary from less than 0.25 mg l^{-1} NO_3-N to 28.5 mg l^{-1} NO_3-N, with a median value of 6.1 mg l^{-1} NO_3-N. The distribution of measured nitrate concentrations in the Dumfries basin corroborate the findings of the residence time indicators. High nitrate concentrations are found in the Doweel Breccia in the west of the basin, 5–10 mg l^{-1} NO_3-N. For boreholes sampled in the Locharbriggs Sandstone Formation, nitrate concentrations generally less than 5 mg l^{-1} NO_3-N, with the exception of three boreholes in the south-east of the basin, in which nitrate concentrations of over 10 mg l^{-1} NO_3-N were measured.

2.3 TOPOGRAPHY

The Dumfries Basin comprises gently rolling land outwith the flatter river terraces, the topography being controlled both by mounded superficial sands and peat infilled hollows. A distinct ridge of higher ground to the south of Dumfries from Larchfield, through Crichton Royal towards Caerlaverock Castle near the coast, rises to over 90 m aOD, and was formed by selective erosion of the bedrock (Figure 13).

The Dumfries Basin is bounded to the west by steeply rising land with hills of up to 250 m aOD and to the south is Criffel which peaks at 569 m aOD. The eastern edge of the basin gives way to gently rising and undulating land up to 200 m aOD in elevation.

The River Nith flows into the Dumfries Basin via a narrow gorge from the Thornhill Basin, another smaller basin of Permian deposits. Above the Thornhill Basin the river drains the hills of upper Nithsdale, and the Sanquhar Coalfield. These areas are characterised by steeply sloping hillsides typical of much of the Southern Uplands.

The Nith in the Dumfries Basin follows a mature and long established profile. The topography of the basin is largely controlled by the superficial geology, but ridges to the south of Dumfries represent strings of hard breccia overlying softer sandstone, the latter preferentially removed by fluvial erosion. Fault bounded to the west this line of hills formed the Permian mountain front from which wadi flow brought the coarse detritus to form the breccia, and wind blown sands accumulated to the east to form the sandstone. To the east of the basin the country forms rolling hills the result of fluvial degradation of the pre-Cretaceous plateau.

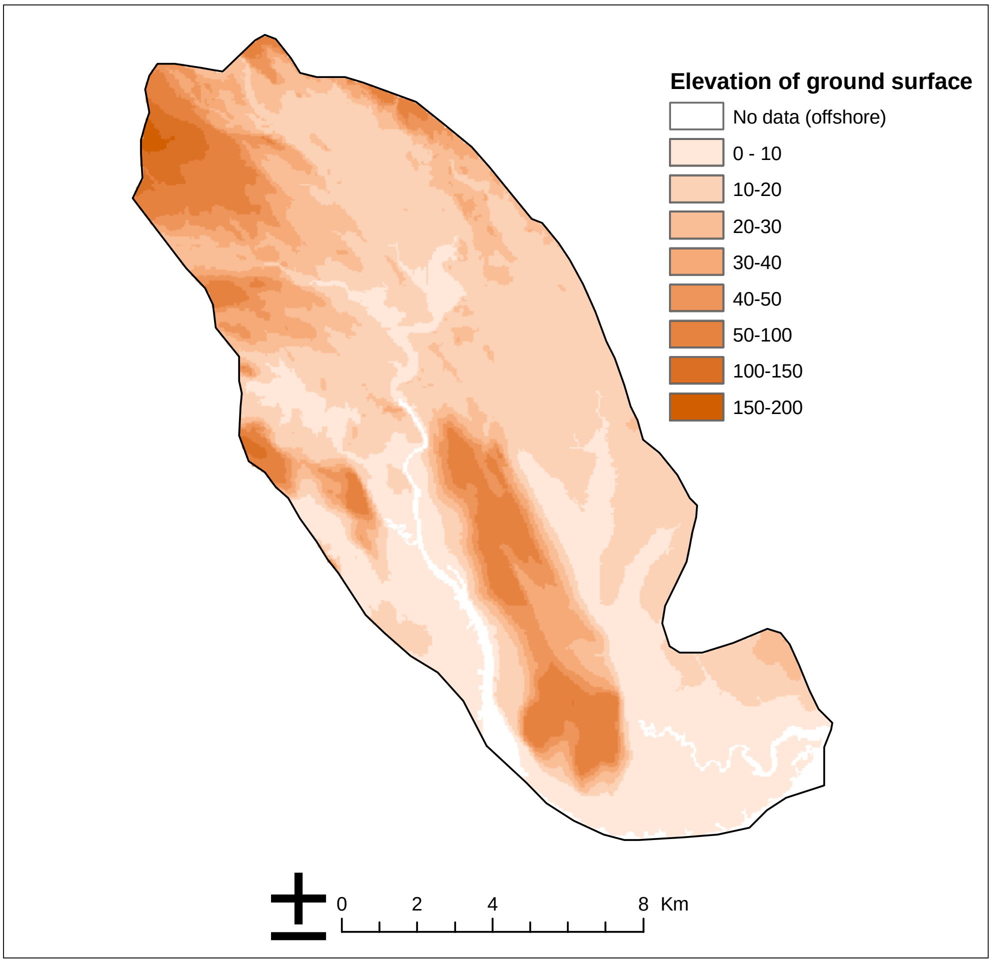


Figure 13 Ground surface elevation from 50 m DTM

2.4 HYDROLOGY

2.4.1 Climate

The prevailing winds are westerly moisture laden maritime winds. Average daily temperatures in Dumfries are 3 °C in January and 13 °C in July. There is an average 3.7 hours sunshine per day.

Annual precipitation totals vary from approximately 1000 mm in coastal areas to more than 2000 mm over the high ground near the western watershed. Some of the winter precipitation falls as snow with an average of 25 snowfall days per winter. The wettest months are October to March).

There has been a significant increase in annual rainfall (5-15%) in the catchment, generally as a result of increased winter rainfall

Average potential evaporation is typically in the range 450 to 550 mm a^{-1}.

2.4.2 Rivers

The names of the rivers and the locations of the gaugings stations within the basin are shown in Figure 14. The major channel is that of the River Nith, which flows onto the basin at its northern edge and discharges into the Solway Firth in the south. A number of tributaries feed the Nith, the majority of which rise on the higher ground off the Permo-Triassic aquifer. The major tributary of the Nith is the Cluden Water.

The Lochar Water forms the second catchment within the basin but this is a significantly smaller river than the Nith. This river flows approximately parallel to the Nith from north to south along the eastern edge of the aquifer.

There are three permanent gauging stations in the basin at Friars Carse, Fiddlers Ford and Kirkblane, which are located on the Cluden Water, River Nith and Lochar Water, respectively. These are marked by squares in Figure 14. Friars Carse is located on the edge of the aquifer and consequently, provides a good record of the flow coming onto the basin in the Nith. In addition to these permanent gauging stations, daily flows have been measured at sites on the Cargen Water, Duncow Burn, Lochar Water and Wath Burn between approximately April 2002 and October 2003. These are shown by the triangles in Figure 14.

Mean flow data for these permanent and temporary gauging stations is listed in Table 4. For each of the daily flow records a hydrograph separation has been performed to estimate the baseflow component of total river flow. This is undertaken using the separation method described by the Gustard et al. (1992). The analysis has been checked by comparison with the data presented by the IH/BGS (1996), which gives baseflow indices for Friars Carse and Fiddlers Ford which are identical to those calculated here.

Whilst the period of the record is too short to have confidence in the calculated baseflow indices at the non-permanent gauging stations, more certainty can be ascribed to a comparison of the baseflow indices at the three permanent gauging stations. This comparison shows that the baseflow index at Kirkblane is approximately 15% higher than at the Fiddlers Ford and Friars Carse. Whilst it should be noted that Fiddler's Ford and Friars Carse are near to the upstream ends of the rivers within the basin, and thus dominated by flow from the relatively impermeable Silurian rocks, the increased proportion of baseflow at Kirkblane is also likely to be due to the presence of the peat deposits in the Lochar Water catchment. This relatively low lying and wet area of peat is artificially drained and this may maintain the baseflow in the Lochar Water.

To improve the accuracy of a water balance for the Dumfries aquifer, SEPA undertook a programme of flow gauging during July 2003, to measure the flow in the rivers as they cross the boundary of the basin. This data set is shown in Figure 15 in addition to other spot gauging data. The flows measured on the edge of the river basin, on the 14th and 15th July 2003, are plotted in blue. Three other spot gaugings, taken on the 13th July 1993, are plotted in green and the remaining flows measurements, taken on arbitrary dates, are plotted in black.

In addition to this spot gauging data, one further set of flow measurements is presented by Cheney and MacDonald (1993). This data set for 21st May 1992 is shown in Figure 16. Each of these figures is examined in turn next and a set of observations made regarding the variation of river flows.

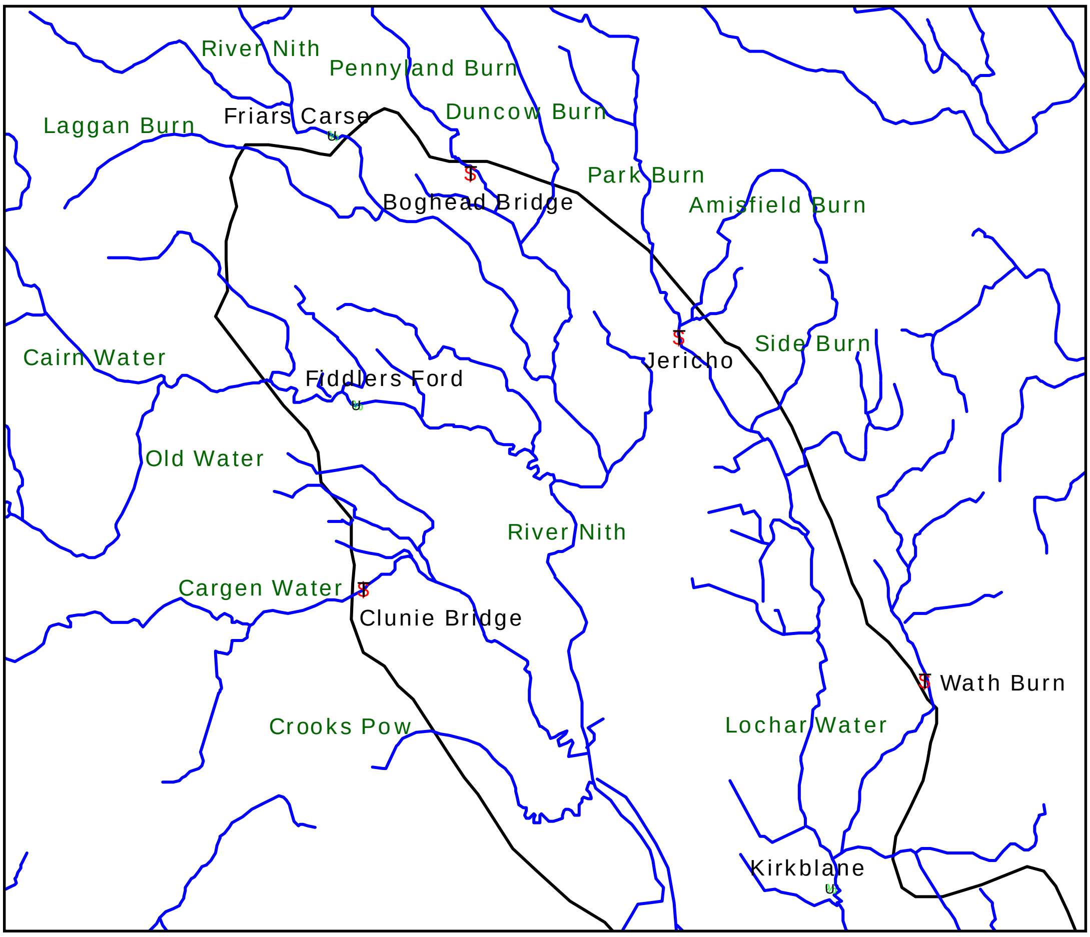


Figure 14 River names and river flow gauging stations
(Green squares: permanent gauging stations; red triangles: temporary gauging points)

Table 4 Mean total and baseflows at gauging stations with historical record

Gauging station	**Mean total flow (Ml day^{-1})**	**Mean baseflow (Ml day^{-1})**	**Calculated BFI**	**Period of record**
Fiddlers Ford (Cluden Water)	692	280	0.38	Jan 1964 to Jan 2003
Friars Carse (River Nith)	2378	998	0.39	Oct 1957 to Jan 2003
Kirkblane (Lochar Water)	191	106	0.53	Jan 1992 to Oct 2003
Jericho (Lochar Water)	42	18	0.40	Apr 2002 to Oct 2003
Clunie Bridge (Cargen Water)	35	19	0.46	Feb 2003 to Oct 2003
Wath Burn	19	10	0.49	Apr 2002 to Oct 2003
Boghead Bridge (Pennyland Burn)	12	7	0.52	Apr 2002 to Oct 2003

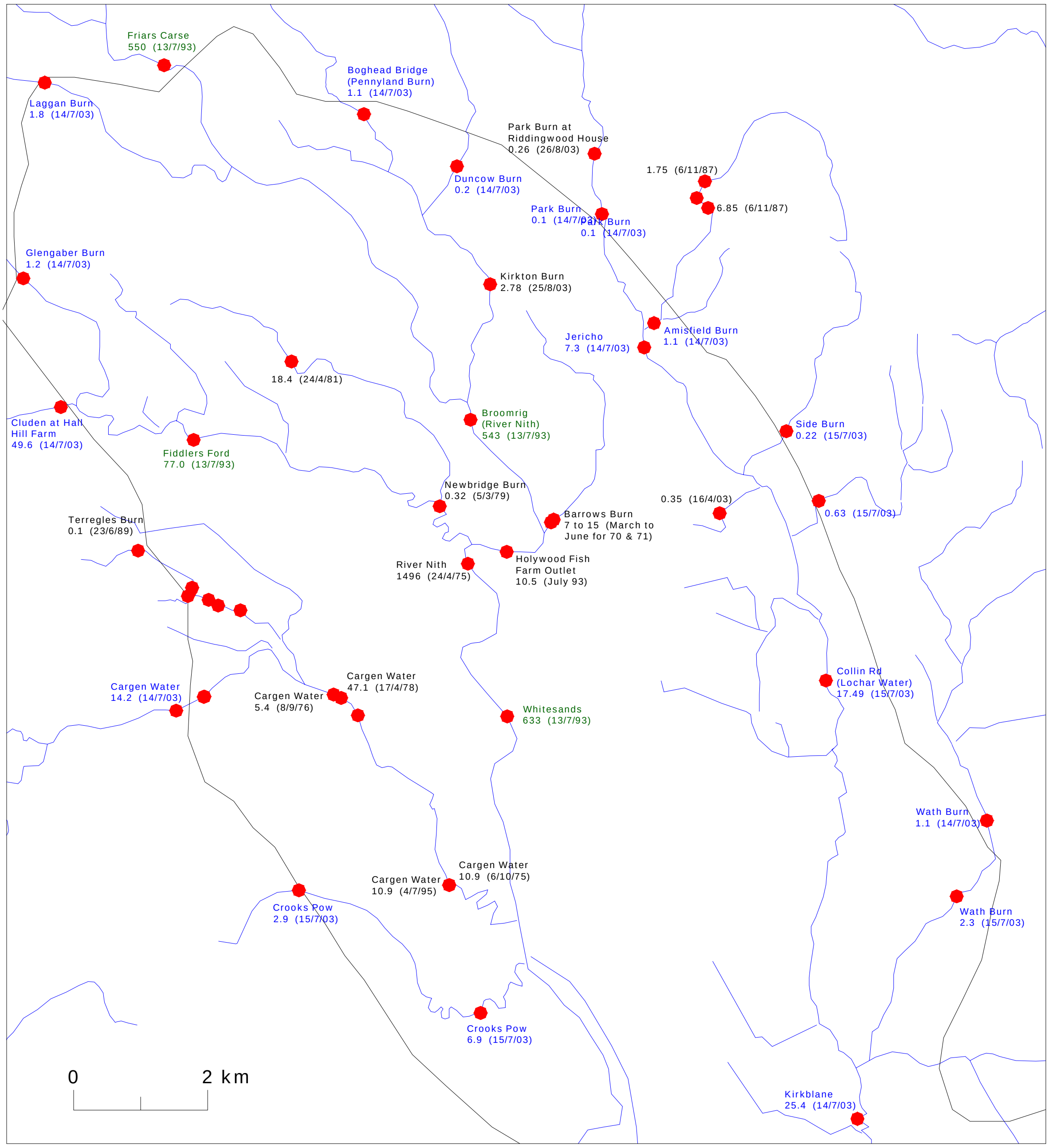


Figure 15 River flow spot gaugings (Ml day^{-1}) for July 2003 (blue), July 1993 (green) and other arbitrary times (black).

2.4.3 Observations made from Figure 15 (River flows for July 2003)

OBSERVATION 1

On 13/7/1993, which represents low flow conditions:

- The Nith loses 7 Ml day^{-1} between Friars Carse and Broomrig.
- The flow at Whitesands of 633 Ml day^{-1} is only 3 Ml day^{-1} less than the summation of the flows at Broomrig and Fiddlers Ford and the estimated discharge into the Nith at Holywood Fish Farm of 10 Ml day^{-1}.

OBSERVATION 2

On 24/4/1975 the flow in the Nith at Nunholm (approximately 2 km north of Dumfries) is 1496 Ml day^{-1}. This is 162 Ml day^{-1} greater than the sum of the flow at Friars Carse (1018 Ml day^{-1}) and the flow at Fiddlers Ford (316 Ml day^{-1}) on the same day. This additional flow will be supplied both from groundwater and from the Laggan Burn, Kirkton Burn and Barrows Burn, or tributaries of the Cluden Water below Fiddlers Ford.

The flow at Friars Carse on this day is 43% of the mean flow. If it is assumed that the flow at Nunholm was also 43% of the mean, then the long-term average total flow at this location would be 3479 Ml day^{-1}. If the assumption is then made that the baseflow index (BFI) at Nunholm is 0.4 the mean baseflow would be 1392 Ml day^{-1}. If it the BFI was 0.5 then the mean baseflow at Nunholm would be 1740 Ml day^{-1}.

Whilst this simple calculation is very crude and uncertain, it assists in the estimation of a possible range of mean flows towards the downstream end of the River Nith. Such calculations are necessary because there is very little flow data on the Nith downstream of Friars Carse.

OBSERVATION 3

On 15/7/2003, which represents low flow conditions

- The total flow onto the basin minus that at Friars Carse is approximately 74 Ml day^{-1}.
- The Crooks Pow gains water from the aquifer between the edge of the basin and its downstream end.
- Only the Cargen Water, Cluden Water and Nith bring significant (>10 Ml day^{-1}) quantities of water onto the basin during the summer period.

2.4.4 Observations made from Figure 16 (River flows for May 1992)

OBSERVATION 1

At this time the Cargen Water gains approximately 200 Ml day^{-1} between the edge of the basin and its downstream end. Comparison with the hydrogeological domain map indicates that the upper half of this river flows over either rock at the surface or predominantly sandy material (i.e. domains 4, 6, 7 and 8 in Figure 5).

OBSERVATION 2

The Kirkton Burn loses approximately 70 Ml day^{-1} along the 4 km reach downstream of its tributary, Duncow Burn.

OBSERVATION 3

The Lochar Water gains approximately 65 Ml day^{-1} to the north of Collin (i.e. north of the 99.4 Ml day^{-1} spot gauging) but gains water significantly more rapidly to the south of this point. Contributions to the increase in river flow over the southern section of the Lochar Water are likely to derive from drainage from the peat, drainage and spring flow from the high ground to the west and from the Wath Burn. The mean and peak flow at the temporary gauging station on the Wath Burn between April 2002 and October 2003 were 19 Ml day^{-1} and 228 Ml day^{-1}, respectively.

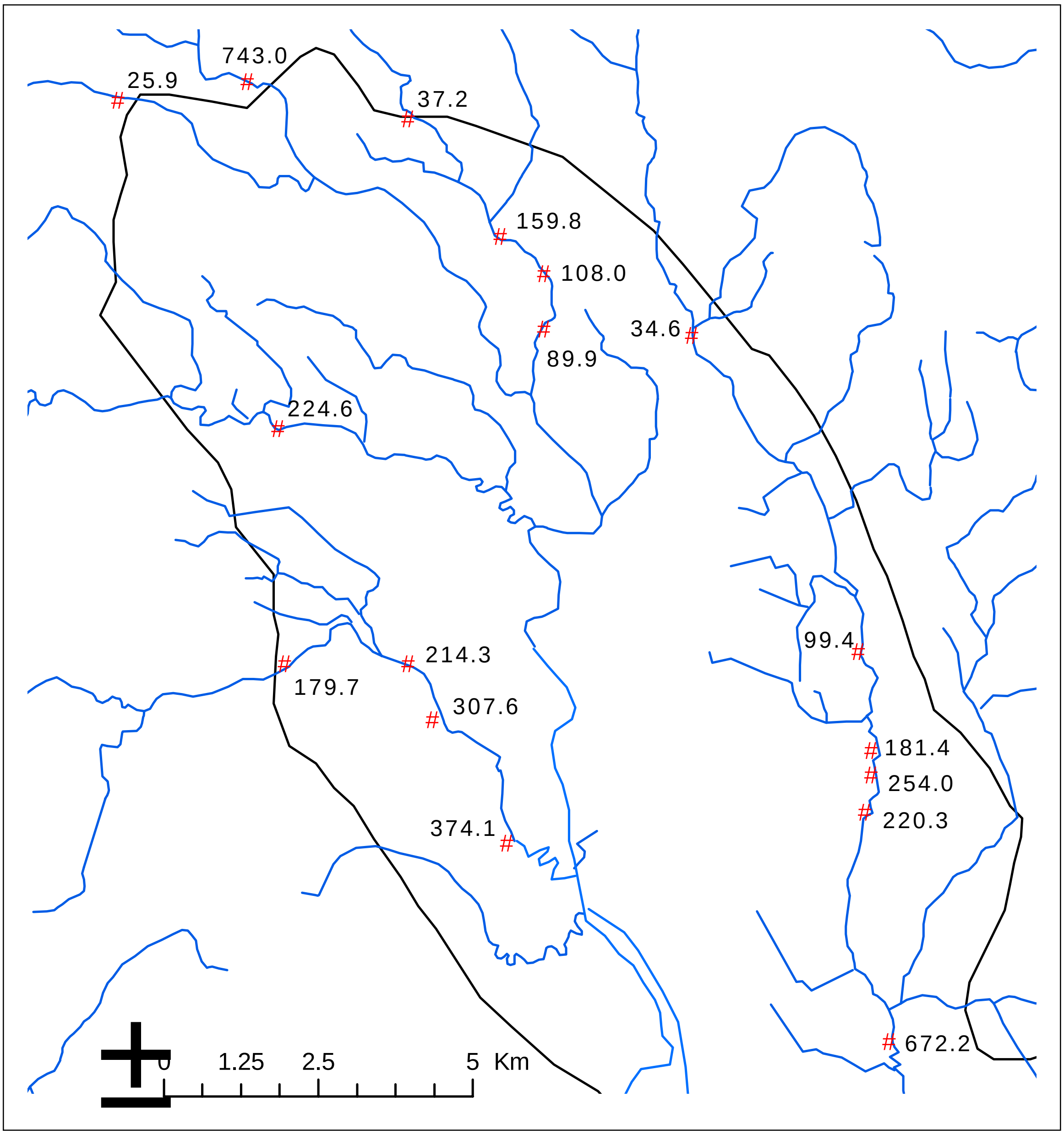


Figure 16 River flow spot gaugings (Ml day^{-1}) on 21st May 1992

2.5 LAND USE

The Nith catchment is the most densely populated and industrialised catchment in Dumfries and Galloway. Surface water quality nevertheless remains high, and the River Nith is a designated salmonid river.

Much of the lowland areas of the Dumfries Basin, and the Thornhill Basin and the flatter land in the higher parts of the Nith catchment are devoted to grassland as pasture for cattle, and in the Hardthorn Road area of the Dumfries Basin also horses. Large areas of the Lochar Water catchment, particularly around Lochar Moss are wooded. The remainder of the Dumfries Basin is urban or industrial and there is a large sandstone quarry at Locharbriggs.

The upland areas of the catchment are largely given over to rough grazing, forestry and moorland.

3 Summary of the conceptual model

3.1 WATER BALANCE

The water balance for the Dumfries basin is dominated by flow in the rivers. However all the components of the water balance need to be identified and, where possible, quantified. These are as follows:

Inflows

- Rainfall recharge.
- Leakage from water supply mains and sewers.
- Rivers.
  - Nith and its tributaries.
  - Lochar Water and its tributaries.
- Runoff supplying river flows along river reach.
- Return to rivers from the fish farms.
- Cross catchment transfer – supply to and from sewage treatment works.

Outflows

- River flows.
  - River Nith and the Lochar Water all discharge to the sea.
- Marshes.
- Springs and seeps.
- Abstraction.
  - Public Water Supply; Scottish Water.
  - Fish farms; Terregles and Holywood.
  - Industrial, agricultural and private supply.
- Infiltration to sewers from shallow groundwater.
- Leakage to the Sea.

3.1.1 Inflows

The main inflows are the flow in the River Nith and the Lochar Water, together with rainfall recharge. The inflow from the River Nith (Section 2.6) is much greater than any other inflow (Figure 16).

3.1.2 Outflows

The river flow data indicates that flows in both the River Nith and the Lochar Water increase across the basin. The reason for this increase is the runoff generated in the catchment and baseflow from groundwater. The fact that the flow increases in both the River Nith and the Lochar Water suggests that most of the rainfall recharge leaves the system as baseflow.

Other than baseflow to the rivers, the main outflows from the groundwater system are abstraction, currently at over 30 Ml day^{-1}, springs issuing from the Larchfield-Caerlaverock ridge and elsewhere, and outflow to the sea via leakage.

These components have been quantified and the results of the time variant water balance are presented in Section 5.

3.2 SUMMARY OF RECHARGE PROCESSES

The main recharge processes operating in the Dumfries basin are:

1. Rainfall recharge.
2. Runoff to surface water systems and subsequent infiltration.
3. Urban recharge processes.

The main component of recharge is likely to be rainfall recharge, however, the other components may be locally significant.

The role of the Quaternary deposits is important in modifying rainfall recharge to the sandstone aquifer and this is discussed below.

3.2.1 Rainfall recharge

The amount of rainfall recharge resulting from rainfall depends on:

- Rainfall; amount, intensity and temporal distribution.
- Evapotranspiration.
- Runoff.
- Soil thickness and type.
- Vegetation.
- Slope of the ground surface.
- Unsaturated zone properties.
- Superficial deposits.

In humid climates the amount of soil-based or direct recharge is dependent on soil processes and how much evapotranspiration occurs from plants growing in the soil. The soil store can fill up as rainfall exceeds actual evaporation. Once the soil store is full, then water flows out of the base of the soil zone and becomes recharge.

The rainfall recharge calculation is detailed in Section 4.

3.2.2 Recharge from the surface water system

Due to the high rainfall in the Dumfries basin, runoff processes are important. Rainfall can reach surface water courses which have the potential to provide recharge to the system. Whilst it is likely that the main water course such as the River Nith and the Lochar Water are receiving baseflow from the groundwater system, leakage from the smaller tributaries could form a source of recharge.

3.2.3 Urban recharge processes

Characterising urban recharge processes is important where large towns or cities overly aquifer outcrops. When water and waste water is moved around the urban environment, a small, but significant proportion can be lost. Leakage from pressurized water mains and from breaks in sewers can become a potential recharge source.

Additionally, the construction of impermeable surfaces such as roads, paved areas, roofs, etc in the urban environment enhances runoff. The runoff resulting from these structures is collected and routed via storm drains to surface water courses. Foul sewers also empty into rivers and streams, either directly or via sewage treatment works and these sources collectively offer a source of recharge.

Open spaces, such as parks and gardens, allow direct, soil-based recharge to occur. Recharge from this part of the urban environment must also be considered.

3.3 BOUNDARIES

The geometry of the basin defines the boundaries to the north, east and west. These boundaries are defined as no-flow at the edge of the Sandstone. To the south, the Sandstone continues under the sea. Thick marine clays separate the Sandstone from the seabed. Groundwater heads in the Sandstone aquifer are higher than sea level and upflow from the aquifer to the sea is likely. A small, but significant amount of outflow may occur by this route. The southern extent of the model is fault bounded and this represents a no-flow boundary. This is discussed in more detail in a Section 6.3.

3.4 NATURE OF GROUNDWATER FLOW IN THE SANDSTONE

Groundwater flow in the Permian rocks in the Dumfries basin is governed by fracture flow. Detailed geophysical and flow logging in the Hardthorne Road, Manse Road and Cargen boreholes has shown that the majority of inflow to boreholes in the Doweel Breccia Formation is from only 3 to 5 fractures. Individual fractures have been measured as contributing close to 50% of the inflow to the borehole. Groundwater flow mainly occurs in fractures between the sandstone and breccia layers.

Much less is known about groundwater flow in the sandstones of the Locharbriggs Formation as only limited geophysical logging has been carried out in this part of the basin. However, comparison of core hydraulic parameters and the available pumping tests indicate that fracture flow again accounts for much of the flow into boreholes.

Due to the lack of basin-wide coverage of transmissivity data, the distribution of hydraulic properties is crude and can be summarised as:

- High apparent transmissivities around the Manse Road/Terregles boreholes (of the order of 1000 $m^2\ day^{-1}$).
- Low around the Dupont/ICI site (< 100 $m^2\ day^{-1}$).
- Low under the marine clays and Peat in the south of the basin (50 $m^2\ day^{-1}$).
- The rest of aquifer is of the order of 200-300 $m^2\ day^{-1}$.

3.5 GROUNDWATER FLOW DIRECTION

The groundwater monitoring points are mainly in the central part of the basin. Generalisations, however, can be made regarding groundwater flow (Figure 18). In the northern part of the basin, the direction of groundwater flow is to the south-east. In the central part of the basin, groundwater flow is predominantly towards the rivers. In the southern part of the basin data are very sparse but groundwater flow is inferred as occurring away from the Larchfield-Caerlaverock Ridge.

3.6 ROLE OF THE QUATERNARY DEPOSITS

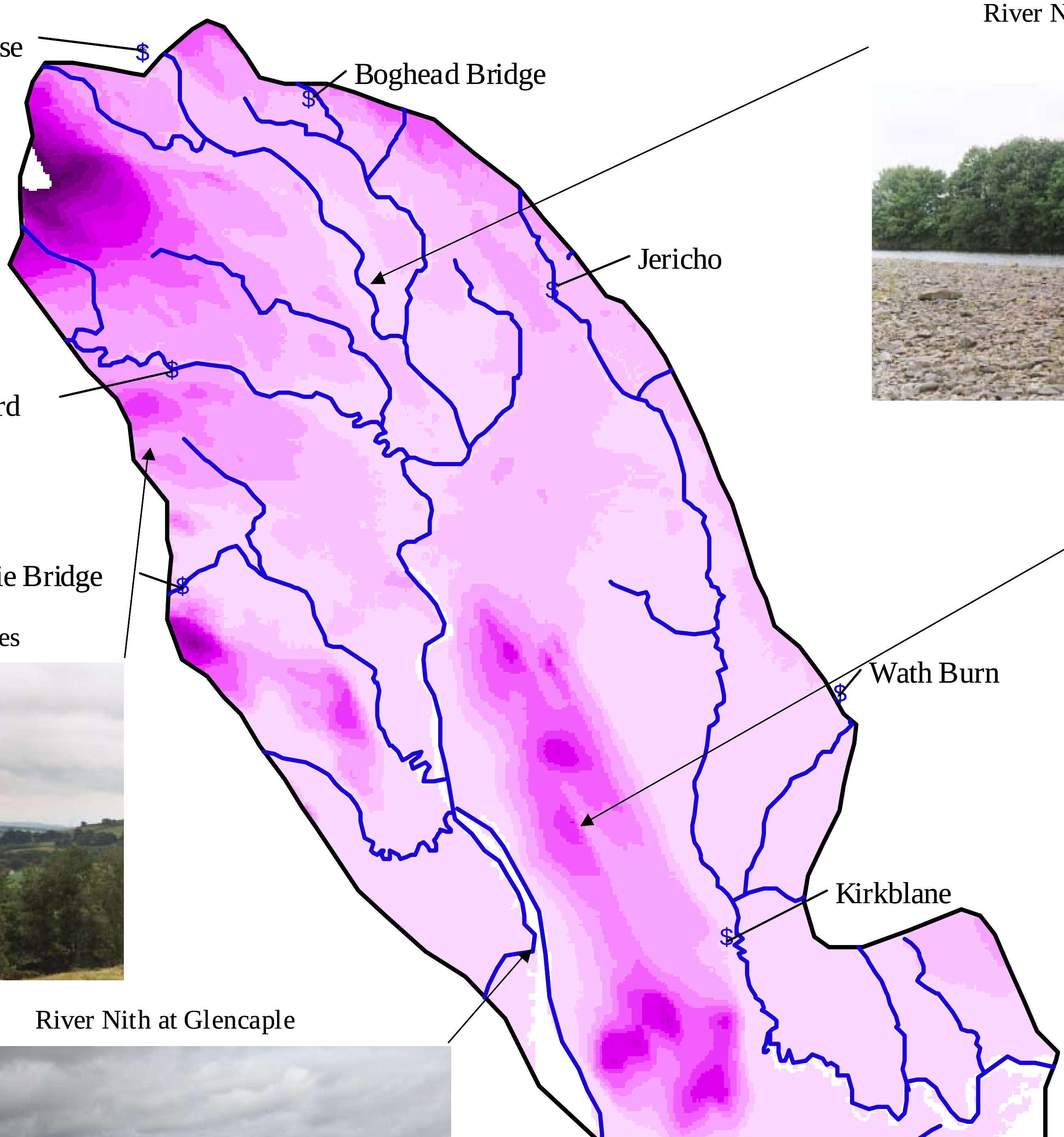
The Dumfries basin has a large coverage of Quaternary deposits, which range from the highly permeable to low permeability. These deposits have to be characterised to enable the impact of Quaternary deposits to be determined. From the work summarised in Section 2.2.1, the majority of the Quaternary deposits in the Dumfries basin are permeable. However, it is worth examining how each type of Quaternary geology impacts on recharge processes and has to be undertaken with reference to the Quaternary map rather than the Quaternary domains described in Section 2.2.1.

Because the majority of the Quaternary deposits are permeable, it is inferred that water can readily infiltrate through these deposits to recharge the sandstone aquifer below (see Figure 19). The notable exceptions are the marine clays in the south of the basin and the peat deposits in the east. Both these Quaternary deposits inhibit vertical recharge and enhance runoff. Where there is peat cover, drainage channels have been cut and these divert potential recharge from the soil to the Lochar Water and its tributaries.

The marine clays have low hydraulic conductivity and limit the interaction between the bedrock aquifer surface waters. Consequently, vertical recharge is inhibited and where the River Nith flows over marine clays it may be disconnected from the Sandstone aquifer. Therefore, groundwater heads in the vicinity of the River Nith may not be controlled by the river levels.

The till, being mostly sandy and gravelly, can act as a local aquifer system. Whilst in the south of the basin, the water table is close to ground surface and the Quaternary deposits are saturated, in much of the north of the basin, groundwater heads are below the base of the Quaternary deposits. Due to its high conductivity, where it is saturated, the Quaternary deposits can collect recharge and supply baseflow to the rivers.

Riverflows/Topography



River Nith at Holywood

View east on Larchfield Ridge

View over basin near Terrregles

River Nith at Glencaple

Gauging station	Mean total flow (Ml day^{-1})	Mean baseflow (Ml day^{-1})	Calculated BFI	Period of record
Fiddlers Ford (Cluden Water)	692	280	0.38	Jan 1964 to Jan 2003
Friars Carse (River Nith)	2378	998	0.39	Oct 1957 to Jan 2003
Kirkblane (Lochar Water)	191	106	0.53	Jan 1992 to Oct 2003
Jericho (Lochar Water)	42	18	0.40	Apr 2002 to Oct 2003
Clunie Bridge (Cargen Water)	35	19	0.46	Feb 2003 to Oct 2003
Wath Burn	19	10	0.49	Apr 2002 to Oct 2003
Boghead Bridge (Pennyland Burn)	12	7	0.52	Apr 2002 to Oct 2003

Figure 17 Summary of topography and surface water features

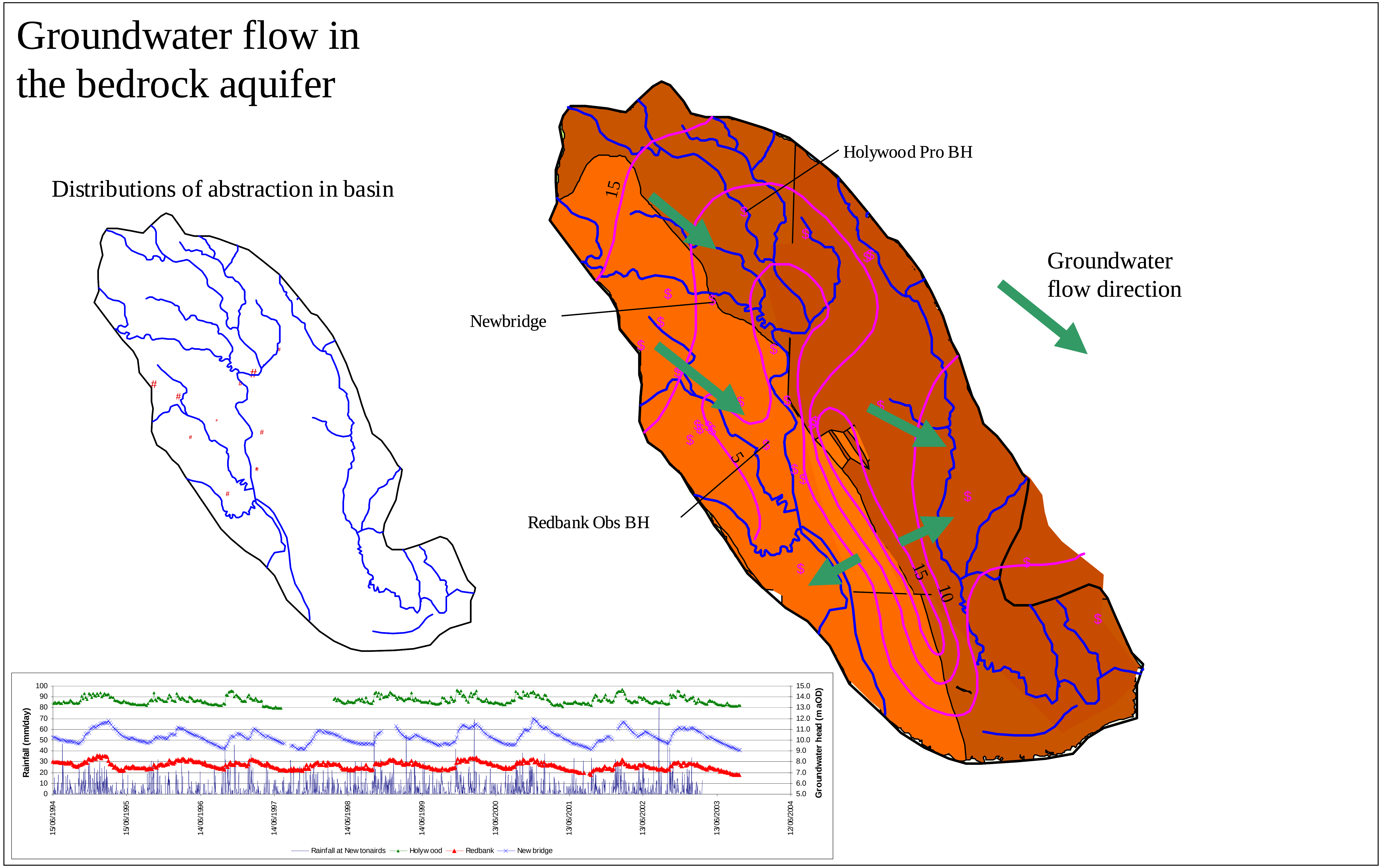


Figure 18 Groundwater flow in the bedrock aquifer

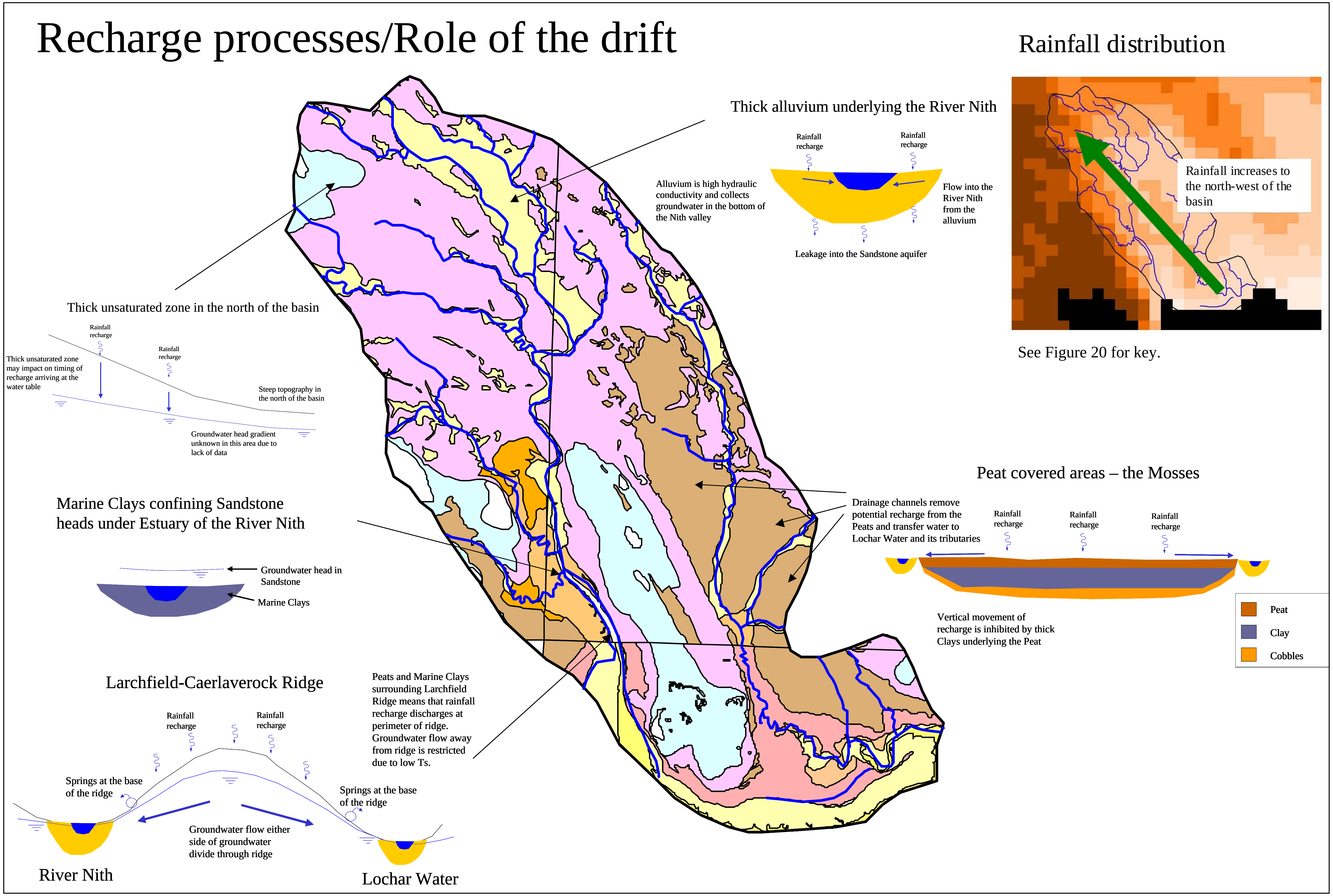


Figure 19 Recharge processes and the role of the superficial deposits

4 Rainfall Recharge

4.1 INTRODUCTION

The following sections describe the development and application of a distributed recharge model. To provide the appropriate recharge input for the regional groundwater modelling, a fully distributed recharge model is required. An existing object-oriented distributed recharge model was adapted for use on the Dumfries modelling work. Modifications included changes to the output for obtaining the water balance. The output of the recharge model is monthly and the format of the output is compatible with both the MODFLOW and ZOOMQ3D groundwater model codes.

In the past few years, object-oriented (OO) approaches to computer programming have been increasingly applied. The BGS in conjunction with the Environment Agency for England and Wales (EA) and the University of Birmingham have developed an OO groundwater flow model, ZOOMQ3D (University of Birmingham, 2001; Jackson, 2001) and an associated particle tracking code ZOOPT (Jackson, 2002). The development of the collection of groundwater models in the ZOOM family has demonstrated the advantages of using OO techniques in groundwater modelling. This experience promoted the development of a distributed recharge model also using OO techniques.

4.2 DESCRIPTION OF THE RECHARGE MODEL

The recharge calculation for the Dumfries study was undertaken using the soil moisture deficit (SMD) method, which is based on the work of Penman (1948) and Grindley (1967). The method calculates the SMD on a daily time-step. The technique calculates the change in soil moisture based on a relationship between actual evaporation (AE) and potential evaporation (PE). The relationship between AE and PE is derived from the SMD in relation to the Root Constant (C) and Wilting Point (D). For the case when the PE is greater than rainfall so that water is being taken out of the soil, the following is true:

- If the SMD is between zero and the Root Constant then AE is equal to PE.
- When the SMD is between the Root Constant and the Wilting Point then the AE is a fraction of the PE. This fraction is usually 0.1 and this is the value used for the Dumfries recharge model.

The distributed recharge model requires that the recharge calculations are undertaken at the appropriate points over the study area. A daily time-step is used for the recharge calculation, with the output supplied as monthly averages.

4.3 DATA REQUIREMENTS

The recharge model requires extensive data sets to be able to calculate recharge on a distributed basis using a daily time step. A single calculation grid is specified for the recharge model with a 500 m spacing. The data used for the model includes:

- Rainfall – daily rainfall and Theissen polygons for selected raingauges (6 stations) and gridded LTA rainfall.
- Landuse – gridded landuse distribution and coefficients required by SMD method; Root Constant and Wilting Point.
- Potential evaporation (PE) – monthly PE from the UK’s Meteorological Office (1 station).

- Runoff – gridded sub-catchments and monthly runoff coefficients for the 22 sub-catchments.

The data needs for the model are described in more detail below.

4.3.1 Rainfall

The recharge model requires a distribution of daily rainfall over the model area. This is achieved using gridded long term average (LTA) rainfall and daily rainfall sequences at selected raingauges. The distribution of LTA rainfall was obtained from CEH Wallingford and is the 1 km^2 gridded long-term average rainfall for 1961 to 1990. The LTA rainfall is shown in Figure 20 and demonstrates that rainfall increases from 954 mm a^{-1} on the coast to 1263 mm/year between Burnhead and Newtonairds, in the north of the basin. The difference in LTA rainfall across the area (approximately 300 mm a^{-1}) is mainly due to the combination in rise in topography coupled with the westerly prevailing wind direction.

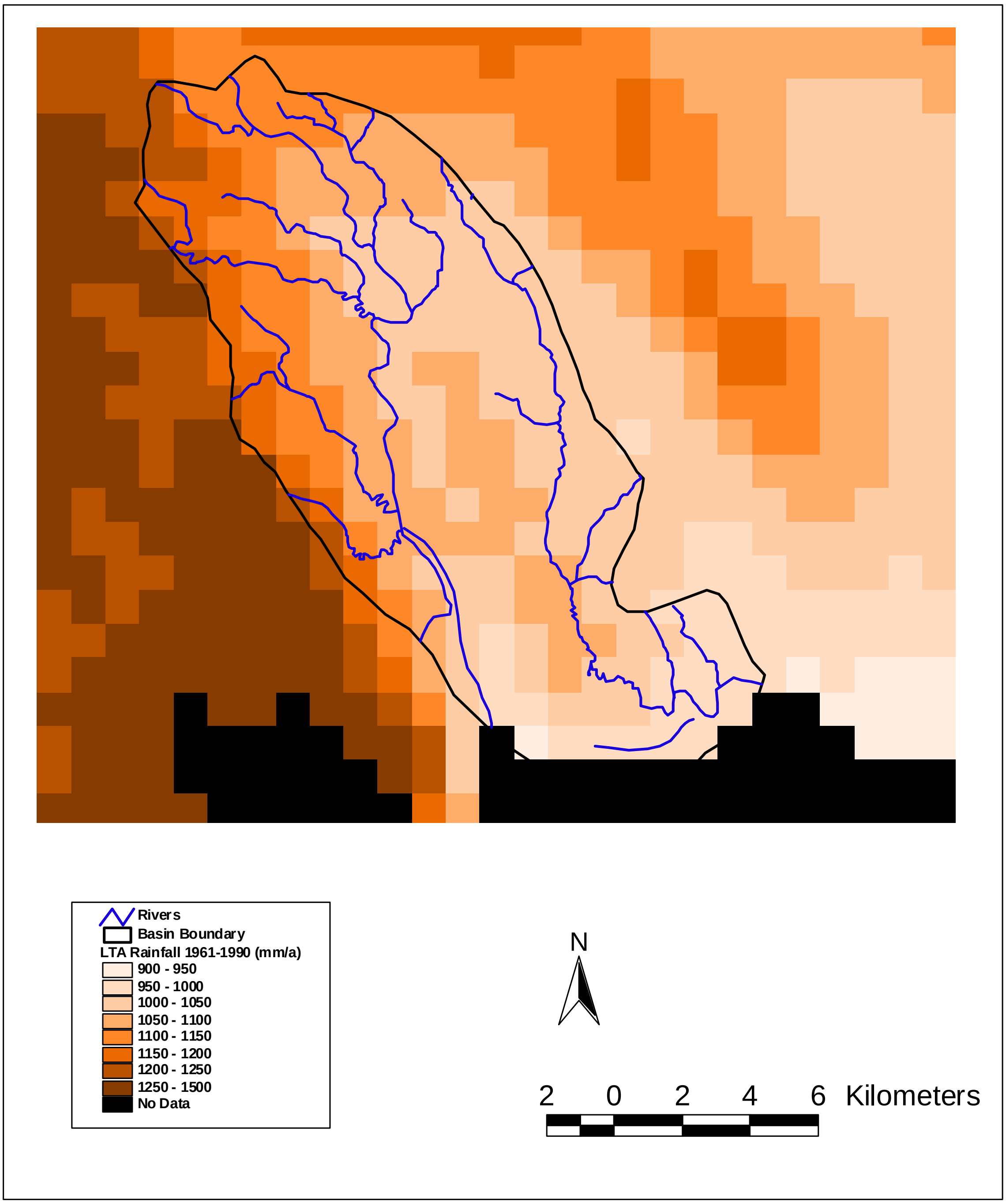


Figure 20 Distribution of long-term average rainfall

The raingauges chosen for inclusion in the recharge model are summarised in Table 5. Six raingauges were chosen based on a combination of location and length of data record. The ideal would be a continuous data record from January 1970 to October 2003. Some of the raingauges have significantly shorter record lengths, but have to be used to provide the best possible geographical coverage of rainfall data. To ensure a continuous distribution of rainfall, when data do not exist, a substitute raingauge is used. This is specified in the input file to the model. If this raingauge has no data, then a default raingauge is used. For Dumfries this is the raingauge at Glencaple.

Table 5 Rainfall gauging stations used for the rainfall recharge calculation

Rainfall gauging station	ID	Substitute ID	LTA rainfall mm/yr	Start Month	Start Year	End Month	End Year
Blackwood	1	1	1139	1	1961	12	2001
CrichtonRoyal	2	1	1042	1	1961	11	1998
LochruttonWWks	3	1	1191	1	1961	2	2001
DrungansFactory	4	1	1098	1	1979	12	2001
Glencaple	5	1	1033	1	1970	10	2003
Newtonairds	6	1	1274	1	1975	3	2003

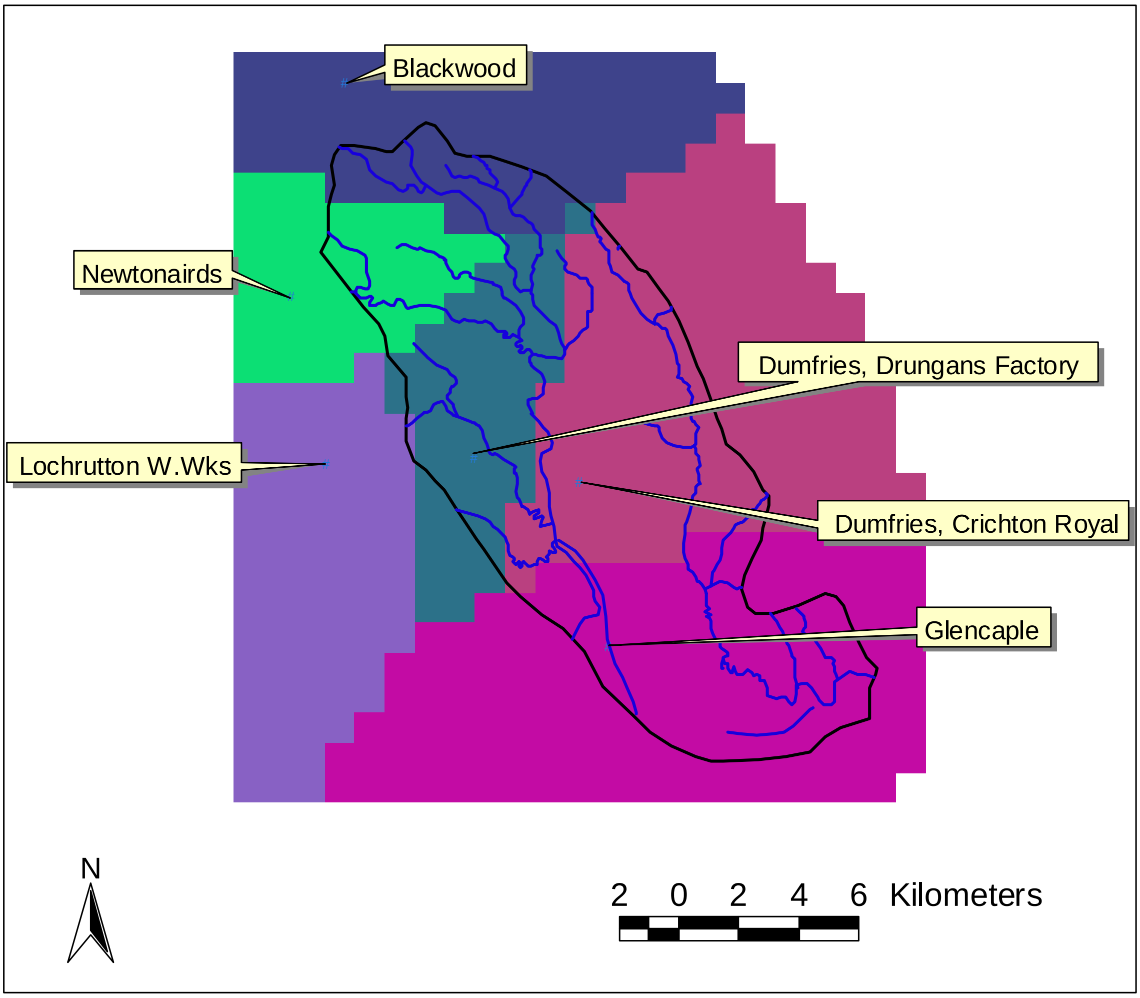


Figure 21 Theissen polygons used for recharge model

To distribute raingauges over the model area, Theissen polygons are used and six are specified for the Dumfries recharge model (Figure 21).

4.3.2 Landuse

The use of the SMD method requires that the Root Constant (C) and Wilting Point (D) are specified where the recharge calculation is undertaken. The C and D coefficients are related to crop type and, therefore, landuse. By determining the spatial distribution of landuse the corresponding spatial distribution of C and D values can be determined. To derive a distribution of landuse for the Dumfries model area the Land Cover Map (LCM) 2000 data produced by the Institute of Terrestial Ecology (ITE) was used (Figure 22). These data have to be referred to as ITE © NERC LCM 2000 when used. The twenty-six categories for landuse (Table 6) are amalgamated into the ten master categories:

1. Broad-leaved / mixed woodland.
2. Coniferous woodland.
3. Arable and horticulture.
4. Improved grassland.
5. Semi-natural grass.
6. Mountain, heath, bog.
7. Built up areas and gardens.
8. Standing open water.
9. Coastal.
10. Oceanic seas.

Using these ten types, recharge was calculated for each of the main landuse types at each node using the appropriate C and D coefficients (Table 7). The landuse data were, therefore, processed to produce arrays of percentage landuse for each landuse type.

Table 6 Adapted ITE landuse data

Definition	1 km code		1 km code
Sea / Estuary	1	Oceanic seas	10
Water (inland)	2	Standing open water	8
Littoral rock	3	Coastal	9
Littoral sediment	4	Coastal	9
Saltmarsh	5	Coastal	9
Supra-littoral rock	6	Coastal	9
Supra-littoral sediment	7	Coastal	9
Bog (deep peat)	8	Mountain, heath, bog	6
Dense dwarf shrub heath	9	Mountain, heath, bog	6
Open dwarf shrub heath	10	Mountain, heath, bog	6
Montane habitats	11	Mountain, heath, bog	6
Broad-leaved / mixed woodland	12	Broad-leaved / mixed woodland	1
Coniferous woodland	13	Coniferous woodland	2
Improved grassland	14	Improved grassland	4
Neutral grass	15	Semi-natural grass	5
Setaside grass	16	Semi-natural grass	5
Bracken	17	Semi-natural grass	5
Calcareous grass	18	Semi-natural grass	5
Acid grassland	19	Semi-natural grass	5
Fen, marsh, swamp	20	Semi-natural grass	5
Arable cereals	21	Arable and horticulture	3
Arable horticulture	22	Arable and horticulture	3
Arable non-rotational	23	Arable and horticulture	3
Suburban / rural development	24	Built up areas and gardens	7
Continuous urban	25	Built up areas and gardens	7
Inland bare ground	26	Mountain, heath, bog	6

Table 7 Categories of ITE LCM 2000 landuse data and related C and D values

ITE LCM 2000 Landuse code	Description	Average % cover	C	D
1	Broad-leaved/mixed woodland	5.58	203	254
2	Coniferous woodland	8.70	203	254
3	Arable and horticulture	14.36	VARIABLE	
4	Improved grassland	47.00	76	127
5	Semi-natural grass	13.65	13	51
6	Mountain, Heath, Bog	2.93	1000	1000
7	Built-up areas and gardens	4.13	50	83
8	Standing open water	0.47	1000	1000
9	Coastal	3.13	13	51
10	Oceanic Seas	0.05	1000	1000
	TOTAL	**100.00**		

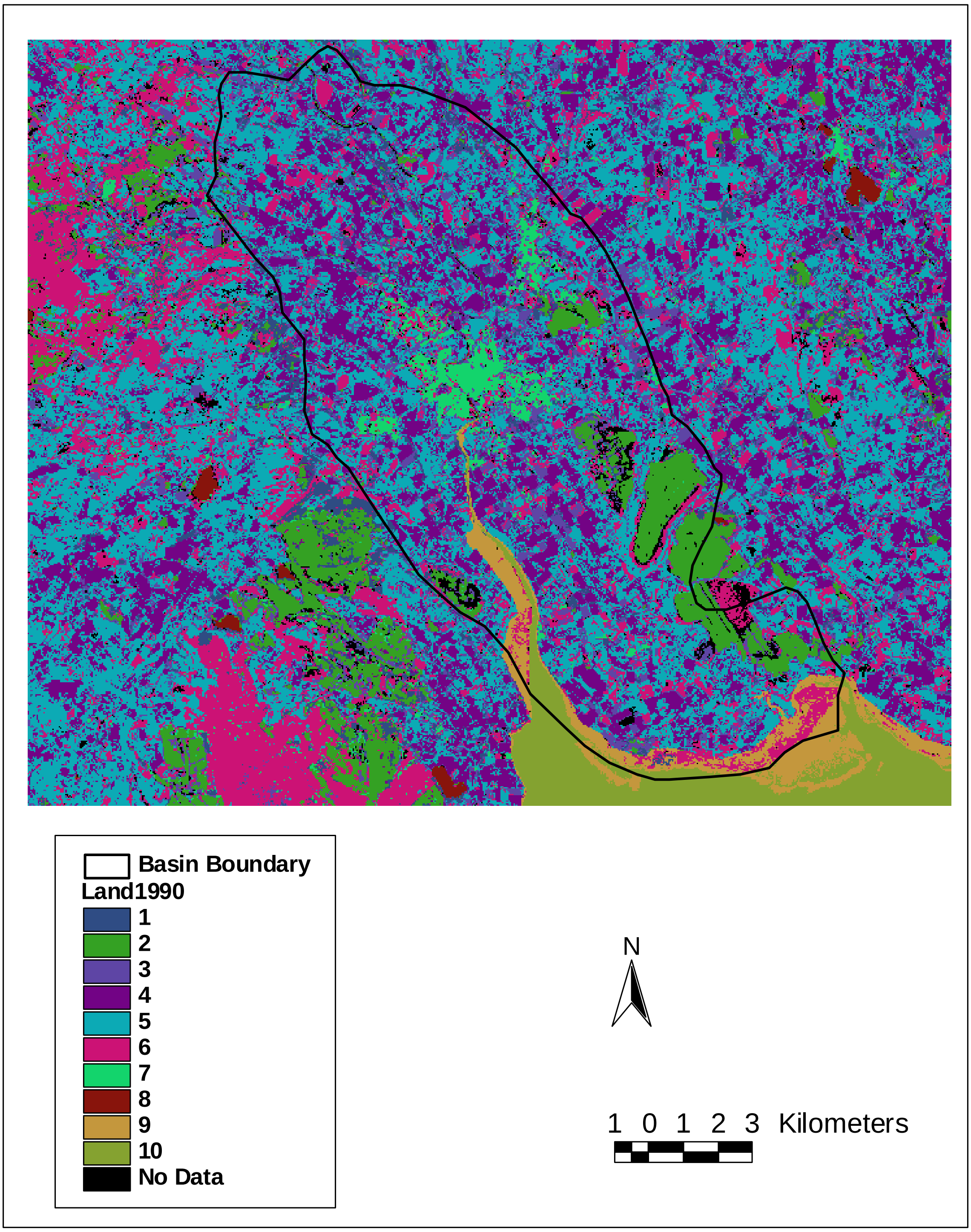


Figure 22 ITE landuse data set used in recharge model

4.3.3 Other data requirements

Other data required for the recharge model included potential evaporation (PE). Monthly PE data was provided by MORECS and square 70 was used. The recharge model area was divided up into two surface catchments, the River Nith and the Lochar Water, and a number of sub-catchments for each Quaternary domain were specified (Figure 23). The use of sub-catchments enabled runoff coefficients to be varied across the model area according to the nature of the Quaternary deposit. Runoff coefficients of 10 % were applied to the majority of the sub-catchments and 95 % was applied to areas of relatively impermeable cover such as the marine clays. A runoff coefficient of 95% was also applied to the peat covered mosses to represent the increased drainage in this area.

The user has to specify the start and end time of the model simulation. In addition, the distribution of nodes required for the calculation has to be specified. This is done using an array of ones and zeros to determine which nodes are to be included in the recharge calculation. Time series output of monthly recharge can also be produced at specified locations.

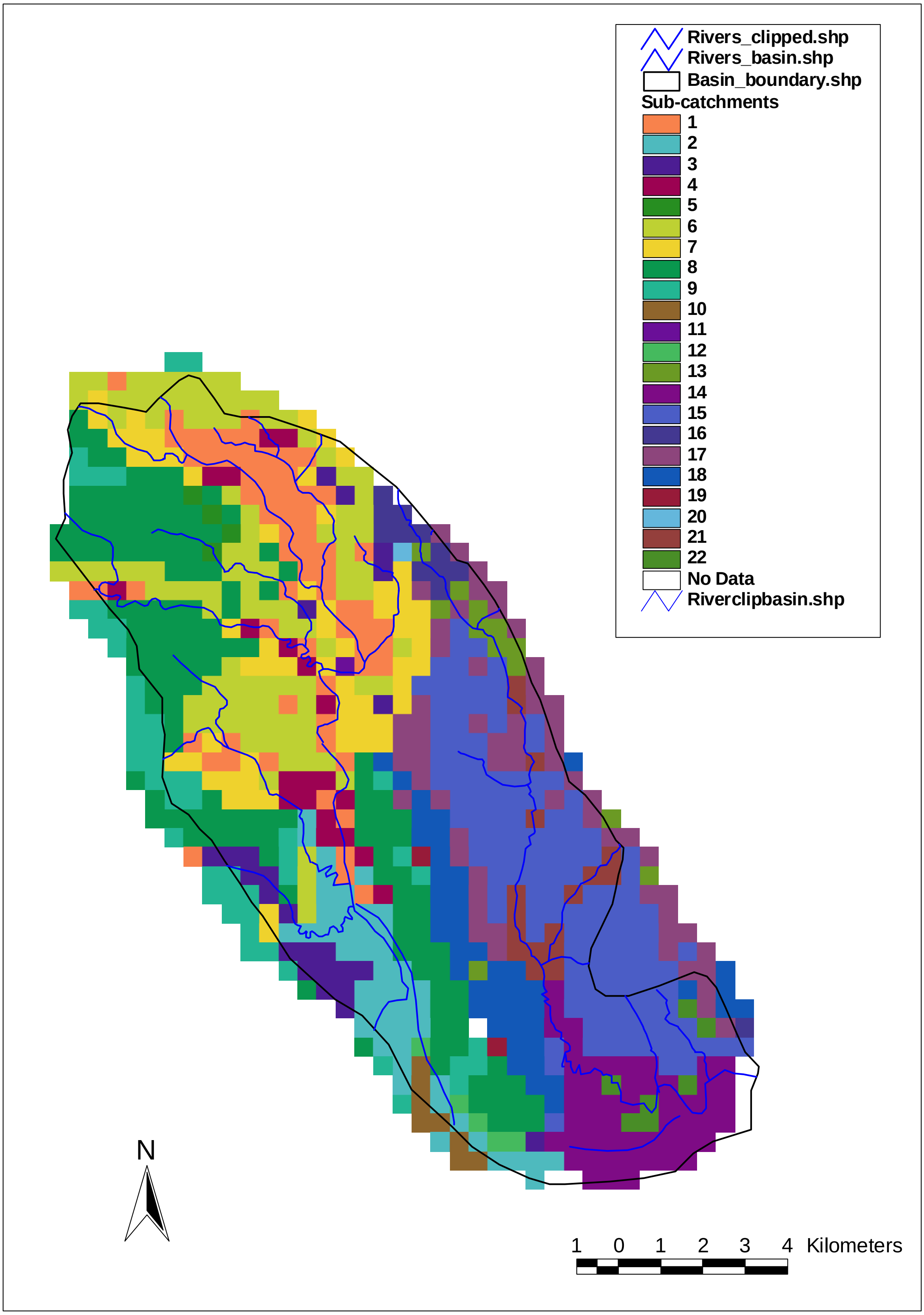


Figure 23 Sub-catchments specified for recharge model

4.4 RESULTS

The nodal values of long-term average recharge produced by the model are presented in Figure 24 and summarised by zone in Table 8. The zones are based on the Quaternary domains for the Nith and Lochar Water catchment in the Dumfries basin. Where the area of the Quaternary domains is negligible, then the Quaternary domains are combined with others, for example Quaternary domains 10 and 11 for the Nith catchment.

Figure 24 shows that recharge is highest in the north-west corner of the study area. This is due to the LTA rainfall being the highest in the north-west of the basin and landuse that is predominantly grassland which, in combination, provides the optimum conditions for recharge. The zero values of recharge are associated with the marine clays and peat, which are assigned a high runoff coefficient, which reduces the rainfall supplied to the recharge calculation.

Since the Nith catchment is larger than the Lochar Water catchment area within the Dumfries basin, and it has the higher elevations, the Nith catchment has the greatest rainfall (Table 8). Runoff is, however, higher in the Lochar Water catchment and this is due to the impact of the mosses (Quaternary domain 3) restricting vertical recharge and draining water to the Lochar Water and its tributaries. The resulting long-term average (1970-2003) recharge for the Nith is nearly three times that for the Lochar Water catchment. This is due to the higher rainfall in the Nith and the higher runoff in the Lochar Water catchment. The long-term average recharge for the Nith catchment in the Dumfries basin is 434 mm a^{-1} and for the Lochar Water catchment is 200 mm a^{-1}. This is based on an area of 125 km^2 for the Nith and 81.25 km^2 for the Lochar Water catchment in the recharge model. The difference in area of the Nith and Lochar Water catchments exacerbates the difference in total recharge represented in flow units between each catchment.

To enable the validity of the time variant nature of the recharge to be examined, a time series of recharge is compared with normalised borehole hydrographs (Figure 25). Three long-term borehole hydrographs are available for Holywood, Newbridge and Redbank (see Section 2.2.3). The consecutive record for all three boreholes runs from January 1993 to September 2003 and this is the period used with which to compare recharge. Normalised groundwater levels are obtained by taking away the minimum and dividing by the difference between the maximum and the minimum groundwater level for each groundwater head measurement. Recharge at the node nearest to each observation borehole is used for comparative purposes.

Examining the time series shows that the normalised groundwater hydrograph for Newbridge is much smoother than either Holywood or Redbank. Both Holywood and Redbank are “flashy” and show responses to individual rainfall/recharge events. The groundwater heads were obtained from transducer measurements and are taken on a weekly basis. Weekly readings of groundwater head can therefore show more detailed responses than the monthly readings usually taken (i.e. by the Environment Agency in England and Wales).

Recharge time series for the three boreholes, in contrast, show similarity between Newbridge and Redbank, but recharge calculated for Holywood shows greater maximum and different timing. In general for all observation boreholes, peaks in the recharge time series are followed by peaks in the groundwater hydrographs. This is noticeable for the “double peaks” observed in the winters of 1993/4, 1996/7 and 2000/1. It is also possible to identify recharge occurring in the summer months, e.g. June 1998 and May 2001. The recharge model predicts that recharge should occur during these months and is confirmed by the groundwater levels responding accordingly. It is difficult to identify any consistent time lag between recharge calculated by the model and a response by the groundwater level hydrographs. It is possible that a delay of up to one month can be determined at various times.

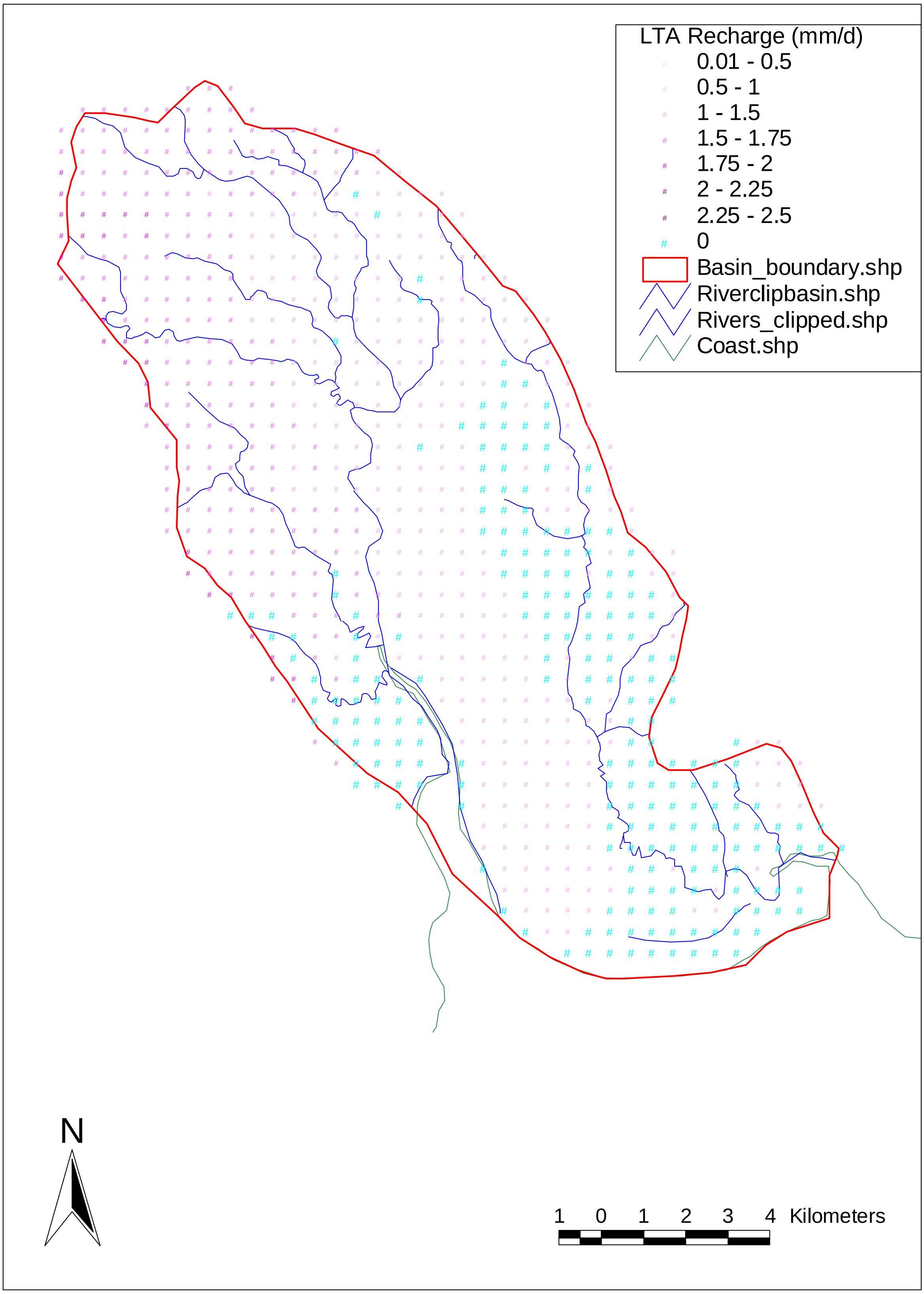


Figure 24 Long term average recharge results for base grid (1970-2003)

Table 8 Summary of output from recharge model by zone (All values in Mlday^{-1})

Zone	**Rainfall**	**Runoff**	**PE**	**Recharge**	**Quaternary domains**	
1	47.03	4.70	21.85	23.08	1	
2	21.63	20.55	10.31	0.00	2	
3	16.79	15.95	7.58	0.00	3	
4	15.31	1.53	7.05	7.63	4	
5	3.13	0.31	1.41	1.55	5	
6	66.40	6.64	30.49	32.80	6	**Nith**
7	43.71	4.37	20.18	21.51	7	
8	103.66	10.37	46.52	51.88	8	
9	17.22	1.72	7.75	8.59	9	
10	0.00	0.00	0.00	0.00	10 to 11	
11	0.73	0.07	0.35	0.35	12	
12	2.63	0.26	1.41	1.17	13 to 14	
13	7.01	0.70	3.44	3.32	1	
14	32.00	30.40	16.56	0.00	2	
15	78.44	74.52	38.59	0.00	3	
16	9.00	0.90	4.32	4.30	4 to 6	
17	30.28	3.03	14.71	14.32	7	
18	29.61	2.96	14.45	14.22	8	**Lochar Water**
19	1.45	0.14	0.70	0.68	9	
20	0.74	0.07	0.35	0.35	10 to 12	
21	11.56	1.16	5.64	5.22	13	
22	4.74	0.47	2.47	2.15	14	
Total	**543.09**	**180.85**	**256.14**	**193.12**		
Nith	338.25	66.49	154.90	148.57		
Lochar	204.84	114.36	101.24	44.55		

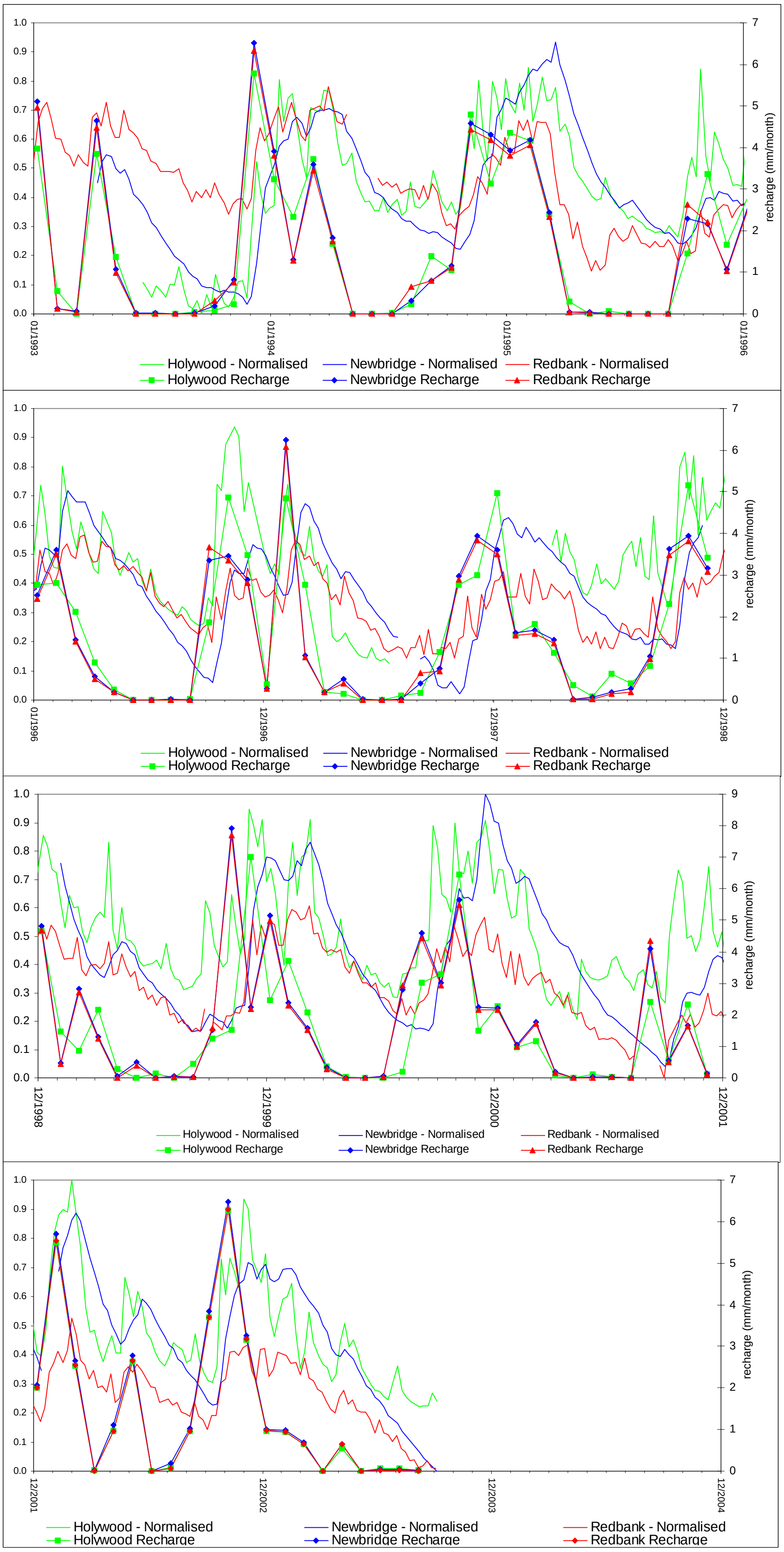


Figure 25 Comparison of normalised groundwater hydrographs with monthly recharge

5 Water balance

5.1 INTRODUCTION

The water balance is required to develop an understanding of the system in support of the conceptual model and to calculate the available resource. It is developed to a time variant water balance based on a monthly time-step and running from January 1970 to September 2003.

Not all the likely inflows and outflows are easy to quantify. Those that are readily quantified and have been used in the water balance are listed below and further illustrated in Figure 26.

Inflows

- Rainfall recharge.
- Leakage from water supply mains and sewers.
- Rivers.
    - Nith and its tributaries.
    - Lochar Water and its tributaries.
- Runoff supplying river flows along river reach.
- Returns from fish farms.

Outflows

- River flows.
- Nith and Lochar Water all discharge to the sea.
- Abstraction.
    - Public Water Supply; Scottish Water.
    - Fish farms; Terregles and Holywood.
    - Industrial; agricultural, etc.
- Leakage to the sea.

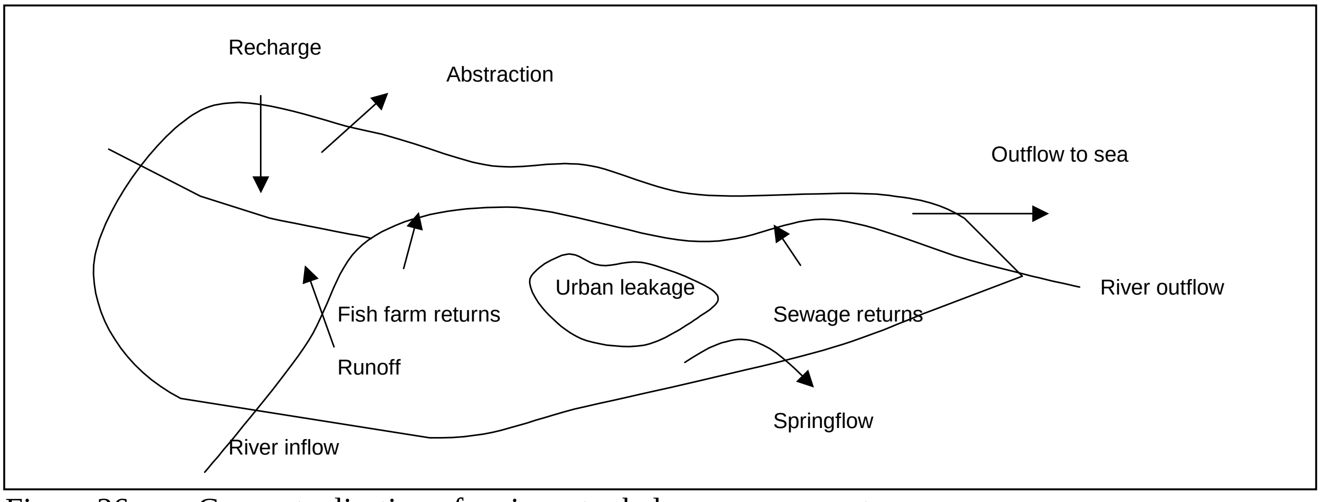


Figure 26 Conceptualisation of main water balance components

The water balance is based on a catchment scale for each river; Nith and the Lochar Water. The surface water divide is used to determine the boundary between the two catchments for the basin (Figure 27). The water balances for each catchment in equation form are as follows:

Nith

rainfall recharge + runoff + total river flow from tributaries joining the basin + return from fish farms + leakage from water mains + leakage from sewers	=	abstraction + total river flow at bottom of the catchment + spring flow + leakage to the sea

Lochar Water

rainfall recharge + runoff + total river flow from tributaries joining the basin + leakage from sewers	=	abstraction + total river flow at bottom of the catchment + springs+ leakage to the sea

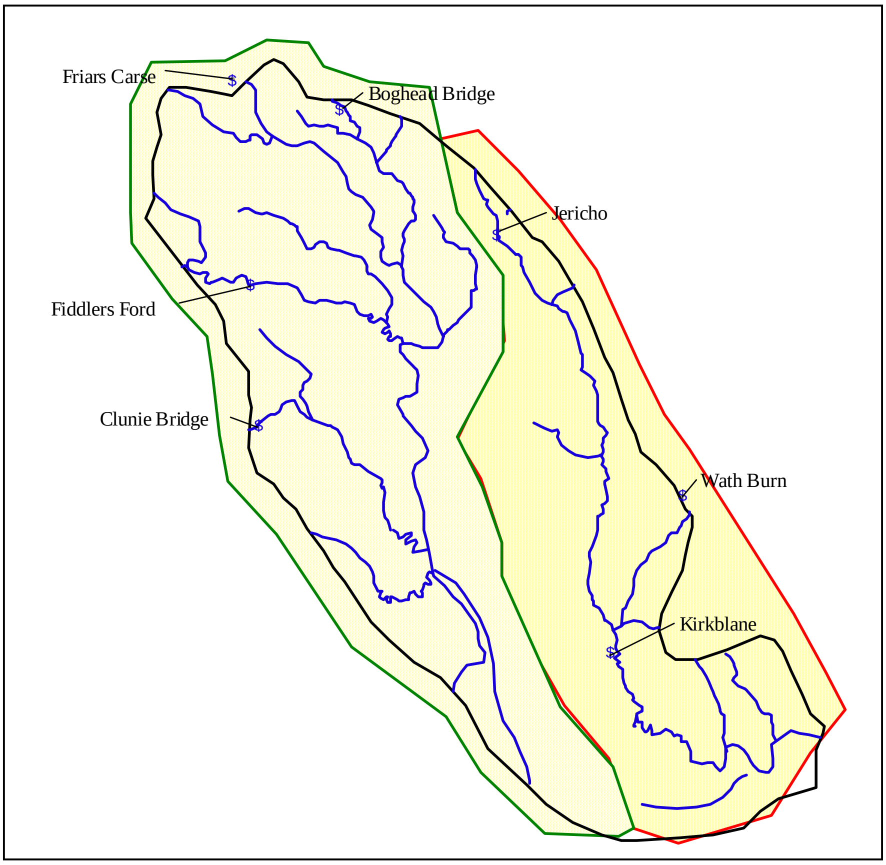


Figure 27 Catchments used for the water balance

5.2 SOURCES OF DATA

5.2.1 Rainfall recharge

Rainfall recharge is calculated from January 1970 to October 2003 using the recharge model described above.

5.2.2 Runoff

Runoff is derived from the recharge model and calculated as a percentage of rainfall. A runoff coefficient of 10% is used for the recharge model except where there are low permeability superficial deposits, such as peat overlying clay or the marine clays, in which case a runoff coefficient of 95 % is used. The choice of this high runoff coefficient results in little or no recharge occurring through these deposits. The validation of the runoff coefficients requires more data in the River Nith catchment and a better understanding of the peat deposits in the Lochar Water catchment.

5.2.3 River flow

Daily river flows are available for various gauging stations on the Nith and the Lochar Water. Details of the river flow gauging network are given in Section 2.6. These daily data have been averaged to monthly values and the monthly river flow values used in the water balance. The main issue for the water balance is that the flow at the tidal limit of the River Nith, Greensands in Dumfries has to be estimated. The flow is assumed to be 200 $Mlday^{-1}$ greater than the combined inflows for the River Nith and its tributaries. This assumption is based on the few spot gauging data available for the River Nith.

Returns to the river from sewage treatment works and fish farms are also included in the water balance. However, the returns from sewage treatments works are estimated. The flows from the fish farms at Terregles and Holywood are estimated based on the assumptions that all the groundwater abstraction is returned to the water course.

5.2.4 Leakage from pressurised water mains

A nominal value of 10 Ml day^{-1} of leakage from pressurized water mains is assumed to recharge the aquifer under Dumfries. This value is a guestimate using leakage rates for similar sized urban areas in the UK.

5.2.5 Abstraction

Akhurst et al. (in press) summarise the current rates of groundwater abstraction from boreholes in the basin. These are listed in Table 9 and shown in Figure 28. This is the best available data but only provides the mean pumping rates at each of the wells. Because there has not been an abstraction licensing requirement under Scottish Law few records of historic pumping rates have been taken.

For the water balance, an assessment of when the abstractions started and what changes in abstraction rate have occurred over time has been undertaken. This enables a time series of abstraction rate for January 1970 to October 2003 to be developed (see Figure 29). Examining Figure 29 shows that abstraction increased markedly in the late 1980s / early 1990’s mainly due to the Terregles and Holywood Fish Farms starting operation.

Aside from the fish farms, another major industrial abstractor is the Dupont plant just outside Dumfries. Akhurst et al. (in press) have estimated their abstraction rate as approximately 0.8 Ml day^{-1}. The abstraction rates listed in Table 9 are those included in the model. Akhurst et al. (in press) estimate that agricultural boreholes within the basin could pump a total of 1 Ml day^{-1}. This is included in the water balance but not in the groundwater flow model because it is divided between a number of small boreholes, which are effectively insignificant.

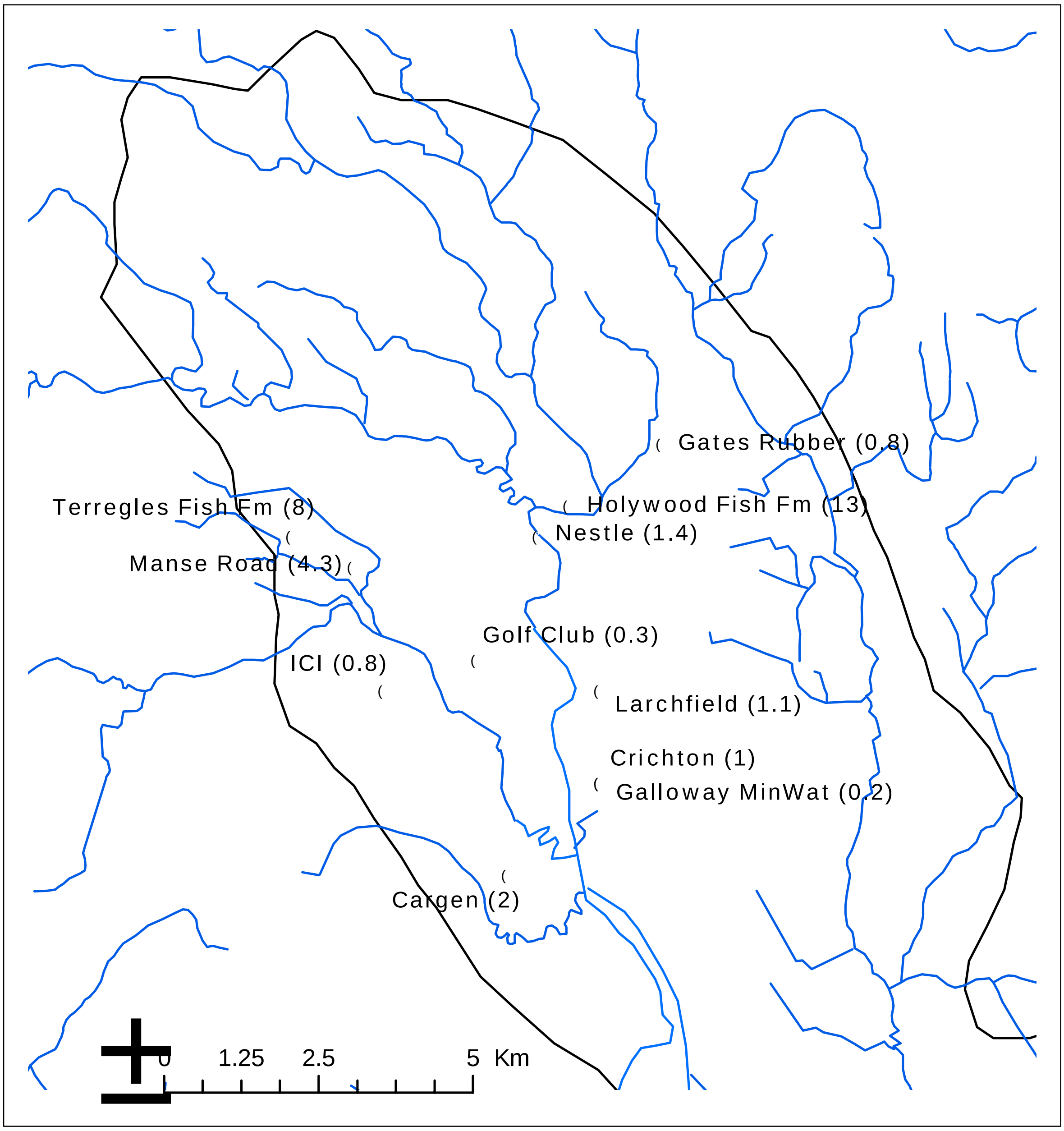


Figure 28 Abstraction boreholes and estimated mean pumping rates (Ml day^{-1})

Table 9 Estimated groundwater abstraction in the Dumfries basin

Name	Easting	Northing	Pumping rate (Ml day^{-1})
Cargen Public Supply	296380.0	572030.0	2
Crichton Royal Hospital	297840.0	573250.0	1
Galloway MineralWater	297800.0	573300.0	0.2
Gates Rubber	298930.0	579060.0	0.8
Golf Club	295880.0	575620.0	0.3
Holywood Fish Farm	297700.0	577920.0	13
Dupont	294620.0	574830.0	0.8
Larchfield Public Supply	298050.0	575040.0	1.1
Manse Road Public Supply	294020.0	576770.0	4.3
Nestle	297010.0	577410.0	1.4
Terregles Fish Farm	292890.0	577370.0	8
		Total	**32.25**

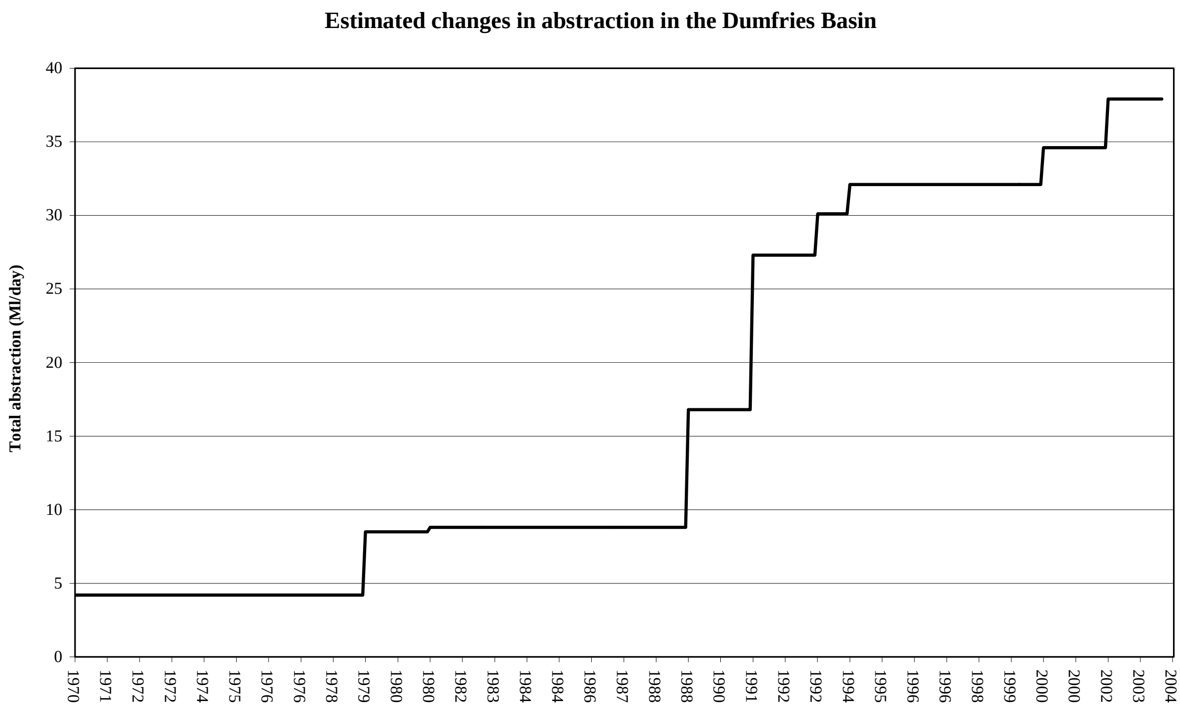


Figure 29 Time series of abstraction in the Dumfries Basin (1970-2003)

5.2.6 Springs

In conjunction with the groundwater flow modelling, areas of springs were identified in the Dumfries basin. These areas are the Larchfield ridge, running from Crichton to Bankend, and Lochhead Muir. From examining the 1:10 000 Ordnance Survey maps potential areas of discharge were identified. The discharge was estimated at about 20 $Mlday^{-1}$ for the Larchfield ridge and 5 $Mlday^{-1}$ for the area around Lochhead Muir. These guestimates were made based on the number of springs found on the OS map and assigning a flow of 1 $Mlday^{-1}$ for each spring.

5.2.7 Leakage to the sea

In the south of the basin, the sandstone aquifer passes under the sea and is overlain by marine clays. These marine clays confine the aquifer and the current understanding is that they only allow limited connection with the sea. Therefore a small amount of leakage occurs from the Sandstone aquifer to the sea and is estimated to be about 5 $Mlday^{-1}$.

5.3 RESULTS

To produce an overview of the water balance the components in the time variant water balance are summarised as long term averages for the Nith and Lochar Water catchments are presented in Table 10 and Figure 30 and 31. The importance of surface water flows in the Dumfries basin (as evidenced by the magnitude of the inflow to the River Nith catchment at over 3200 Mld^{-1}) requires a combined surface water and groundwater balance to be developed. Recharge to the groundwater system in the basin is calculated at just under 200 Mld^{-1}, surface water flows are approximately sixteen times that of rainfall recharge. The high ratio of surface water to groundwater means that river-aquifer interaction is difficult to determine. The situation in the catchment of the River Nith is further compounded by the lack of a continuous flow measurement at the bottom of the River Nith catchment, close to the tidal limit. The current water balance assumes that flow in the River Nith at Greensands is 200 Ml day^{-1} greater than the sum of the measured inflows. This figure is based on the few spot gauging data that are available. This estimate can only be improved by continuous measurement of flow in the River Nith at Greensands

The water balance for the Lochar Water is more straightforward and can be summarised as being rainfall recharge supplying baseflow to the Lochar Water with a few minor additional components. Runoff is a significant component of the water balance due to the impact of the mosses where peat overlies clayey material. The mosses are a significant proportion of the Lochar Water catchment. It is assumed that vertical recharge is restricted in the peat covered areas and the potential recharge that could reach the sandstone is diverted to surface water courses. The mosses have been drained for a number of decades and numerous channels have been cut into the Peat to lead water to the Lochar Water and its tributaries. This mechanism has been included in the water balance as runoff.

Table 10 also includes estimate of percentage errors in each of the components of the water balance. The most significant absolute error is the flow of the Nith at the bottom of the basin. River flows at this point is only accurate to ± 10% giving a change in water balance of 347 Ml d^{-1}, which is more than all the other components combined. Lack of gauging data at the bottom of the River Nith also impacts on the accuracy of the runoff calculation. The runoff calculated by the recharge model cannot be validated. For the water balance for the Lochar Water, the largest absolute error is for the runoff. This is related to the role of the mosses in reducing vertical recharge and increasing surface flows to the Lochar Water.

Table 10 Summary of water balance

		Nith (Ml day^{-1})	Error (%)	Error (Ml day^{-1})	Lochar Water	Error (%)	Error (Ml day^{-1})	Total (Ml day^{-1})
IN	Recharge	148.57	15%	22.29	44.90	15%	6.74	193.47
	Runoff	66.49	50%	33.24	114.43	50%	57.22	180.92
	River inflow	3264.92	10%	326.49	61.50	10%	6.15	3326.42
	Urban Leakage	10.00	100%	10.00	0.00			10.00
	Irrigation return	0.00			0.00			0.00
	Fish Farm return	8.41	10%	0.84				8.41
	Sewage return	15.00	100%	15.00	5.00	100%	5.00	20.00
	TOTAL	3513.39		407.86	225.83		75.10	3739.22
OUT	River flow	3470.00	10%	347.00	192.61	10%	19.26	3662.61
	GW outflow	5.00	200%	10.00	2.00	200%	4.00	7.00
	Abstraction							
	Scottish Water	4.00						
	Fish Farms	7.70						
	Other	5.21						
	TOTAL	16.91	25%	4.23	1.00	25%	0.25	17.94
	Springs	10.00	100%	10.00	10.00	100%	10.00	20.00
	TOTAL	3501.94			205.61		113.61	3707.55
IN-OUT		11.45			20.22			31.67

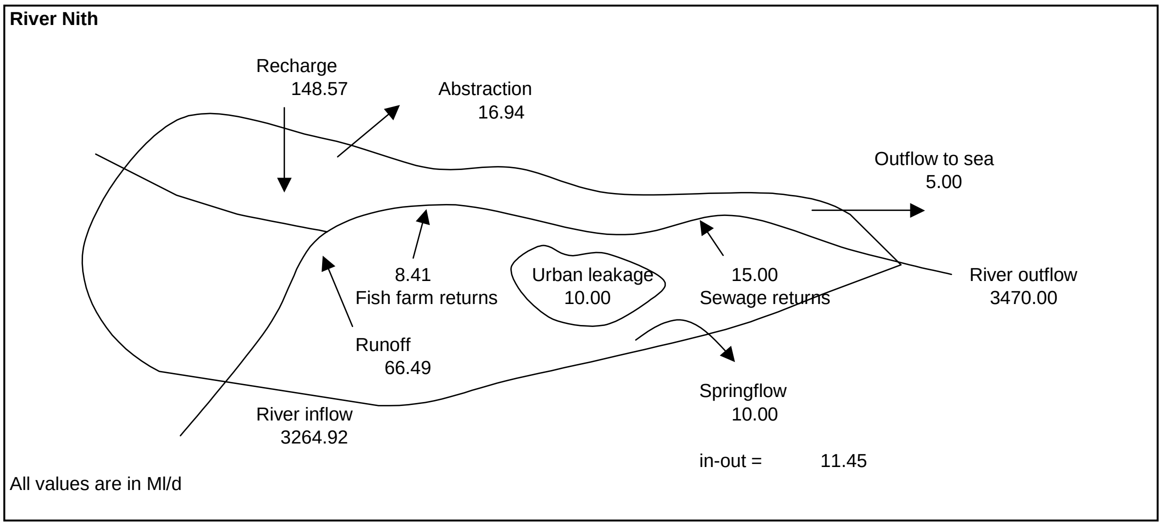


Figure 30 Summary of water balance in the River Nith catchment

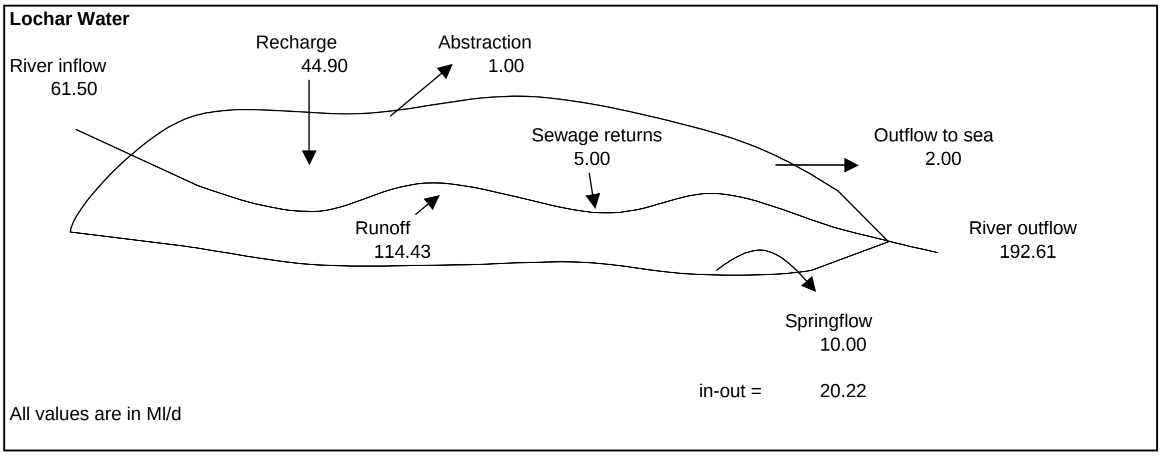


Figure 31 Summary of the water balance in the Lochar Water catchment

6 Groundwater flow modelling

6.1 BACKGROUND

The Dumfries aquifer is modelled using the regional groundwater flow code ZOOMQ3D, (Jackson, 2001). This finite difference model has been developed collaboratively by the University of Birmingham, the Environment Agency and the British Geological Survey. The decision to use ZOOMQ3D instead of, for example MODFLOW, was made because it greatly simplifies the process of representing multiple rivers. In addition to this, any modifications that are required to the structure of the model grid or rivers, for example in order to represent river-aquifer in more detail, can be performed quickly.

6.2 MODEL EXTENT

The model covers the area shown in Figure 32, the boundary of which is defined by the edge of the Permo-Triassic Dumfries basin. The boundary along the south-eastern edge of the model is defined by the Waterbeck Fault, which represents the physical limit of the sandstone. Consequently, the model extends approximately nine kilometres offshore into the Solway Firth.

The model incorporates the downstream parts of the river catchments of the Nith and the Lochar Water. The Nith, which is the major river in the system, flows on to the model at Friars Carse in the north-west. The Lochar Water flows approximately parallel to the axis of the basin and towards the eastern model boundary. The model area is enclosed by the rectangle defined by the co-ordinates (290000, 558500) in the south-west and (311500, 585500) in the north-east.

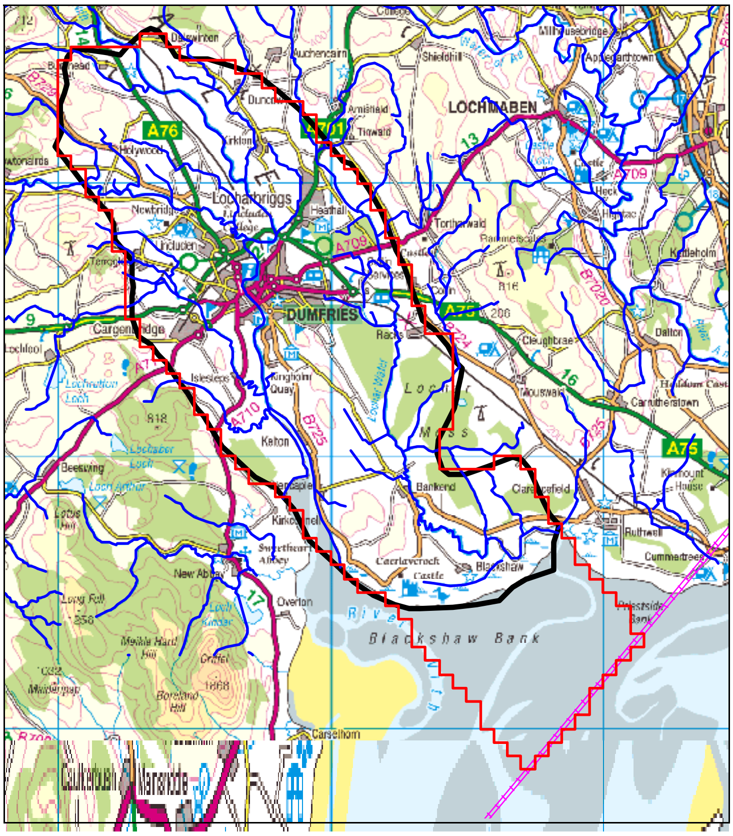


Figure 32 Model extent (red), basin boundary (black) and line of Waterbeck fault (magenta)

6.3 MODEL GRID AND BOUNDARY CONDITIONS

Figure 33 shows the ZOOMQ3D model mesh superimposed onto the geological map. The mesh is composed of regular 500 m square cells over the whole domain. The boundaries for a regional groundwater model should ideally be based on physical features, such as impermeable geological formations, as this minimises the uncertainty associated with a boundary condition and reduces model errors. The edge of the Permo-Triassic basin provides such a well defined boundary for the numerical model as it is surrounded by low permeability Palaeozoic rocks. Towards the south-east of the model the Locharbriggs Sandstone is underlain by Carboniferous limestone and calcareous sandstone, which also have relatively low permeability, and consequently little groundwater flow is assumed to cross this boundary. A recently drilled borehole at Ironhirst Moss showed Carboniferous strata at rockhead and consequently it is known that the Locharbriggs Sandstone thins to the south-east.

The offshore southern boundary along the centre of the Solway Firth is also defined as an impermeable boundary. This coincides with the Waterbeck Fault, to the east of which the Mercia Mudstone Group predominates.

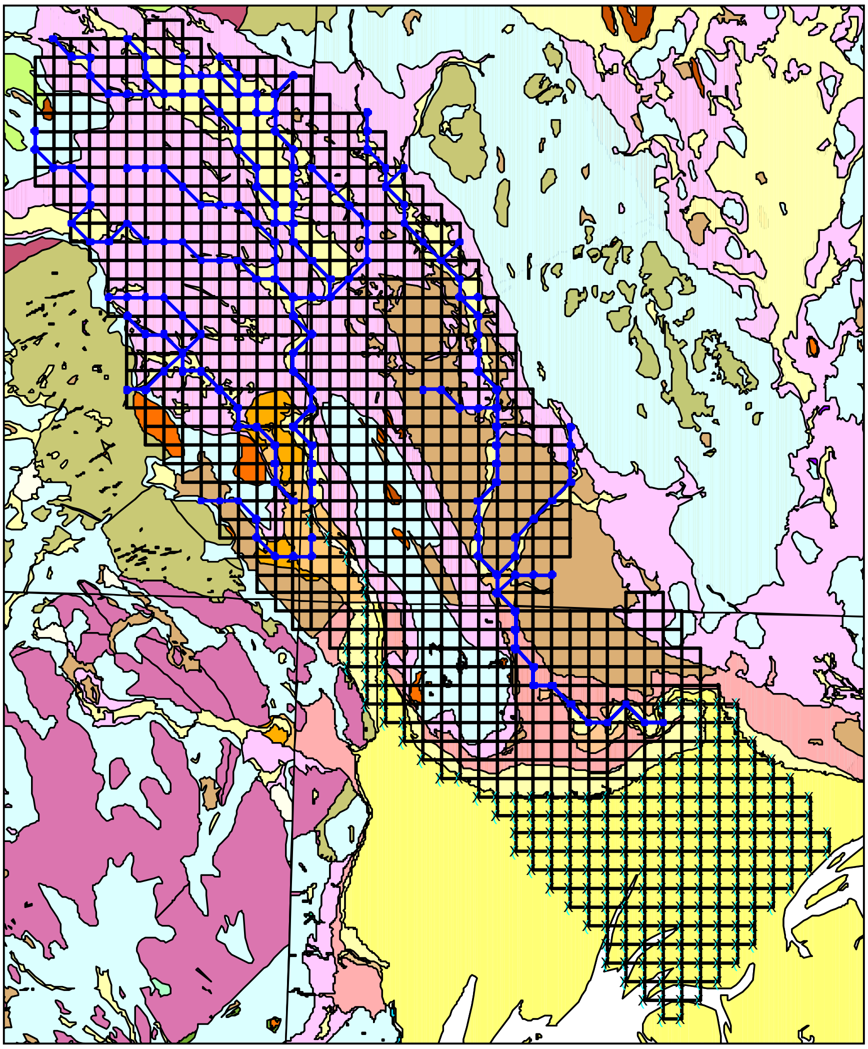


Figure 33 Model grid superimposed on geological map

6.4 MODEL LAYERING

The model contains two layers. The upper layer (layer 1) represents the superficial Quaternary deposits and the lower layer (layer 2) represents the bedrock aquifer. The thickness of layer 1 is taken directly from the Quaternary deposits thickness map shown in Figure 6. The bedrock aquifer is specified to be 200 m thick. This is an acceptable thickness when considering the depths of the flowing fractures within the basin through an analysis of borehole records.

6.5 RIVERS

Parts of four river catchments are included the model. These are the Crooks Pow, the Cargen Water, the River Nith and the Lochar Water. Each of these is composed of a series of interconnected river branches that are represented by a series of interconnected reaches, or river nodes, each of which interacts with the aquifer and along which simple flow accounting is performed. The structures of the model rivers and the node numbering scheme is shown in Figure 34. These numbers are used to refer to nodes at which, for example, the baseflow is monitored over time.

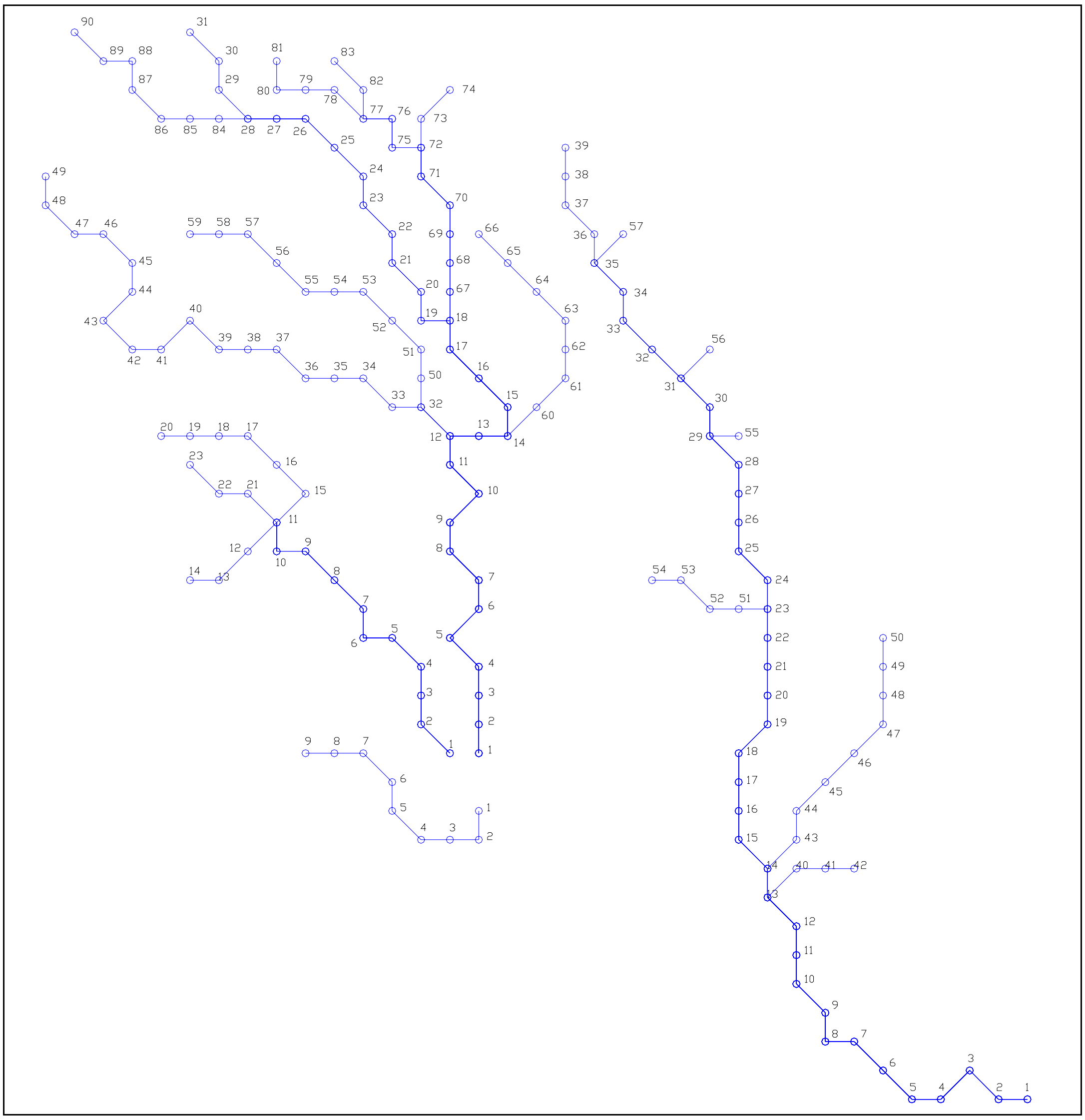


Figure 34 Model river structure and river node numbers

6.5.1 River-aquifer interaction

To clarify the representation of rivers in the model, the mechanism for river-aquifer interaction is briefly described in this section. In ZOOMQ3D river-aquifer interaction is represented as a linear head-dependent leakage mechanism. The rate of leakage depends on the difference between groundwater head and river stage and is expressed by:

$$Q_z = \frac{K_z}{B} \cdot W \cdot L \cdot \left(h_a - h_r\right) \qquad (3.2)$$

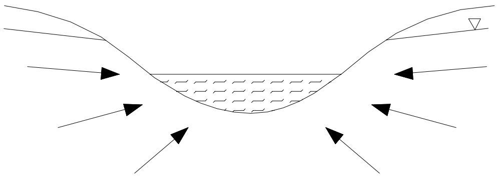
where

- Q_z is the leakage rate ($m^3 day^{-1}$),
- K_z is the vertical hydraulic conductivity of the river bed ($m\ day^{-1}$),
- B is the thickness of the river bed (m),
- W is the width of the river (m),
- L is the length of the river reach (m),
- h_a is the head in the aquifer (m) and,
- h_r is the river stage (m).

This equation is modified when the head in the aquifer falls below the base of the river. In this case the vertical hydraulic gradient is assumed to equal unity and the leakage from the river is defined as:

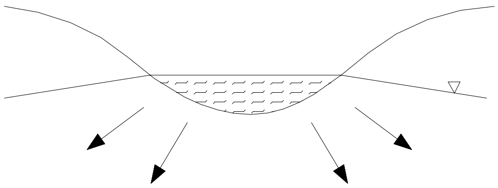
$$Q_z = -K_z \cdot W \cdot L$$

In addition to limiting the flow between the aquifer and the river when the groundwater head falls below the river bed, different hydraulic conductivity values are applied between influent and effluent conditions. The difference reflects the seepage force applied to the bed material and the associated increase in permeability when groundwater is discharging to the river. The hydraulic conductivities are defined by the user in an input file. The different relative positions of the river stage and groundwater head are shown in Figure 35. The appropriate vertical flow equation representing the interaction is written next to each scenario.



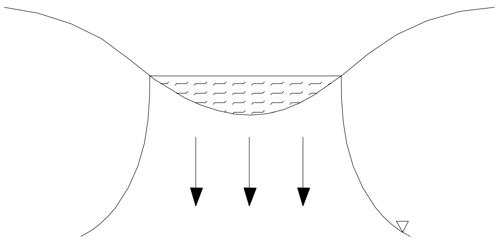
a) Influent river

$$Q_z = \frac{K_Z^I}{B} \cdot W \cdot L \cdot (h_a - h_r)$$



b) Effluent river. Groundwater head above the base of the river but below river stage

$$Q_z = \frac{K_Z^E}{B} \cdot W \cdot L \cdot (h_a - h_r)$$



c) Effluent river. Groundwater head below base of the river

$$Q_z = -K_Z^E \cdot W \cdot L$$

Q_z is the flow rate (m^3 day^{-1}) from the aquifer to the river,

K_Z^E is the vertical hydraulic conductivity of the river bed (m day^{-1}) under effluent river conditions,

K_Z^I is the vertical hydraulic conductivity of the river bed (m day^{-1}) under influent river conditions,

B is the thickness of the river bed (m),

W is the width of the river (m),

L is the length of the river reach (m),

h_a is the head in the aquifer (m) and,

h_r is the river stage (m).

Figure 35 Formulation of river aquifer interaction under influent and effluent conditions

6.6 REPRESENTATION OF THE NITH ESTUARY AND THE SOLWAY FIRTH

A shown in Figure 33, the model grid extends into the Solway Firth. The Waterbeck fault is assumed to represent an impermeable boundary but groundwater may discharge from the aquifer upwards into the coastal waters. To represent this process the Nith Estuary and the Solway Firth are represented using head-dependent leakage nodes. These are shown in Figure 33 by the cyan circles. Groundwater discharges through these leakage nodes based on the Darcian type equation:

$$Q = C \cdot A \cdot (h_a - Z)$$

where,

Q is the flow rate (m^3 day^{-1})

C is the bed conductance (day^{-1})

h_a is the head in the aquifer (m)

Z is the elevation of the leakage node (m) which is mean sea level (zero m OD)

A is the area of the model node (m^2)

6.7 SPRINGS

An examination of the 1:10 000 scale Ordnance Survey topographic map shows that a significant number of springs and drains issue at the edge of the high ground in the area to the north-west of Caerlaverock. These springs and drains flow into the Lochar Water catchment to the east, into the Nith to the west and towards the coast to the south. To represent these discharge points a second set of leakage nodes is included in the model. These are shown by the green squares in Figure 36. The two outlying leakage nodes in the area of Longbridgemuir represent springs, which issue from the high ground near the edge of the model.

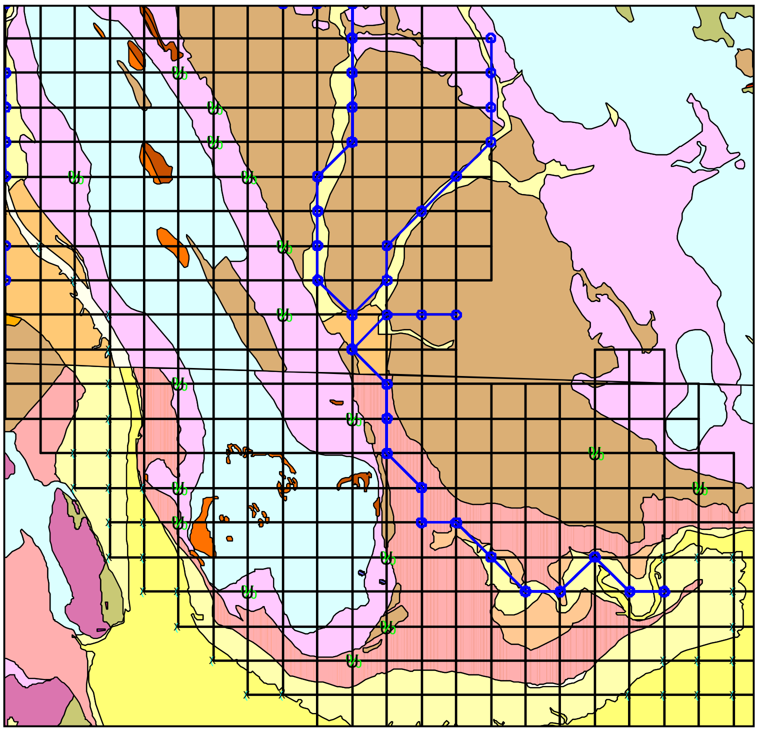


Figure 36 Location of model springs (green squares)

6.8 HYDRAULIC PROPERTIES

6.8.1 Hydraulic conductivity of the superficial deposits

The specification of the hydraulic conductivity of the Quaternary deposits is based on the domains shown in Figure 5 and described in Table 1. Appropriate hydraulic conductivity values have been specified according to the type of the sediment. Table 11 has been used as a guide in this parameterisation. Using this table the Quaternary domains have been assigned the values shown in Table 12. Where the Quaternary domain has been described as being horizontally stratified or bedded, the vertical hydraulic conductivity is specified as one-tenth of that of the horizontal hydraulic conductivity. Otherwise, the domain is considered isotropic.

Table 11 Range of values of hydraulic conductivity after Sanders (1998)

Sediment	**Hydraulic conductivity ($mday^{-1}$)**		
Clay	10^{-6}	to	10^{-3}
Silt, sandy silts	10^{-3}	to	10^{-1}
Silty sands, fine sands	10^{-2}	to	10^{0}
Well sorted sands, glacial outwash	10^{0}	to	10^{2}
Well sorted gravel	10^{1}	to	10^{3}

Table 12 Horizontal (K_h) and vertical (K_v) hydraulic conductivity values assigned to Quaternary domains

Domain	**K_h ($mday^{-1}$)**	**K_v ($mday^{-1}$)**
1	10	10
2	0.001	0.0001
3	0.01	0.001
4	1	1
5	0.001	0.0001
6	1	1
7	1	1
8	1	1
9	1	0.1
10	0.001	0.0001
11	0.001	0.0001
12	0.001	0.0001
13	0.01	0.001

6.8.2 Transmissivity of the sandstone and breccia

The distribution of transmissivity in the model is simple due to the limited amount of data available. The transmissivity distribution within the model is based on the definition of the six zones shown in Figure 37. Except for Zone 6, each is located either to the left or right of the mapped boundary between the Doweel Breccia and Locharbriggs Sandstone. The zones are split along this boundary because the Locharbriggs Sandstone is generally considered to be of lower transmissivity than the Doweel Breccia formation. This allows simple sensitivity analyses to be performed to investigate possible broad hydrogeological differences between the two lithologies. The zones have been defined on the following basis, though it should be borne in mind that these are based on limited data.

- Zone 1: To represent possibly higher transmissivity in the Terregles area as part of a sensitivity analysis
- Zone 2: To represent the area in the north over the Locharbriggs Sandstone
- Zone 3: To represent possible low transmissivity in the ICI/Dupont area as part of a sensitivity analysis
- Zone 4: Zone over the Doweel Breccia
- Zone 5: Zone over the Locharbriggs Sandstone
- Zone 6: Zone to represent possible lower transmissivity in the lower Lochar Water catchment and beneath marine tidal deposits. Also covers the aquifer offshore.

In the first model simulation a simple distribution is defined in which all zones are set to 300 m^2day^{-1} except for zones 6, which is defined as 50 m^2day^{-1}. Whilst, there is certainly significant variability in the transmissivity values estimated from pumping tests, it is difficult to convert these discrete data points into regional zones of transmissivity. For example, whilst there are transmissivity values in the area of Terregles of up to 4000 m^2 day^{-1}, it is difficult to construe this as being indicative to the bulk aquifer transmissivity in this area. Rather, the high transmissivity value at Terregles No.1 is indicative of the characteristics of the individual borehole, which intersects flowing fractures.

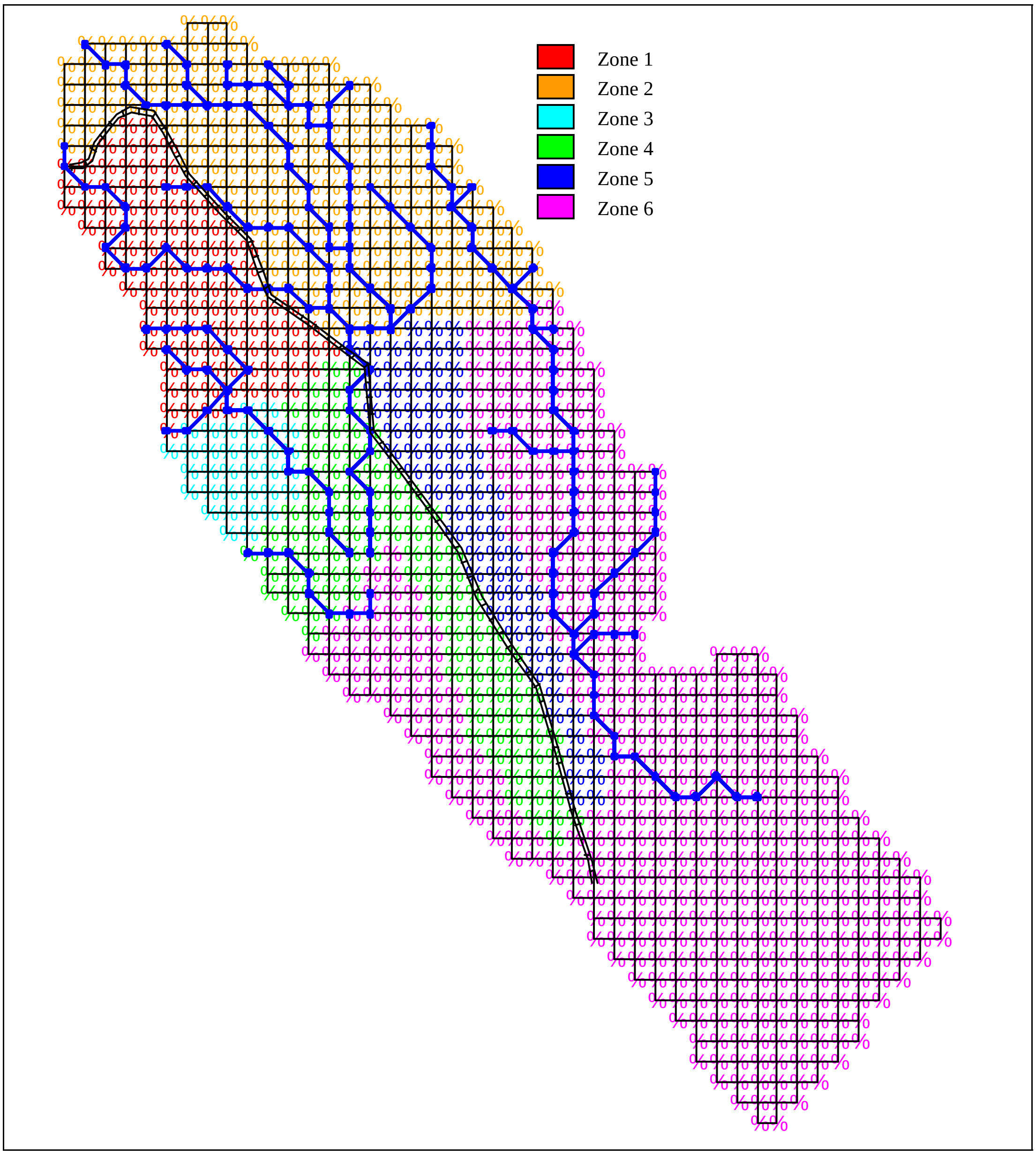


Figure 37 Model transmissivity zones

6.9 STEADY-STATE SIMULATIONS

6.9.1 Abstraction

As discussed in Section 5.2.5, with the exception of the Scottish Water abstraction boreholes groundwater pumping rates are generally not recorded within the basin. The rates listed in Table 9 are those used in the model.

6.9.2 Recharge

Steady-state recharge is calculated using the distributed recharge model discussed in Section 4. This performs a daily soil moisture balance calculation for the period 1970 to 2003. The mean recharge rate is calculated using the full historic period.

6.9.3 River flows onto the basin

In order to run the steady-state model an estimate of the long-term mean baseflow in all the rivers must be made as they enter the basin. This is difficult because of the limited amount of data and consequently a number of assumptions have been made in deriving this data set. The flow data collected on the 14th and 15th July 2003 are used to estimated the mean baseflows onto the basin. This procedure is undertaken as follows:

1. The flow records at the gauging stations listed in Table 13 enable mean total flow and baseflow to be calculated. These flows are also listed in the table.
2. At those sites where the flow was measured during mid-July 2003, the discharge can be expressed as a percentage of the mean. This is listed in Table 14.

Table 13 Flows at temporary gauging locations as percentage of mean

Gauging station	Total flow in mid-July 2003 as % of mean	Baseflow in mid-July 2003 as % of mean
Kirkblane	13.4	22.9
Jericho	17.4	36.5
Clunie Bridge	40.6	60.0
Wath Burn	6.0	10.0
Boghead Bridge	8.0	12.9
Average	**17.1**	**28.5**
Average of non-extreme values	**12.9**	**24.1**

3. Assume that at those locations on the edge of the basin where flow was measured during mid-July 2003 that this flow is equivalent to 15% of the mean total flow at that point.
4. Table 14 shows the calculated baseflow as a percentage of the total flow for the gauging stations with a daily flow record and spot gauging during mid-July 2003.

Table 14 Baseflows in mid-July 2003 at temporary gauging stations as percentage of total flow

Gauging station	**Total flow on 14-15 July 2003 (Ml day^{-1})**	**Calculated baseflow on 14-15 July 2003 (Ml day^{-1})**	**Baseflow as % of total flow on 14/15 July 2003 (Ml day^{-1})**
Kirkblane	25.5	24	94
Jericho	7.3	7.3	100
Clunie Bridge	14.2	12	85
Wath Burn	1.2	0.9	75
Boghead Bridge	1.0	0.9	90
Average			**89**

5. Assume that 90% of the total flow on 14/15th July 2003 is baseflow
6. Calculate the mean flow at the gauging points on the edge of the basin using the assumptions in points 3 and 5, that is,

$$\overline{Q}_{\text{Baseflow}} = \overbrace{\underbrace{Q^{\text{July}-03}_{\text{Total flow}} \times \frac{100}{15}}_{\text{Mean total flow}} \times 0.9}^{\text{Mean base flow}}$$

where,

$\overline{Q}_{\text{Baseflow}}$ is the long-term mean baseflow,

$Q^{\text{July}-03}_{\text{Total flow}}$ is the measured flow on the 14th or 15th July 2003

These mean flows are listed in Table 15.

Table 15 Estimated mean baseflows at spot gauging location on basin boundary

Spot gauging location	**Easting**	**Northing**	**Estimated mean baseflow (Ml day^{-1})**
Glengaber Burn	290400	581900	7.2
Laggan Burn	290600	584700	10.8
Duncow Burn	296800	583700	1.2
Park Burn	298800	582800	0.6
Side Burn	301600	579600	1.3
Mill Cleuch at West Roucan Farm	302100	578600	3.8

The mean baseflows for the remaining rivers as they cross the basin boundary are estimated by similar crude comparisons of the spot gauging data. These are listed in Table 16. From this crude analysis the complete data set specifying the mean flows specified in the model rivers on the edge of the basin can be collated. This is taken from Tables 13, 14 and 15. These inflows at the upstream ends of the model rivers are shown in Figure 38.

Table 16 Estimated mean baseflows at remaining river locations on basin boundary

Spot gauging location	Easting	Northing	Estimated mean baseflow (Ml day^{-1})
Crooks Pow	294500	572700	5
Terregles Burn	292000	577800	2
Tributary of Terregles Burn	292000	578100	2
Cluden at Hall Hill Farm	290800	579900	180
Amisfield Burn	299700	581300	3
Tributary of Wath Burn	304000	570200	3

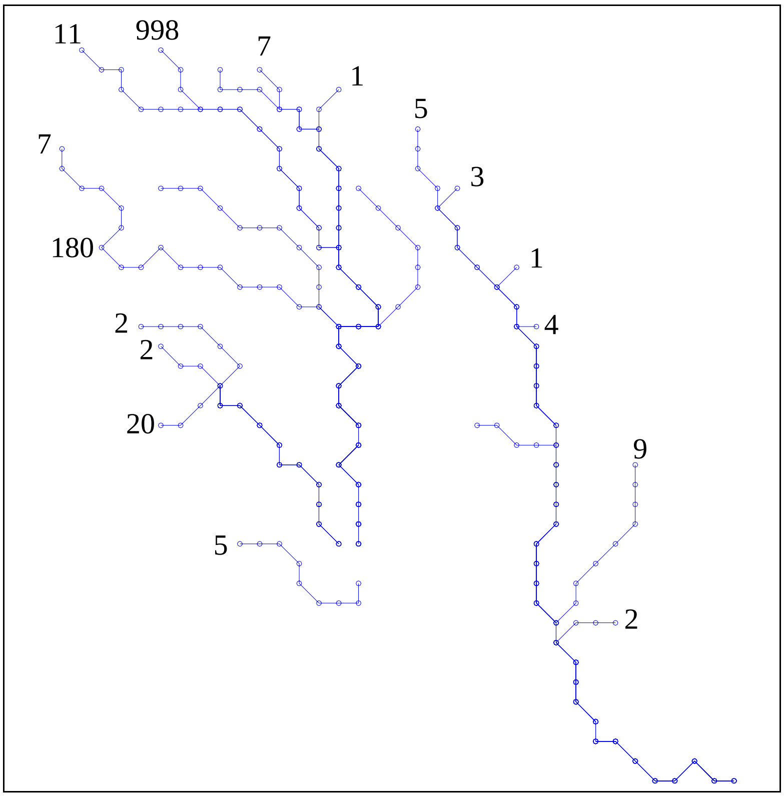


Figure 38 Specified baseflow inputs at upstream ends of rivers in steady-state model

6.9.4 Comparison of model and observed data

GROUNDWATER HEAD CONTOURS

The simulated steady-state groundwater head contours for the sandstone and breccia layer (layer 2 or the bottom layer) of the model are shown in Figure 39. The groundwater head contours from the hydrogeological map, shown in Figure 9, and those presented by MacDonald et al. (2003), shown in Figure 10, which are used for comparison, will henceforth be referred to as the “inferred” contours or “inferred” levels. In general the shape of the simulated contours is similar to the inferred contours. However, there are areas of the model where the modelled groundwater heads differ significantly from the inferred levels. The features of the comparison between these two sets of contours are:

- The pattern of groundwater head contours produced by the model broadly has the same shape as those inferred from the observation well data. The influence of the

River Nith, Cluden Water, Lochar Water and Cargen Water is apparent, though the impact of the rivers is more pronounced in the model than in the inferred contours. This is expected as the inferred contours are based on few observation points.

- Simulated groundwater heads are significantly higher than the inferred levels in the north of the model. However, the head distribution towards the top of the basin is unknown as groundwater levels have not been measured in this area.
- In conjunction with the inspection of the modelled heads, a consideration of the measured heads in the observation boreholes and an examination of the elevation of springs and drains on the 1:10 000 Ordnance Survey map and DTM suggests that the position of the inferred 5 m contour line is possibly incorrect. This is proposed because:
    - Only the observation borehole at Workington brewery has a measured head less than 5 m OD.
    - Springs and drains issuing from the high ground to the east of the Nith are located above 5 m OD.
    - The observed groundwater heads of 7.5 m, 7.6 m and 12.2 m at Redbank, Kingholm and Well Cottage, respectively, are higher than at the Workington Brewery observation borehole. These higher heads may occur because the observation boreholes are drilled through low permeability inter-tidal mudflat deposits that limit the connection between the River Nith and the aquifer. It is conceivable, therefore, that there a groundwater low could exist in the area of Workington Brewery, where the River Nith may be better connected to the bedrock aquifer. This conceptual model of the interaction between the Nith and the aquifer is included in the model and consequently, the simulated contours show a low in this area.
- Simulated heads are approximately 15 m too high at Longbridgemuir. The recharge model simulates infiltration to the aquifer through the sandy Quaternary deposits at the edge of the basin in this area. The combination of this recharge and the low transmissivity specified in this area of 50 m^2 day^{-1} produces a local groundwater high, which is not observed.

Groundwater head contours are not plotted in the Quaternary deposits (Layer 1) because a significant proportion of this layer dewaters. This hinders the production of clear contours. The nodes which the model simulates as being dry are shown in Figure 40. These are located on the high ground around the edge of the basin, in the north west of the model and along the NNW-SSE trending ridge between the Nith and the Lochar Water.

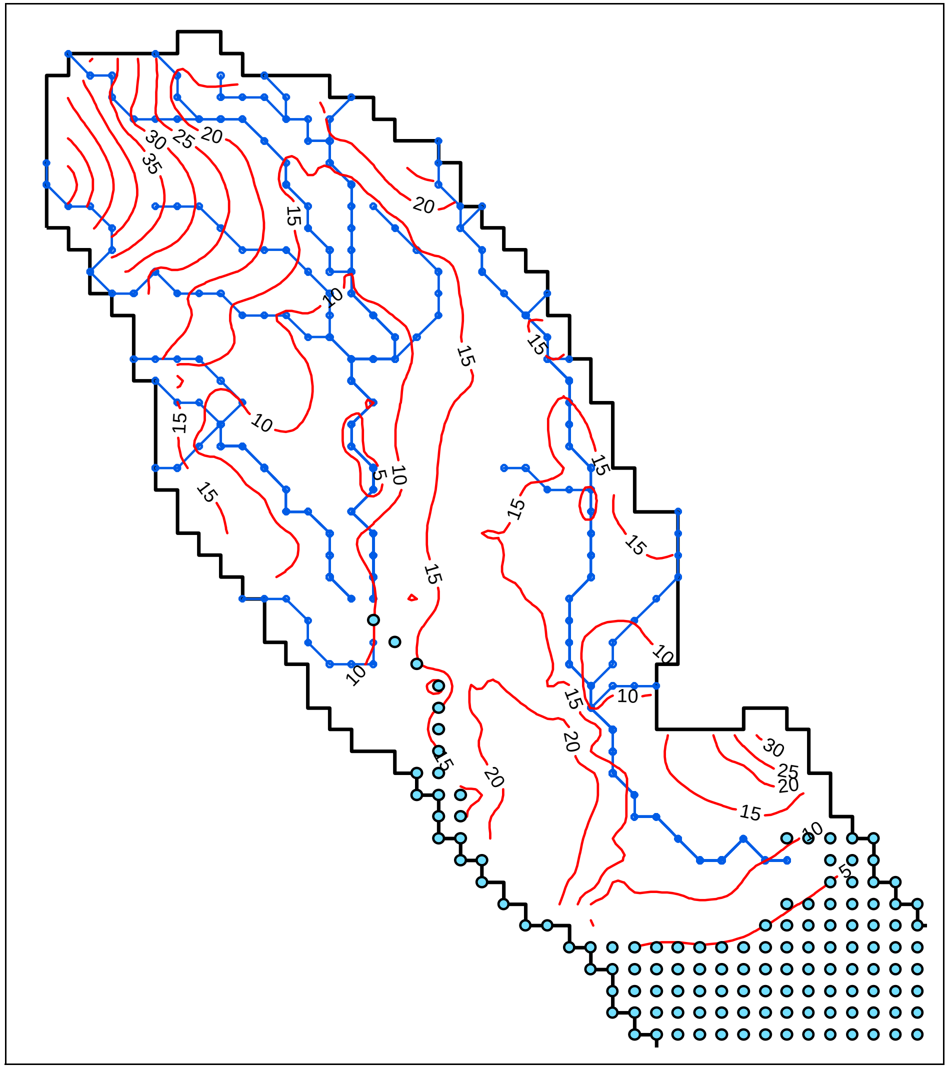


Figure 39 Simulated steady-state contours in Permo-Triassic aquifer (layer 2) of Dumfries basin

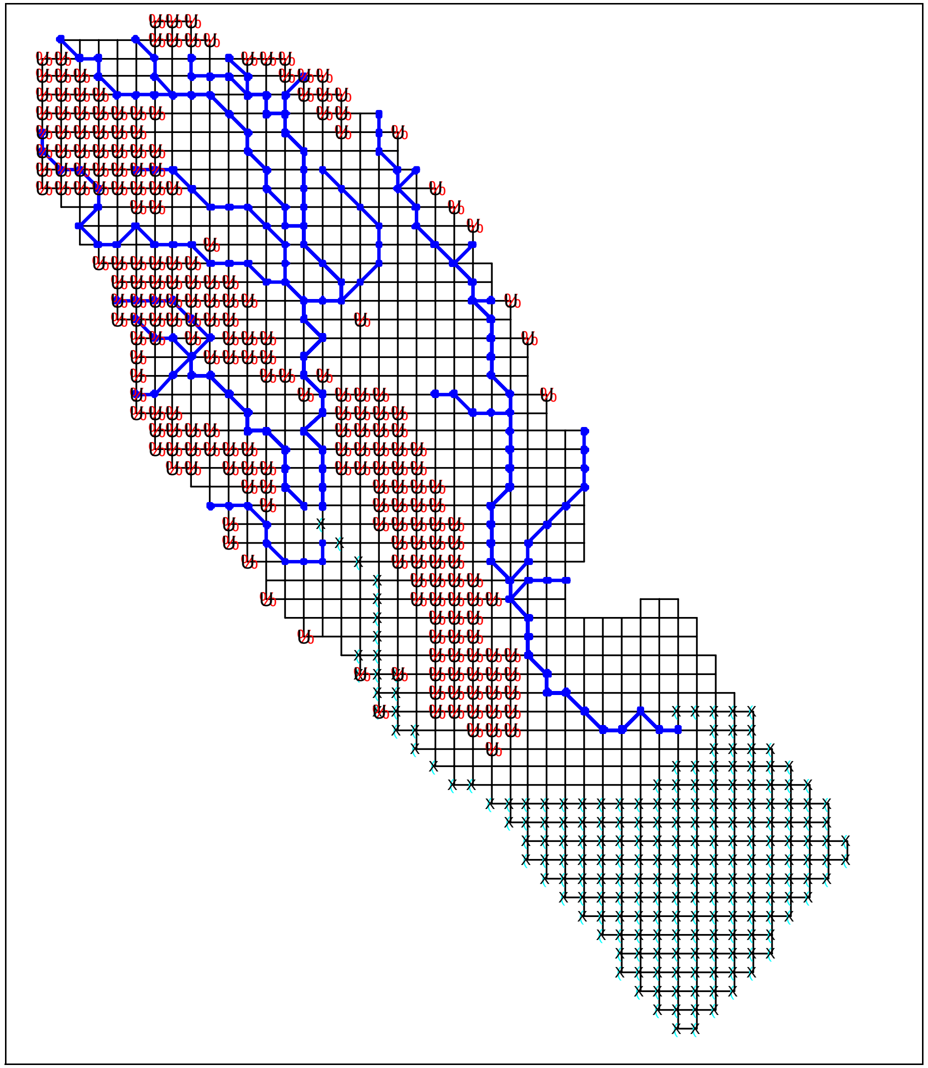


Figure 40 Model nodes in the top layer (layer 1) that dewater (red squares)

GROUNDWATER HEAD PROFILES

Groundwater head profiles for both layers of the model are plotted along five sections. These are shown in Figure 41. The sections were chosen to both cross and run parallel to the axis of the basin and to be located near to observed groundwater heads. The profiles along the sections are plotted in Figures 42 and 43. In general the agreement between the simulated profiles and the observed heads is relatively close, considering that little model refinement has been undertaken. However, there is insufficient observed data to make any substantial claims regarding the adequacy of the model.

The comparison between the simulated and measured heads at the observation wells is presented in Table 17. As might be expected at some of the wells there is close agreement and at some other wells significant differences occur. The following points are made regarding this comparison:

- The simulated heads are significantly (>8 m) higher than those measured at the Terregles No.1, Terregles Obs 1 and Terregles Obs 2 boreholes. A comparison of these levels with the elevations of the nearby rivers indicates that these levels may not be indicative of a real rest water level. The levels are also plotted on the Section 1 profile and show a groundwater depression significantly below the rivers and the groundwater level at the neighbouring Terregeles Fish Farm House. This appears erroneous given that there is no abstraction in this locality.
- There is a high variability in the measured heads at the ICI boreholes, with low values of 1.8 to 3.3 OD and high values greater than 8.5 m OD. These could possibility be pumped and non-pumped levels, respectively. Consequently, a reasonable estimate of a rest water level in this region could be 10 m OD.
- The simulated head at Longbridgemuir is 17.1 m greater than that observed. The combination of recharge and low transmissivity specified in this area result in a high simulated groundwater level.
- The difference in head at the remaining observation wells is adequate given the homogeneity of the model and the inability to justify significant further model refinement.

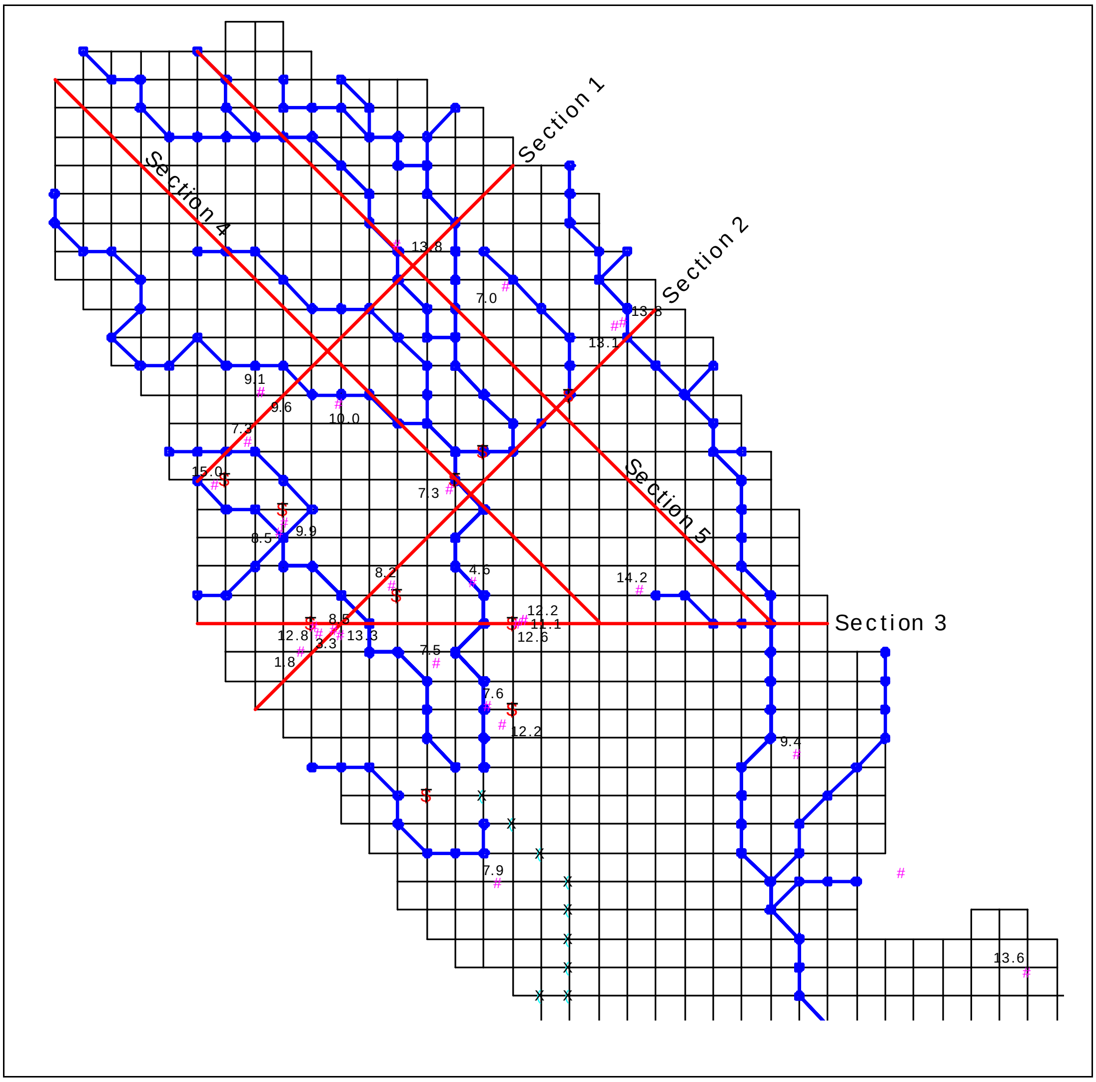
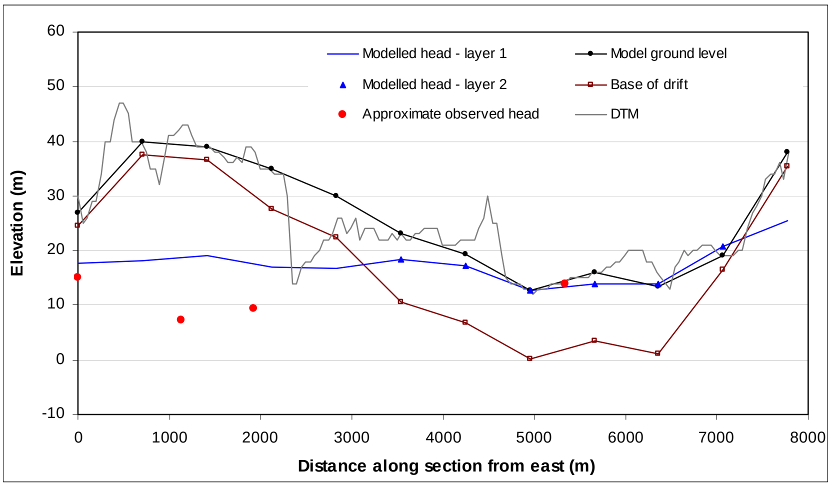
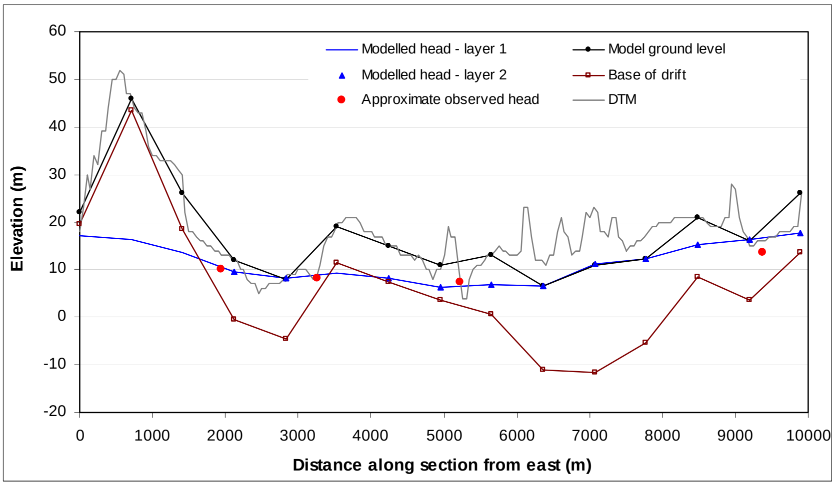


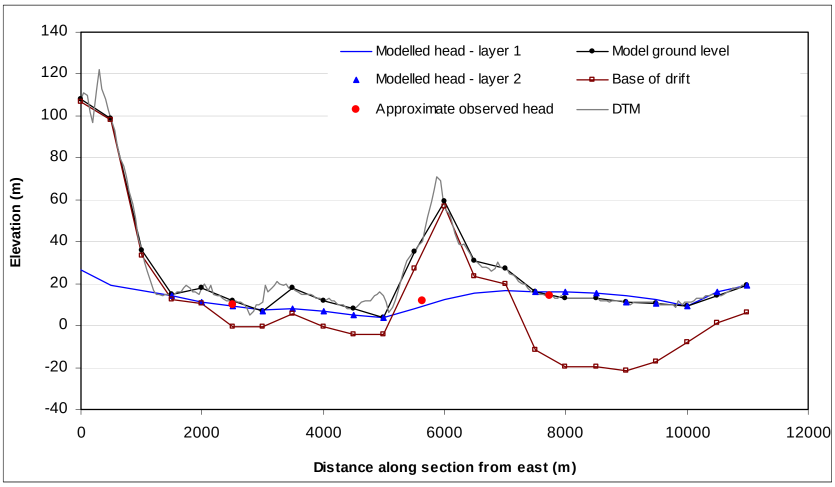
Figure 41 Model sections



(a) Section 1

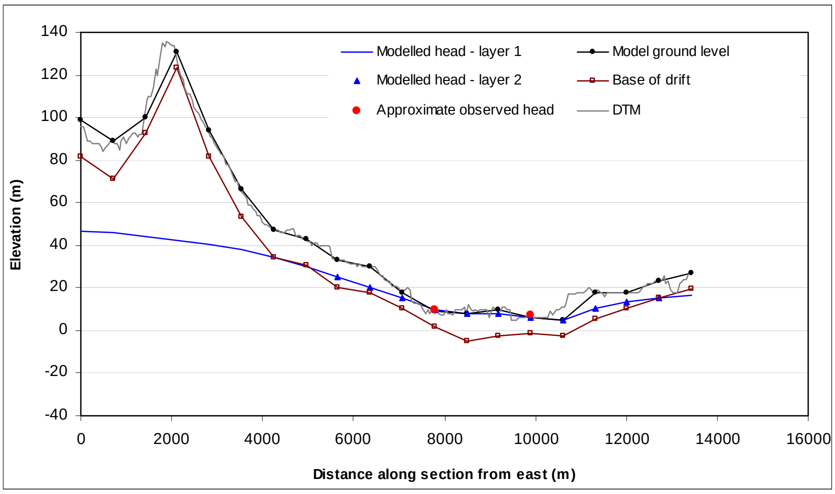


(b) Section 2

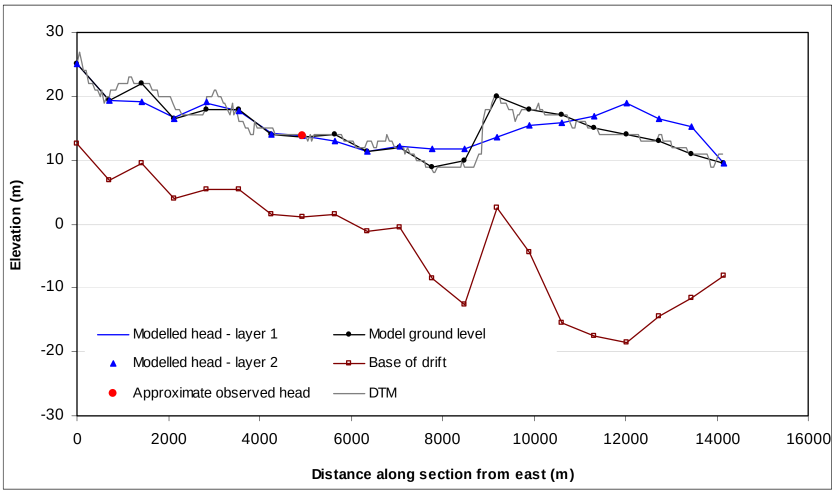


(c) Section 3

Figure 42 Simulated steady-state groundwater head profiles along model Sections 1 to 3



(d) Section 4



(e) Section 5

Figure 43 Simulated steady-state groundwater head profiles along model Sections 4 and 5

Table 17 Comparison between measured and simulated groundwater levels at observation boreholes

Location	Easting	Northing	Observed	Model	Difference	Comments
Carnation No 1	296910	577330	7.3	5.9	-1.4	
Dundas Chem	300230	575580	14.2	16.0	1.8	
Golf Course	295890	575670	8.2	8.3	0.1	
Greenmerse	297760	570480	7.9	12.1	4.3	
Holywood Fish Fm	297890	580900	7.0	13.4	6.4	
Holywood Pro BH	296000	581600	13.8	13.8	0.0	
ICI BH 401	294900	574900	8.5	9.2	0.7	High variability at ICI. Pumped levels? Estimated as 10m OD.
ICI BH 403	295000	574800	13.3	9.2	-4.1	High variability at ICI. Pumped levels? Estimated as 10m OD.
ICI BH 404	294550	574950	3.3	10.9	7.6	High variability at ICI. Pumped levels? Estimated as 10m OD.
ICI BH 501	294300	574500	1.8	13.0	11.2	High variability at ICI. Pumped levels? Estimated as 10m OD.
ICI BH No 2	294620	574830	12.8	10.9	-1.9	High variability at ICI. Pumped levels? Estimated as 10m OD.
Kingholm Mill	297580	573570	7.6	10.7	3.1	
Larchfield Expl BH	298200	575050	11.1	8.6	-2.5	
Larchfield Obs BH	298200	575050	12.2	8.6	-3.6	
Larchfield Pro BH	298100	575000	12.6	8.6	-4.0	
Locharbriggs	299800	580200	13.1	16.2	3.1	
Locharbriggs	299950	580250	13.8	16.2	2.4	
Newbridge	294990	578850	10.0	11.0	1.0	
Redbank Obs BH	296670	574320	7.5	8.5	1.0	
Terregles FF House B	292800	577430	15.0	9.0	-6.0	
Terregles No 1	293620	579050	9.1	19.2	10.1	Suspect data. Significantly below nearby river levels. Pumped level?
Terregles Obs 1	293620	579050	9.6	19.2	9.6	Suspect data. Significantly below nearby river levels. Pumped level?
Terregles Obs 2	293390	578180	7.3	16.1	8.8	Suspect data. Significantly below nearby river levels. Pumped level?
Terregles Pro BH	294020	576770	9.9	7.0	-2.9	
The Manse	293930	576590	8.5	7.1	-1.4	
Well Cottage	297840	573250	12.2	11.0	-1.2	
Workington Brewery	297320	575730	4.6	4.1	-0.5	
Racks Moss	302970	572730	9.4	11.2	1.8	
Longbridgemuir	306990	568910	13.6	30.7	17.1	

RIVER FLOW ACCRETION PROFILES

Simulated steady-state river accretion profiles are plotted for the major rivers in the model in Figures 44 and 45. These graphs show the groundwater head, river stage and river-bed elevation, plotted against the left-hand axis, and the simulated and estimated (or observed) river baseflow plotted against the right-hand axis. The following points summarise the behaviour simulated by the model rivers as shown in these figures:

- The River Nith gains baseflow along its full length except at one model node.
- The Nith gains 87 Ml day-1 above the Cluden Water and 17 Ml day-1 below this tributary.
- The simulated mean baseflow at the downstream end of the modelled Nith is 1311 Ml day^{-1}.
- The reduction of the river-bed permeability from 1 m day^{-1} to 10^{-3} m day^{-1} results in a rise in groundwater head of approximately 5 m at its downstream end.
- The Cluden Water gains approximately 26 Ml day^{-1} along its length.
- The model does not provide enough baseflow to the Lochar Water. The estimated rate of increase in baseflow along the Lochar Water is approximately four times greater than the simulated results. The model could be improved by transferring the spring flow from the high ground to the west into the Lochar. However, this would still not produce a close match. The difference between the accretion profiles is attributed to the role of the peat deposits and their representation in both the recharge and groundwater flow models. Further development of the conceptual model and numerical representation of this area is required to improve the model.
- The smaller rivers, the Cargen Water, Crooks Pow and Wath Burn all gain water from the aquifer along their course.

In addition to the accretion profiles shown in Figures 44 and 45, the baseflow at each node of the model rivers is shown in Figure 46.

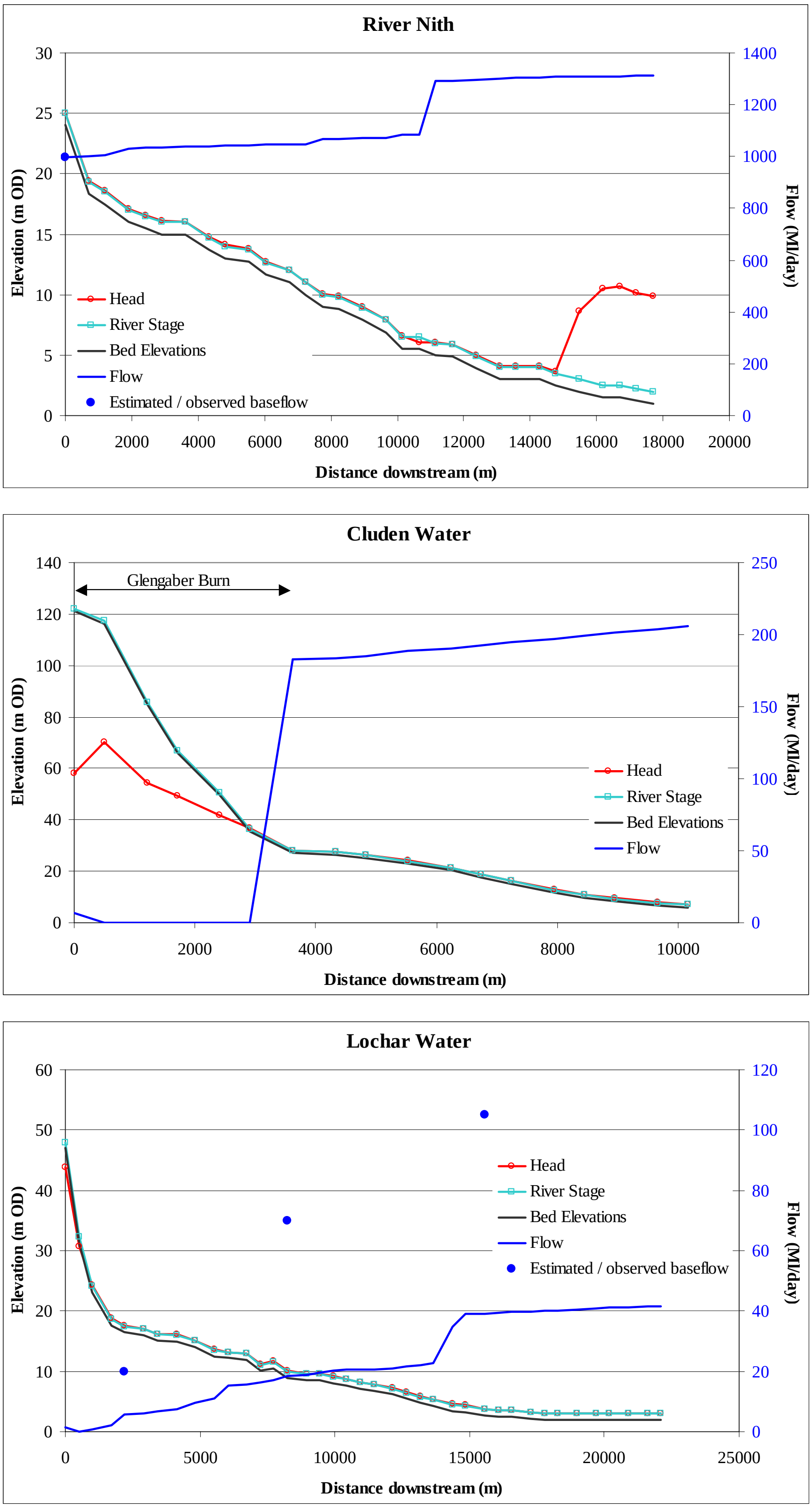


Figure 44 Simulated steady-state baseflow accretion profiles along River Nith, Cluden Water and Lochar Water

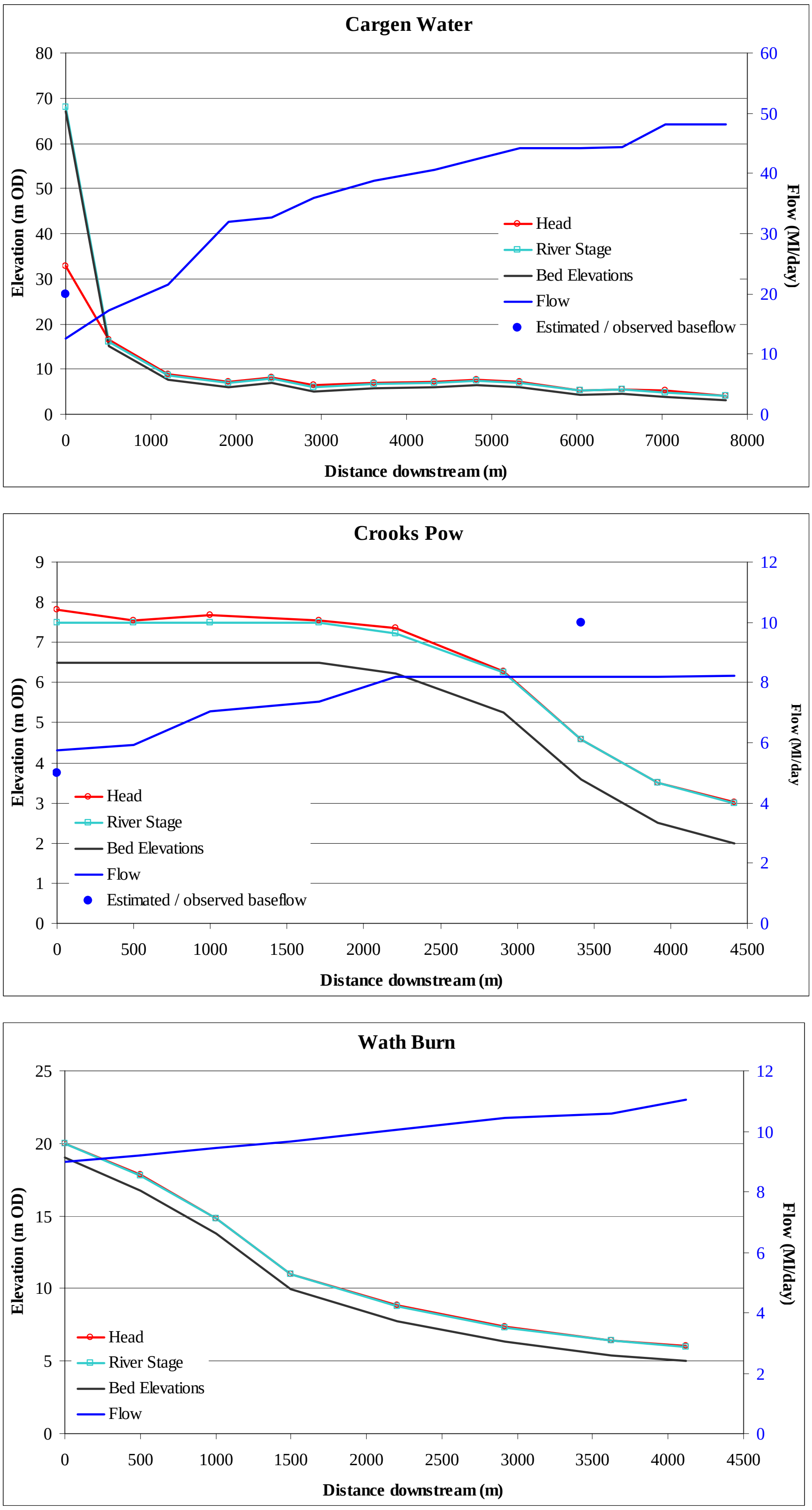


Figure 45 Simulated steady-state baseflow accretion profiles along Cargen Water, Crooks Pow and Wath Burn

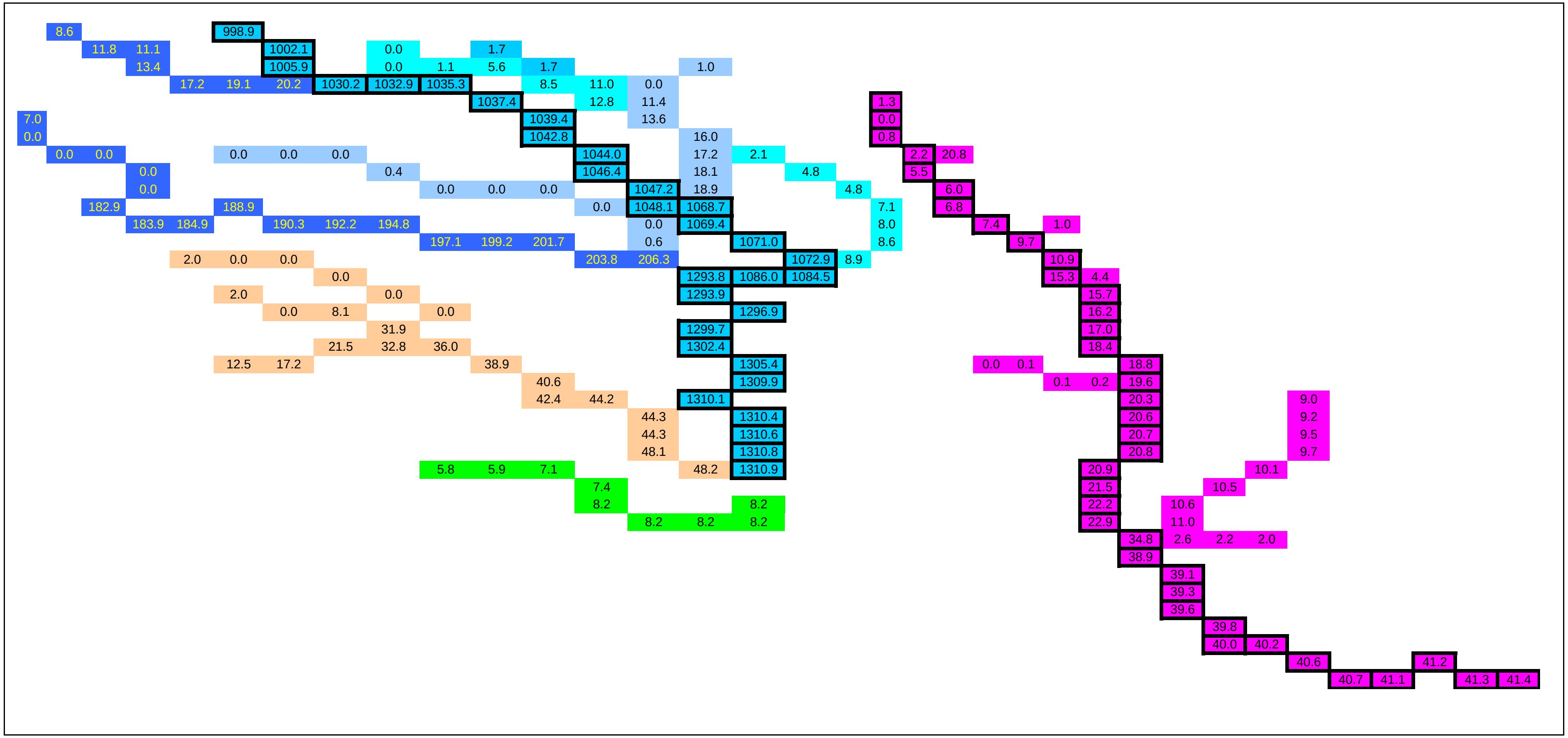


Figure 46 Schematic map of simulated steady-state baseflow at each node of the model rivers

Steady-state model flow balance

The global model flow balance for the steady-state simulation is shown in Table 18. The discharge into the rivers of 21 Ml day^{-1} at the two major fish farms is split between 8 Ml day^{-1} into the Cargen Water and 13 Ml day^{-1} into the Nith. If these amounts are subtracted from the gain in baseflow along these rivers then the groundwater flow balance can be expressed in percentage terms as the following:

- 17.1% of the recharge is abstracted from boreholes.
- 1.7 % of the recharge becomes baseflow in the Crooks Pow.
- 8.4 % of the recharge becomes baseflow in the Cargen Water.
- 48.7 % of the recharge becomes baseflow in the River Nith.
- 9.1 % of the recharge becomes baseflow in the Lochar Water.
- 2.9 % of the recharge discharges into the Solway Firth as groundwater flow.
- 12.1 % of the recharge becomes spring flow.

Table 18 Steady-state model global flow balance in Ml day^{-1}

INFLOWS (Ml day^{-1})		**OUTFLOWS (Ml day^{-1})**	
Recharge	192.6	Abstraction	32.9
River baseflow onto aquifer		River baseflow	
Crooks Pow	5.0	Crooks Pow	8.2
Cargen Water	24.0	Cargen Water	48.2
Nith	1204.0	Nith	1310.8
Lochar Water	24.0	Lochar Water	41.5
Discharge from fish farms into rivers	21.0	Groundwater leakage into Solway Firth	5.6
		Springs flow at edge of Caerlaverock ridge	22.3
		Spring flows at Longbridgemuir	1.1
Total	**1470.6**		**1470.6**

6.10 DYNAMIC BALANCE SIMULATION

A dynamic balance simulation was performed in order to make a comparison between the observed and modelled time-variant response of the aquifer and rivers. A dynamic balance simulation is performed by using monthly average inputs over a cycle of a number of years. If enough years are simulated, the computed heads will eventually follow a cyclical pattern that repeats itself. Although storage changes occur between months, the net change over a year is zero.

Groundwater levels in the unpumped Holywood Production BH, and in the Newbridge and Redbank observation boreholes have been measured for different periods between 1982 and the present. Records of the river flows at the three permanent gauging stations in the basin have been obtained from the end of the 1950's. This dynamic balance simulation makes use of this data to investigate, in a very limited way, the accuracy of the model when run in time-variant mode.

Recharge inputs for the dynamic balance simulation are calculated by the recharge model, described in Section 4. Groundwater abstraction rates are the same as those defined in the steady-state model are constant.

6.10.1 Aquifer storage parameters

Uniform distributions of specific storage and specific yield are assigned to the model layers. Both model layers are assigned a specific yield of 0.1. The specific storage in the top model layer is 10^{-5} m^{-1} and it is 10^{-7} m^{-1} in the lower layer.

6.10.2 River flows onto the basin

In order to represent the fluctuation in the amount of river baseflow coming onto the basin, the mean monthly inputs shown in Figure 38 are factored according to the month. The variation in the mean monthly baseflow inputs is estimated by examining the variation in the monthly baseflows calculated from the long-term records at Fiddlers Ford and Friars Carse. Monthly baseflow inputs peak in January and are approximately 45% higher than the long-term mean baseflow. Mean monthly baseflows are at their lowest during July and are only 37% of the long-term mean.

6.10.3 Comparison of model and observed data

GROUNDWATER HEAD HYDROGRAPHS

Simulated and observed groundwater head hydrographs are shown in Figure 47 for the three observation boreholes with a period of historic record. At Newbridge and Holywood, which are close to the Cluden Water and Nith, respectively the simulated amplitude of the seasonal head variation are significantly smaller than those observed. At Newbridge the simulated and observed head fluctuations are approximately 0.25 m and 2 m, respectively. At Holywood the simulated and observed head fluctuations are approximately 0.06 m and 1 m, respectively.

The model is more accurate at Redbank and the simulated and observed head fluctuations are comparable. The model produces head variations over an annual cycle of 2 m which are approximately double that in the observation well.

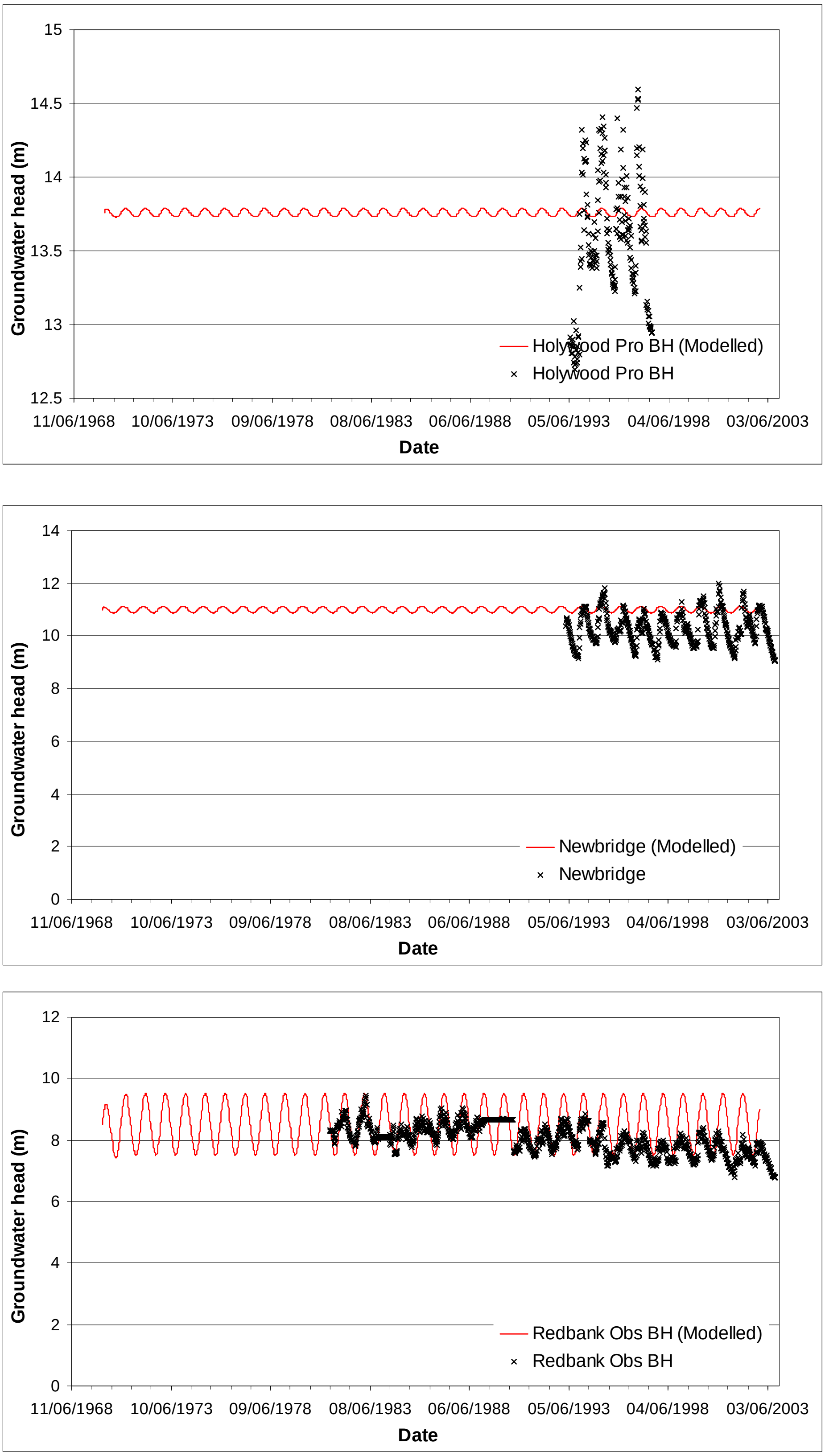


Figure 47 Simulated (dynamic balance) and observed groundwater head hydrographs at observation boreholes with historic record

6.11 HISTORIC SIMULATION

Whilst there is insufficient observed data to begin to determine to the adequacy of the model, it was considered that running a time-variant historical simulation would be beneficial. Whilst a comparison of the model can only be made with three observed groundwater head records and three river baseflow records for the simulation period, it is useful to examine what the model predicts for high and low groundwater levels and river baseflows, and how these fluctuate over time.

The historic simulation simulates the period from the beginning of 1970 to the end of 2002. The initial conditions for the model are calculated by running a steady-state simulation in which only those abstraction wells that were pumping before 1970 are included. The pumping rates included in the model vary in the same manner as in the time-variant water balance discussed in Section 5.2.5.

6.11.1 River flows onto the basin

Except at the upstream ends of the Nith and Cluden Water, the flow of water onto the basin in the rivers is the same as that included in the dynamic balance simulation. At Friars Carse the historic monthly baseflow record forms a direct input to the model. At the upstream end of the Cluden Water, the historic monthly baseflow record at Fiddlers Ford is multiplied by $9/14$, to define the inflow at this point. This factor expresses the rough estimate of the difference in baseflow between Fiddlers Ford and the point at which the Cluden Water crosses the basin boundary.

6.11.2 Comparison of model and observed data

GROUNDWATER HEAD CONTOURS

The lowest and highest flows on the River Nith between 1970 and 2002 are recorded during August 1984 and December 1986, respectively. Though this may not be strictly true, these dates are taken as being analogous to lowest and highest groundwater levels. Simulated groundwater level contours are plotted (for layer 2 of the model) in Figures 48 and 49 at these times. As there is no historic data with which to compare these contours it is only possible to make a few simple observations:

- During dry conditions, the contours (Figure 48) show that the model predicts that the rivers gain water from the aquifer along generally all but the upstream ends of their channels.
- The model indicates that the regional groundwater head minimum is controlled by the Nith and is approximately 5 m OD.
- During wet conditions the influence of the rivers on the shape of the groundwater contours is clearer.
- The difference in groundwater head in the north-west of the model between dry and wet conditions is approximately 40 m.
- The 5 m, 10 m and 15 m contours cross the Cargen Water, Cluden Water and Nith at approximately the same positions in Figures 48 and 49.

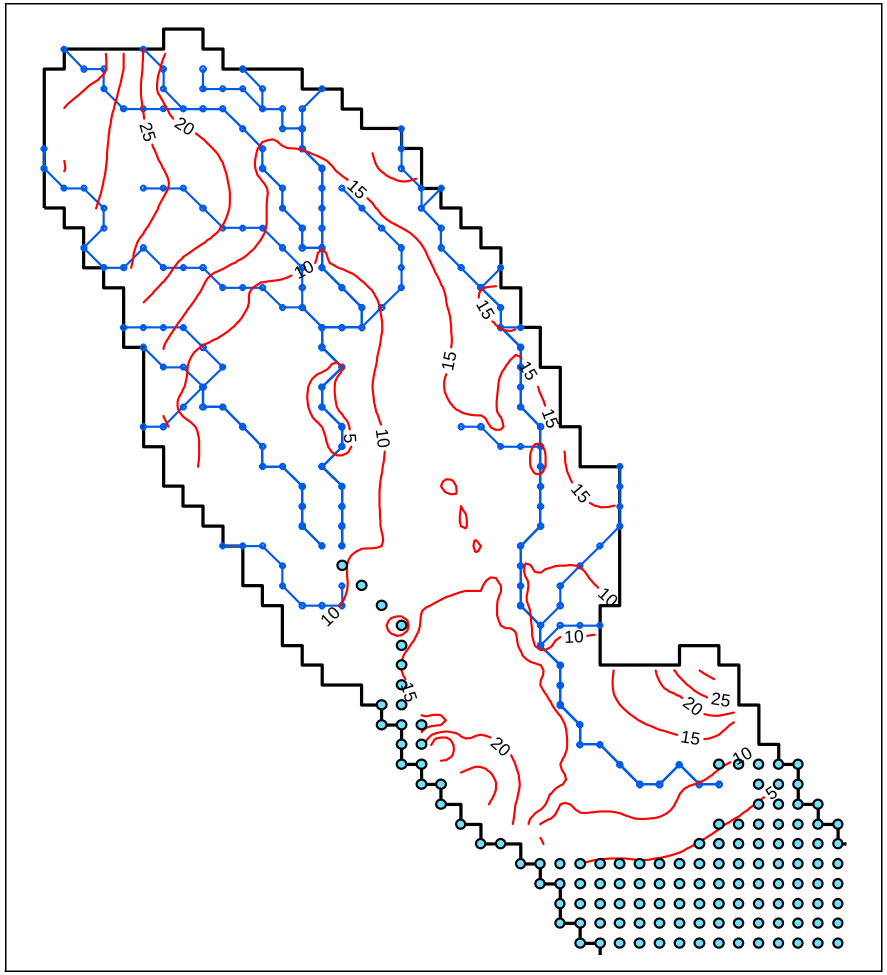


Figure 48 Simulated contours at the end of August 1984 (dry conditions)

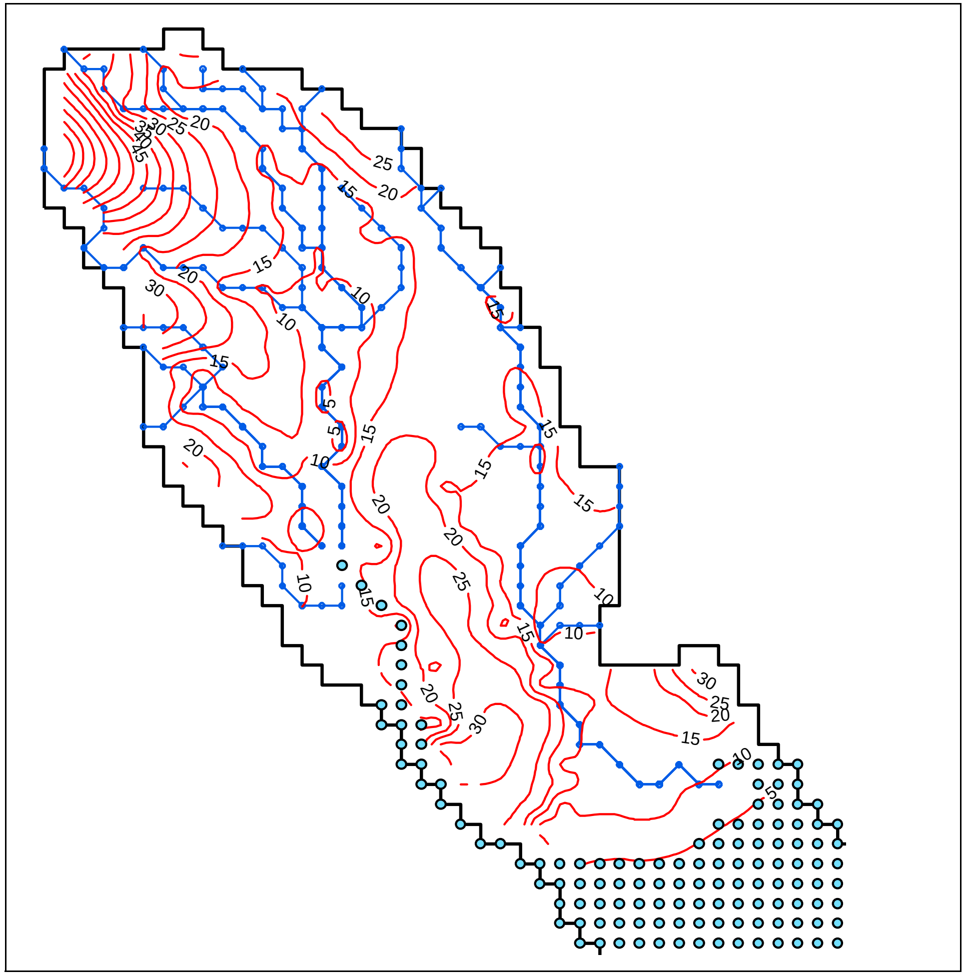


Figure 49 Simulated contours at the end of December 1986 (wet conditions)

GROUNDWATER HEAD HYDROGRAPHS

Simulated and observed groundwater head hydrographs are shown in Figure 50 for the three observation boreholes with a period of historic record. As in the dynamic balance simulation, the simulated amplitude of the seasonal head variation is significantly smaller than those observed at Newbridge and Holywood.

Again as with the dynamic balance run, the model is more accurate at Redbank and the simulated and observed head fluctuations are comparable. The model produces head variations over an annual cycle of 2 m which are approximately double that in the observation well. Whilst it is difficult to compare the timings of the variation in head at Holywood and Newbridge, it is possible to make a visual comparison at Redbank. This indicates that there is reasonably close agreement between the timings of the minima and maxima of the two hydrographs. Furthermore, it is possible to claim that corresponding peaks and troughs can be identified within individual annual cycles, for example during the winters of 1985 and 2002, at which times multiple peaks in the historic record can also be identified in the simulated hydrograph. This may increase confidence in the recharge calculation, however, this is a somewhat bold claim.

To improve the accuracy of the model it is necessary to examine in more detail the storage characteristics of the Quaternary deposits and bedrock aquifer and the interaction between the two in addition to the construction of the observation boreholes and the portion of the aquifer which these are sample. However, further model improvements are dependent of the collection of more data. In particular, monitoring of the seasonal variation in groundwater levels across the whole basin is a priority.

RIVER FLOW HYDROGRAPHS

River flow hydrographs for the three permanent gauging stations in the basin and at Whitesands are shown in Figure 51. The modelled and observed flows are similar at Friars Carse because this gauging station is on the edge of the basin. As stated previously, the record at Friars Carse forms a direct input to the model river at this point. The difference between the peaks and troughs of the two hydrographs is because the model takes mean monthly baseflow as its input, whereas the observed hydrograph is a plot of the daily record.

The simulated mean baseflows for the historic period are listed in Table 19. At Fiddlers Ford the simulated mean baseflow is approximately 100 Ml day^{-1} less than the observed value. This is probably due to a poor estimate of the flow onto the basin in the Cluden Water, which may be underestimated at 180 Ml day^{-1}. The model does not simulate enough baseflow in the Lochar Water at Kirkblane. As discussed previously, this is likely to be because the effect of the peat deposits has not been considered in detail and because drainage from the high ground to the west has not been routed to the river. The model calculates the baseflow at Whitesands to be 1258 Ml day^{-1}, though there is insufficient measured data to estimate if this is accurate.

Table 19 Observed and simulated mean river baseflows from the historic time-variant simulation

Gauging point	Observed mean baseflow (Ml day^{-1})	Simulated mean baseflow (Ml day^{-1})
Fiddlers Ford	280	184
Friars Carse	998	998
Whitesands	?	1258
Kirkblane	105	38

RIVER FLOW ACCRETION PROFILES

River flow accretion profiles are plotted for the River Nith and for the Lochar Water at the end of August 1984 (low flow conditions) and December 1986 (high flow conditions) in Figure 52. In addition to the baseflow along the river, the change in baseflow between river nodes is also plotted, which shows whether the river is losing or gaining more clearly. The spikes in the curves showing the increase in baseflow between nodes are caused by a tributary joining the main branch of the river. The position of these tributaries is shown by the letter 't' on the figures. The following observations are made with respect to these figures:

- During wet conditions the Nith gains water from the aquifer along its full length.
- During dry conditions the Nith loses water to the aquifer at only one of its model nodes. This may be caused by the simulated abstraction at Holywood Fish Farm.
- The rate of increase in baseflow is relatively uniform along the River Nith.
- The simulated baseflow along the Lochar Water at high flow conditions is less than the estimated mean baseflow along the river.
- The model predicts that the Lochar Water gains most of its water from aquifer towards its upstream end. However, the river loses water to the aquifer at its extreme upstream end. The estimated baseflows in the river indicate that the river gains water along its full length. As stated previously, recharge and runoff processes and river-aquifer interaction across the peat deposits need to be examined in more detail to improve the model in this area.

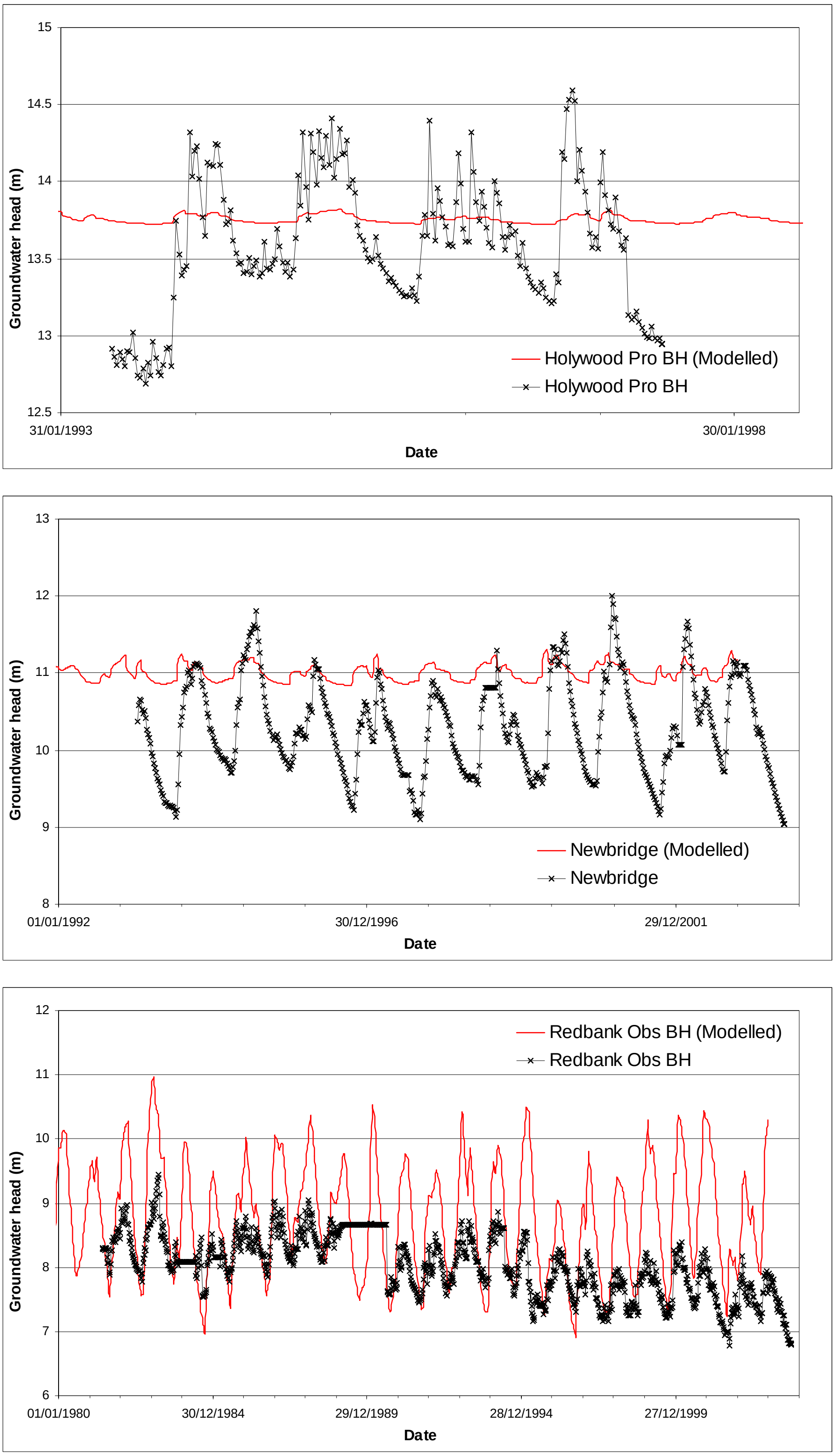


Figure 50 Simulated (time-variant) and observed groundwater head hydrographs at observation boreholes with historic record

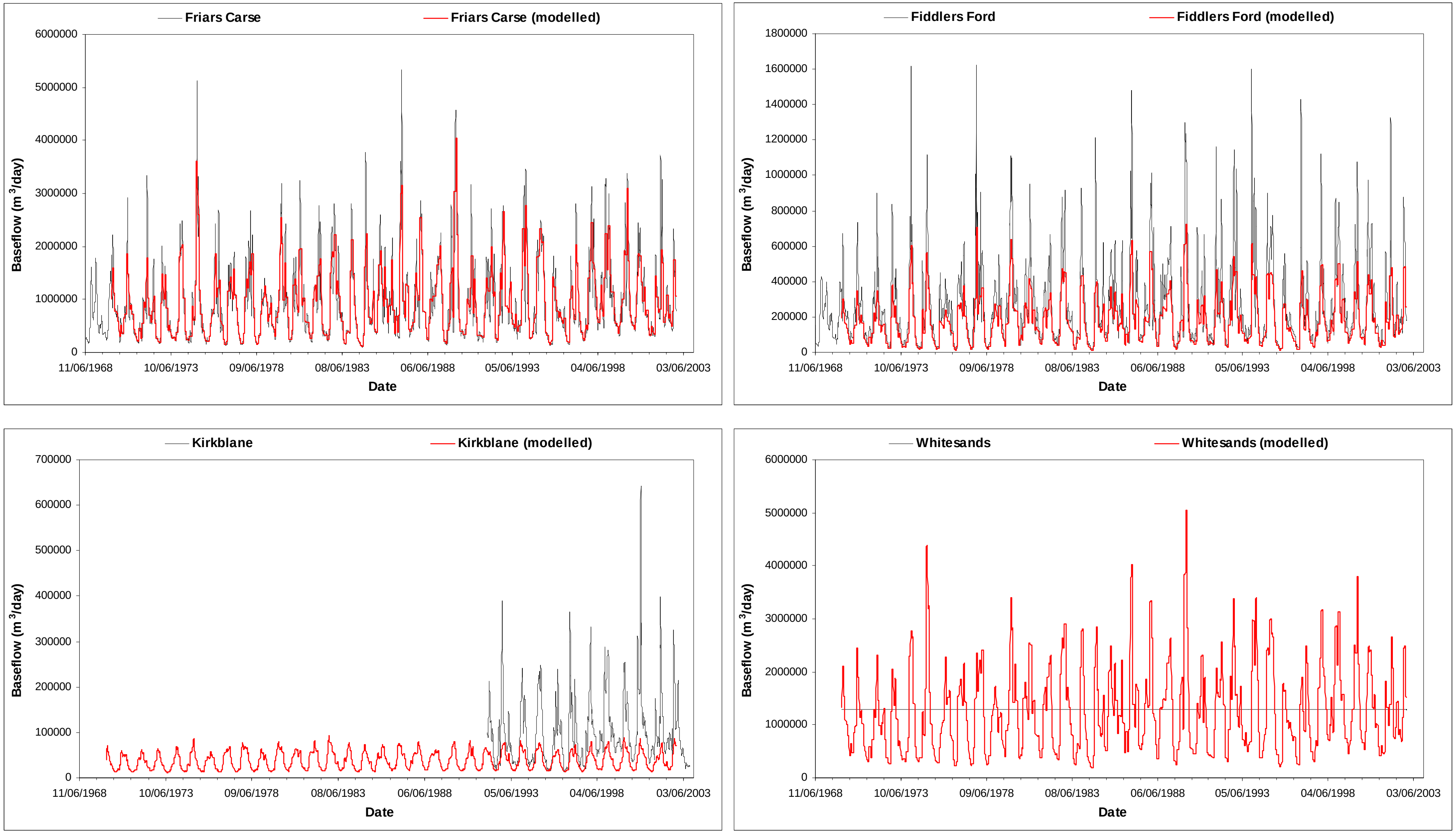
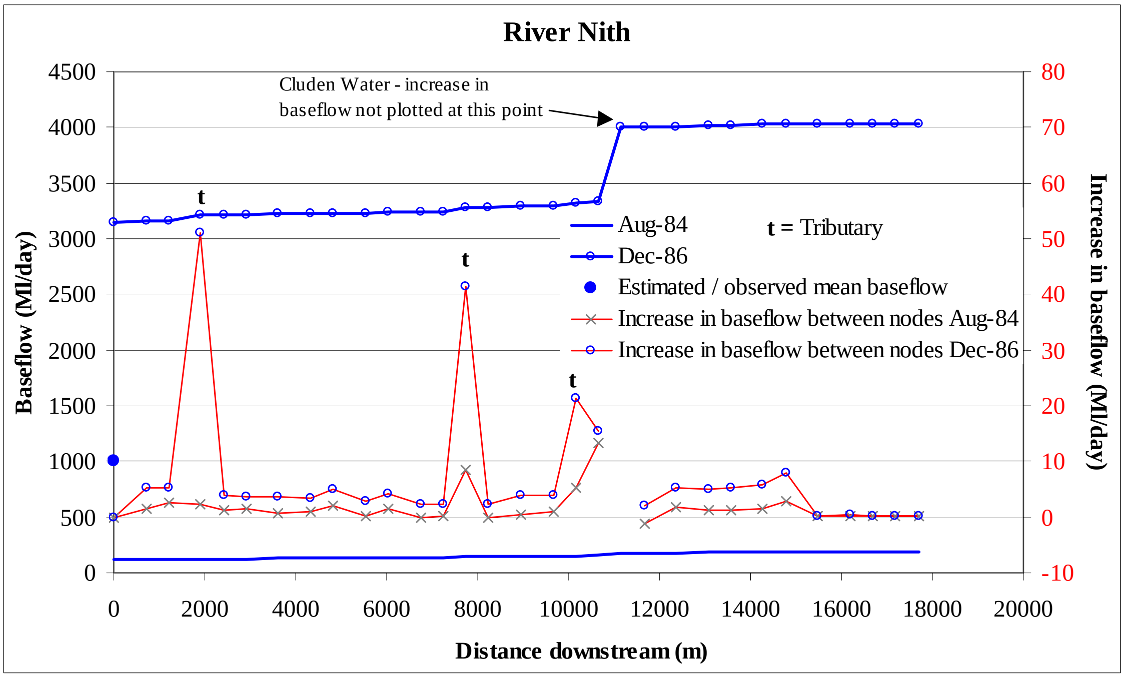


Figure 51 Simulated (time-variant) and observed river baseflow hydrographs at permanent gauging stations and at Whitesands (Observed baseflow is estimated at Whitesands)



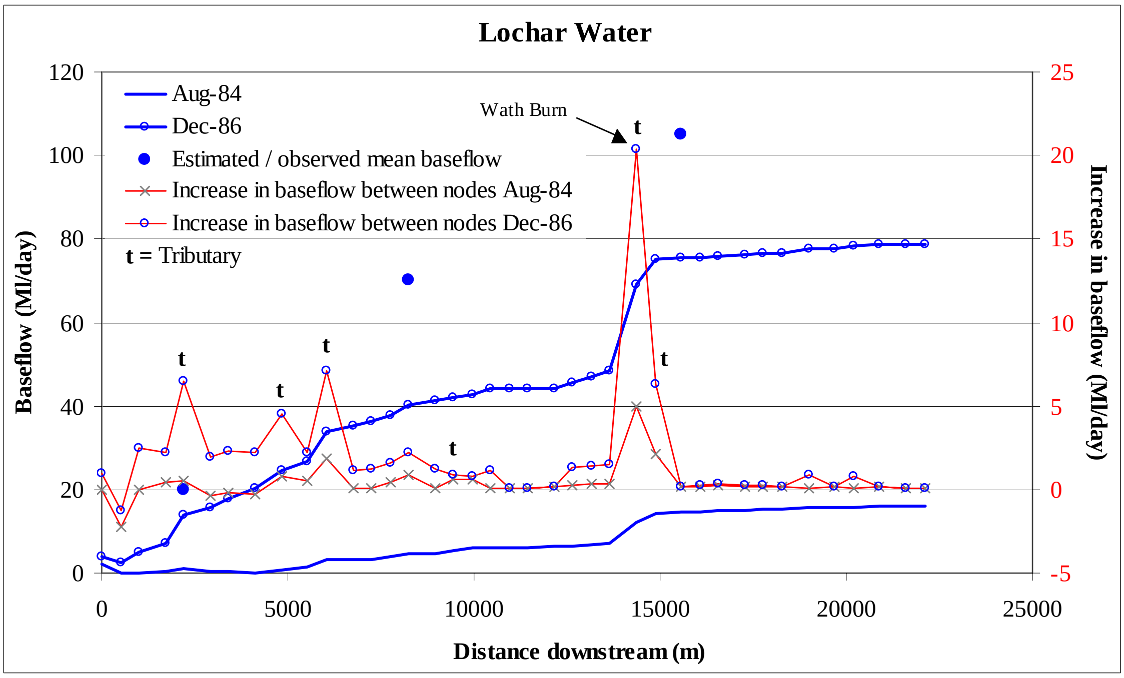


Figure 52 River flow accretion profiles along the River Nith and Lochar Water at high and low flow conditions during the historic simulation.

6.12 SENSITIVITY ANALYSES

To examine the sensitivity of the model results to the input parameters, seven further steady-state model simulations are performed. These runs are intended to investigate the uncertainty associated with the values specified for two model hydraulic parameters and for recharge. Simulated groundwater head values and river baseflows from each of the seven sensitivity analysis runs are compared with the steady-state model described in Section 6.9. In each of the following seven sensitivity runs only a single model parameter is modified when compared to original steady-state model. These runs are described in Table 20. In the first two runs recharge is altered, in Runs 3, 4 and 5 transmissivity is modified, and in the final two runs the bed conductivity of the rivers is adjusted. The impact of these changes on the model results in discussed in the following subsections. The results of each run are represented by three different plots:

1. The difference in groundwater head, in layer 2 of the model, between the original steady-state simulation and the sensitivity analysis run is drawn as a gridded map. A reduction in groundwater head compared to the original model is plotted as a negative value.
2. The simulated steady-state contours for the sensitivity analysis run are plotted.
3. The difference in river baseflow, along the River Nith and Lochar Water, between the original steady-state simulation and the sensitivity analysis run is plotted as an x-y graph.

Table 20 Summary of runs performed as part of sensitivity analysis

Run No.	**Description**					
Run 1	Recharge halved					
Run 2	Recharge increased by half					
	Transmissivity					
	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Initial steady-state	300	300	300	300	300	50
Run 3	600	600	600	600	600	
Run 4	600		600	600		
Run 5	600	150	600	600	150	
Run 6	Reconnecting bottom (5 nodes) of Nith River where on inter-tidal mudflat deposits with aquifer. River bed conductivity increased from 0.001 m day^{-1} to 1.0 m day^{-1}					
Run 7	Reducing conductivity of bed of all rivers (except bottom five nodes of Nith) from 1.0 m day^{-1} to 0.01 m day^{-1}.					

N.B. transmissivities are only shown if they are different from the original steady-state simulation

SENSITIVITY ANALYSIS - RUN 1

In this simulation recharge is halved across the aquifer. The results are presented diagrammatically in Figures 53, 60 and 61. The following observations are made with respect to the comparison of this simulation run to the original steady-state model:

- Halving the recharge reduces the groundwater heads in the interfluve areas more significantly than along the river valley. This is because the river control groundwater levels along their length. Heads fall by up to approximately 9 m in the north-west of the model and by approximately 7 m over the high ground near Caerlaverock.

- The maximum simulated groundwater head is approximately 50 m OD, which is significantly greater than that shown on the hydrogeological map of the basin.
- The impact of the rivers on the contours is less pronounced when compared to the original steady-state model.
- The total recharge is 96.2 Ml day^{-1} lower than in the original steady-state model. This reduces the flow at the downstream ends of the River Nith and Lochar Water by 51.5 Ml day^{-1} and 11.1 Ml day^{-1}, respectively. The reduction in baseflow to the rivers is more pronounced towards their upstream ends.
- The flow at the downstream end of the Nith is 261.4 Ml day^{-1} greater than at Friars Carse. This is not an unrealistic estimate of the mean baseflow towards the bottom of the Nith.

SENSITIVITY ANALYSIS - RUN 2

In this simulation recharge is increased by half across the aquifer. The results are presented diagrammatically in Figures 54, 60 and 61. The following observations are made with respect to the comparison of this simulation run to the original steady-state model:

- Increasing the recharge by half generally increases the groundwater heads by up to 2 metres, except in the interfluve area where heads rise more. Heads rise by up to approximately 6 m in the north-west of the model and by approximately the same over the high ground near Caerlaverock.
- The maximum simulated groundwater head is approximately 60 m OD, which is significantly greater than that shown on the hydrogeological map of the basin and possibly unrealistic.
- The total recharge is 96.2 Ml day^{-1} higher than in the original steady-state model. This increases the flow at the downstream ends of the River Nith and Lochar Water by 51.8 Ml day^{-1} and 11.0 Ml day^{-1}, respectively. The increase in baseflow to the rivers is more pronounced towards their upstream ends.
- The flow at the downstream end of the Nith is 364.7 Ml day^{-1} greater than at Friars Carse. Again, this estimate of the mean baseflow towards the bottom of the Nith falls within the bounds possible values.

SENSITIVITY ANALYSIS – RUN 3

In this simulation transmissivity is doubled except in Zone 6 (refer to Figure 37) where it is not modified. The results are presented diagrammatically in Figures 55, 60 and 61. The following observations are made with respect to the comparison of this simulation run to the original steady-state model:

- By doubling the transmissivity, except in zone 6, a smoother distribution of groundwater head contours is produced, though the influence of the rivers remains clear.
- The maximum head in the north-west of the model is approximately 40 m OD, which is significantly greater than that shown on the hydrogeological map.

- Heads are generally less than 2 m lower than in the original steady-state model, except in the interfluve areas. The maximum reduction in head is approximately 20 m which occurs in the north-west of the model.
- The impact of the increase of transmissivity on river baseflows is not simple, though there is only a small effect of the modification. Whilst the groundwater heads reduce because of the increase in transmissivity they remain above the rivers in the valleys. Broadly the baseflow decreases in the Nith at it upstream end and increases further downstream. This is due to the flattening of the groundwater head profile compared to the profile of the Nith. Overall the baseflow in the Nith increases by approximately 5 Ml day^{-1}.
- Whereas the baseflow in the Nith increases overall compared to the original steady-state model, the baseflow in the Lochar Water reduces. This is due to the increase in the size of the Nith Catchment, which results from the increase in transmissivity. Overall the baseflow in the Lochar Water decreases by approximately 5 Ml day^{-1}.

SENSITIVITY ANALYSIS - RUN 4

In this simulation transmissivity is doubled in zones 1, 3 and 4 i.e. the zones within the area mapped for the Doweel breccia. The results are presented diagrammatically in Figures 56, 60 and 61. The following observations are made with respect to the comparison of this simulation run to the original steady-state model:

- By doubling the transmissivity in zones 1, 3 and 4, a smoother distribution of groundwater head contours is produced within the area of the mapped Doweel breccia, though the influence of the rivers remains clear.
- The maximum head in the north-west of the model is approximately 45 m OD, which is significantly greater than that shown on the hydrogeological map.
- Heads are generally less than 2 m lower than in the original steady-state model, except in the interfluve areas in the west of the basin. The maximum reduction in head is approximately 17 m which occurs in the north-west of the model.
- The impact of the increase of transmissivity on river baseflows is again minimal in both the River Nith and Lochar Water. The increase transmissivity causes a slight increase in the baseflow in the Cargen Water which compensates for the small reductions in baseflow in the two larger rivers.

SENSITIVITY ANALYSIS - RUN 5

In this simulation transmissivity is doubled in zones 1, 3 and 4, i.e. the zones within the area mapped for the Doweel breccia, and halved in zones 2 and 5, i.e. the zones within the area mapped for the Locharbriggs sandstone. The transmissivity of zone 6 is not modified. The results are presented diagrammatically in Figures 57, 60 and 61. The following observations are made with respect to the comparison of this simulation run to the original steady-state model:

- By doubling the transmissivity in zones 1, 3 and 4, a smoother distribution of groundwater head contours is produced within the area of the mapped Doweel breccia, though the influence of the rivers remains clear. Groundwater head gradients increase towards the east of the basin where transmissivity is halved.
- The maximum head in the north-west of the model is approximately 50 m OD, which is significantly greater than that shown on the hydrogeological map.

- Heads are generally less than 2 m lower than in the original steady-state model, except in the interfluve areas in the north-east the basin. The maximum reduction in head in the north-west is approximately 13 m and the groundwater heads increase in the north-east by up to 5 m.
- The impact of the increase of transmissivity on river baseflows is again minimal in both the River Nith and Lochar Water. The increase in transmissivity in the west causes a slight decrease in the baseflow in Nith. The decrease in transmissivity in the east, resulting in higher groundwater heads causes the baseflow in the Lochar Water to increase along its full length.

SENSITIVITY ANALYSIS - RUN 6

In this simulation the bottom five nodes of the River Nith are, in effect, reconnected to the aquifer. In this run the bed conductivity of these nodes is increased to 1.0 m day^{-1} from 0.001 m day^{-1}, in other words to the same values specified for the other river nodes. A lower conductivity is assigned to the bottom five nodes of the Nith in the original steady-state model to simulate the effect of the low conductivity inter-tidal mud deposits on the interaction between the river and the aquifer. The results are presented diagrammatically in Figures 58, 60 and 61. The following observations are made with respect to the comparison of this simulation run to the original steady-state model:

- The re-connection of the bottom of the River Nith with the aquifer causes a significant change in the pattern of the groundwater head contours south of Dumfries. The increase in bed conductivity causes the 5 m contour to expand along the Nith valley. An examination of the observed groundwater levels shows that there is a possible high in the groundwater head profile both to the north and south of the Workington Brewery observation borehole. The higher head to the south could be due to the influence of the low permeability inter-tidal muds. The re-connection of the Nith in the model results in similar groundwater heads being simulated both to the north and south of Workington Brewery.
- The increase in river bed conductance causes and increase in the baseflow at the downstream end of the Nith of approximately 8 Ml day^{-1}, which is not significant.

SENSITIVITY ANALYSIS - RUN 7

In this simulation the hydraulic conductivity of the bed of the all the model river nodes (except the bottom five nodes of the Nith) is reduced from 1.0 m day^{-1} to 0.01 m day^{-1}. The results are presented diagrammatically in Figures 59, 60 and 61. The following observations are made with respect to the comparison of this simulation run to the original steady-state model:

- The reduction in the river bed conductance at all model nodes results in a increase of groundwater head in the river valleys and generally results in groundwater heads that are two high when compared to the levels measured at observation boreholes.
- Reducing the degree of connection between the rivers and the aquifer results in the deepening and spreading of the cones of depression around the pumped well, particularly at Holywood Fish Farm.

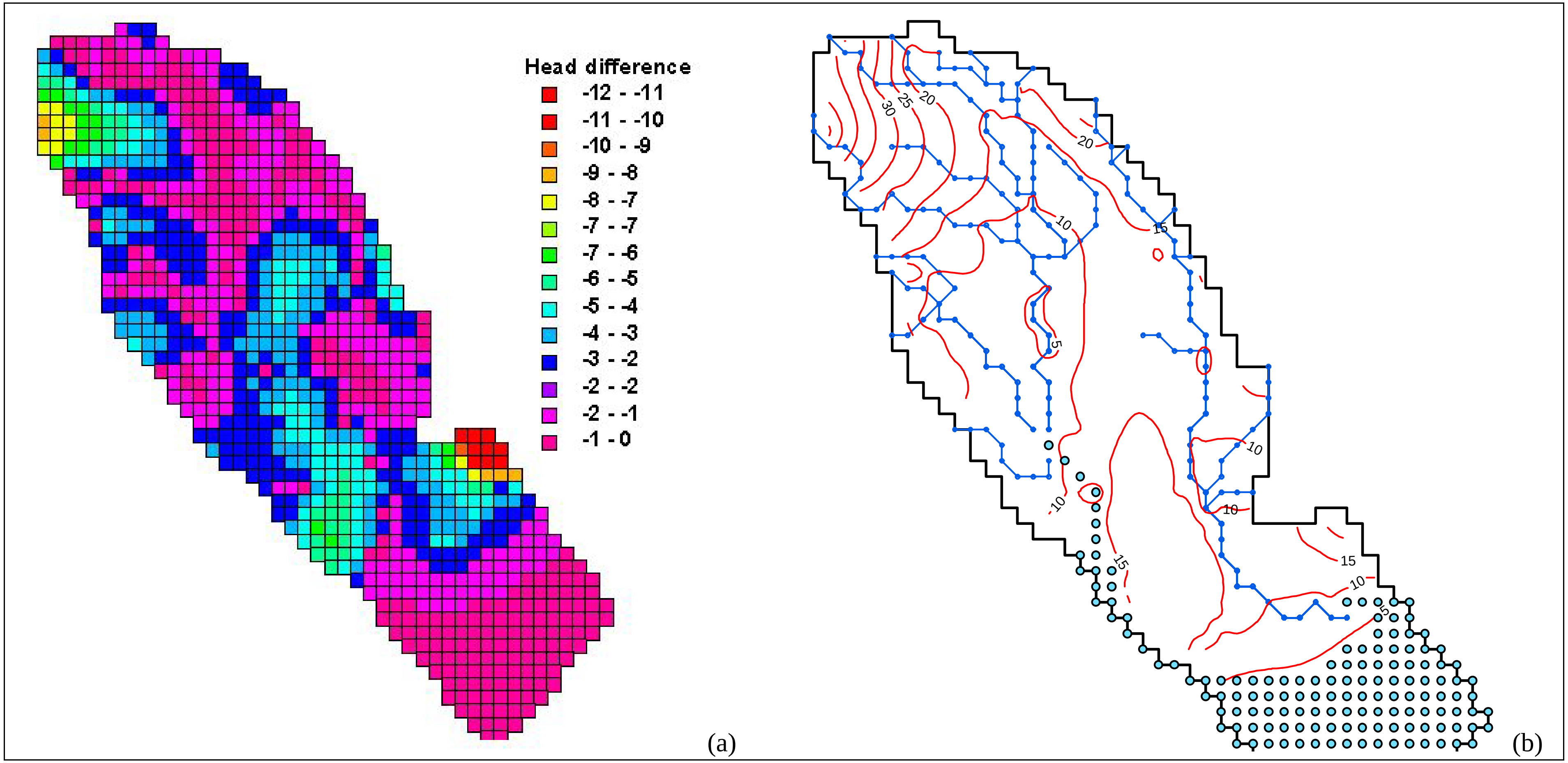


Figure 53 (a) Difference in groundwater head between sensitivity analysis Run 1 and initial steady-state model and (b) simulated groundwater head contours for sensitivity analysis Run 1

N.B. A reduction in groundwater head compared to the original model is plotted as a negative value.

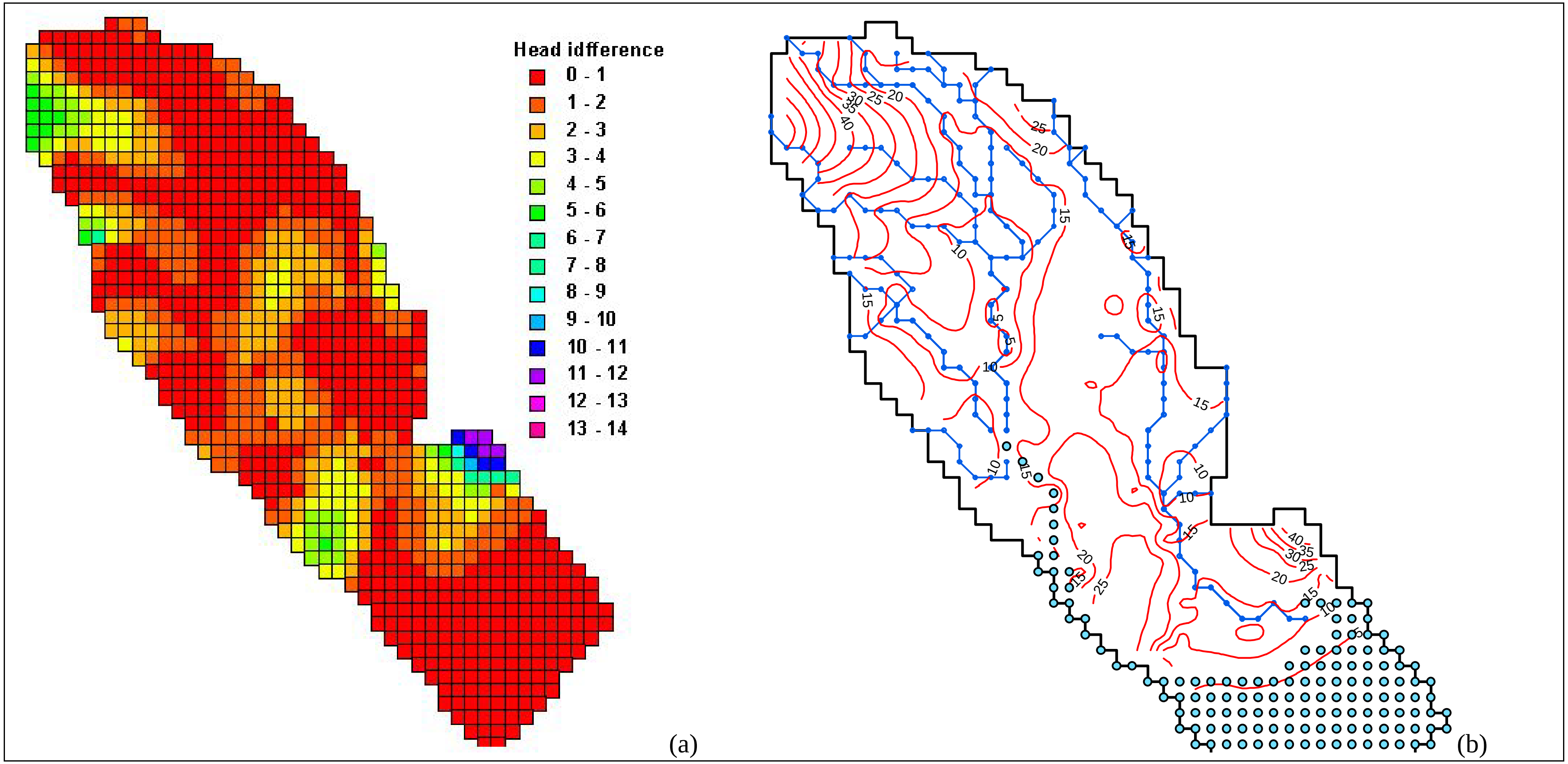


Figure 54 (a) Difference in groundwater head between sensitivity analysis Run 2 and initial steady-state model and (b) simulated groundwater head contours for sensitivity analysis Run 2

N.B. A reduction in groundwater head compared to the original model is plotted as a negative value.

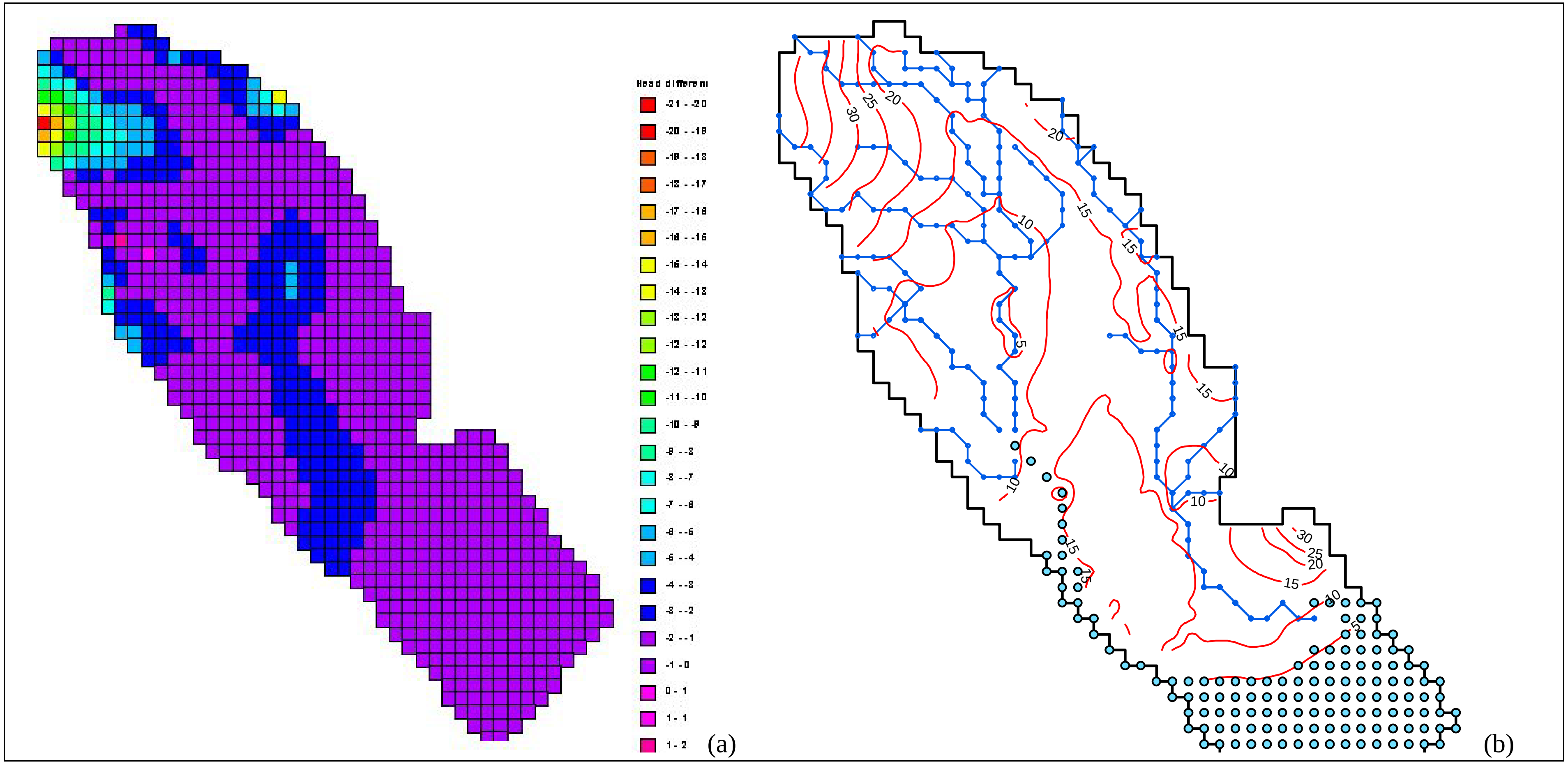


Figure 55 (a) Difference in groundwater head between sensitivity analysis Run 3 and initial steady-state model and (b) simulated groundwater head contours for sensitivity analysis Run 3

N.B. A reduction in groundwater head compared to the original model is plotted as a negative value.

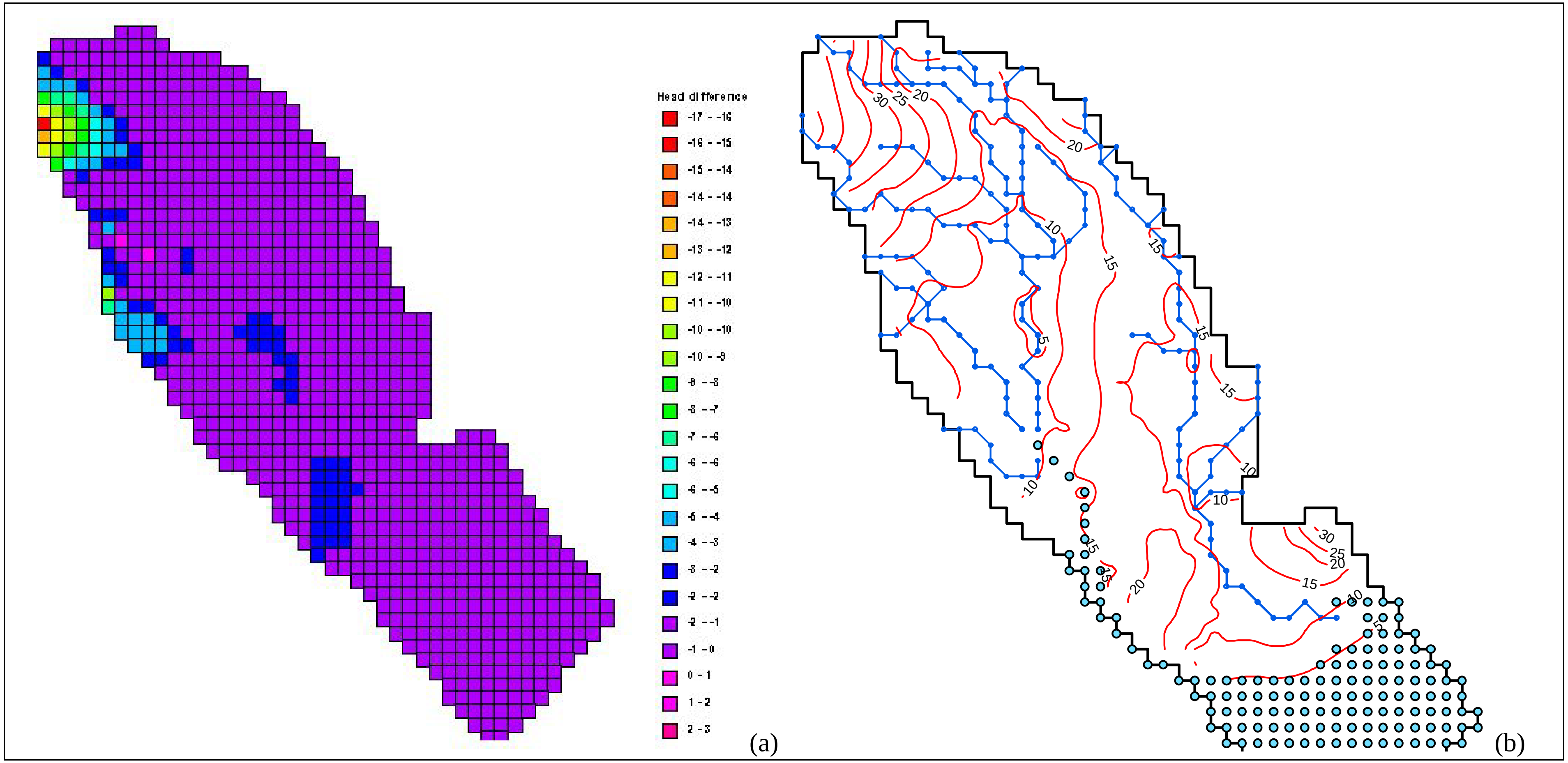


Figure 56 (a) Difference in groundwater head between sensitivity analysis Run 4 and initial steady-state model and (b) simulated groundwater head contours for sensitivity analysis Run 4

N.B. A reduction in groundwater head compared to the original model is plotted as a negative value.

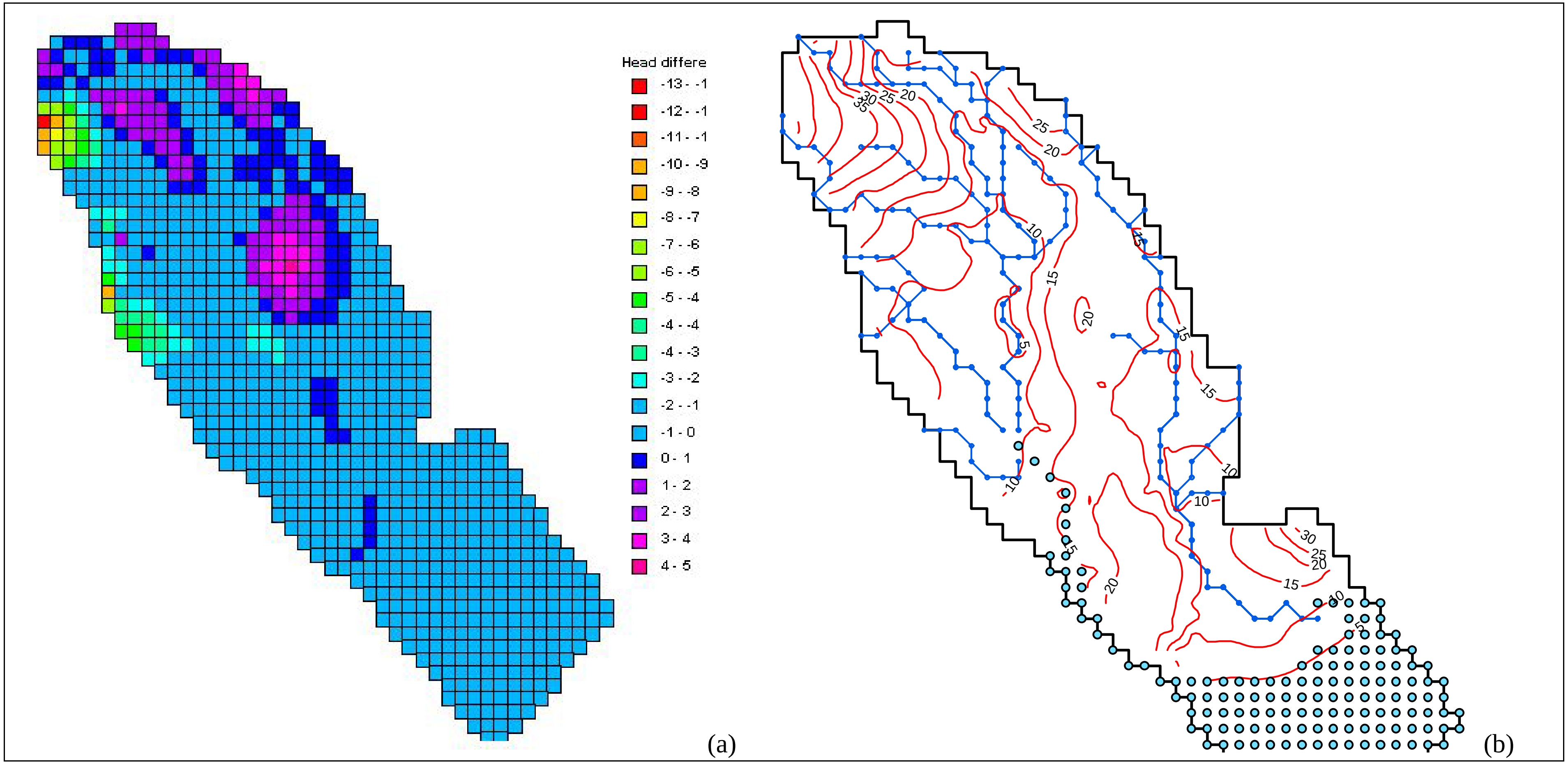


Figure 57 (a) Difference in groundwater head between sensitivity analysis Run 5 and initial steady-state model and (b) simulated groundwater head contours for sensitivity analysis Run 5

N.B. A reduction in groundwater head compared to the original model is plotted as a negative value.

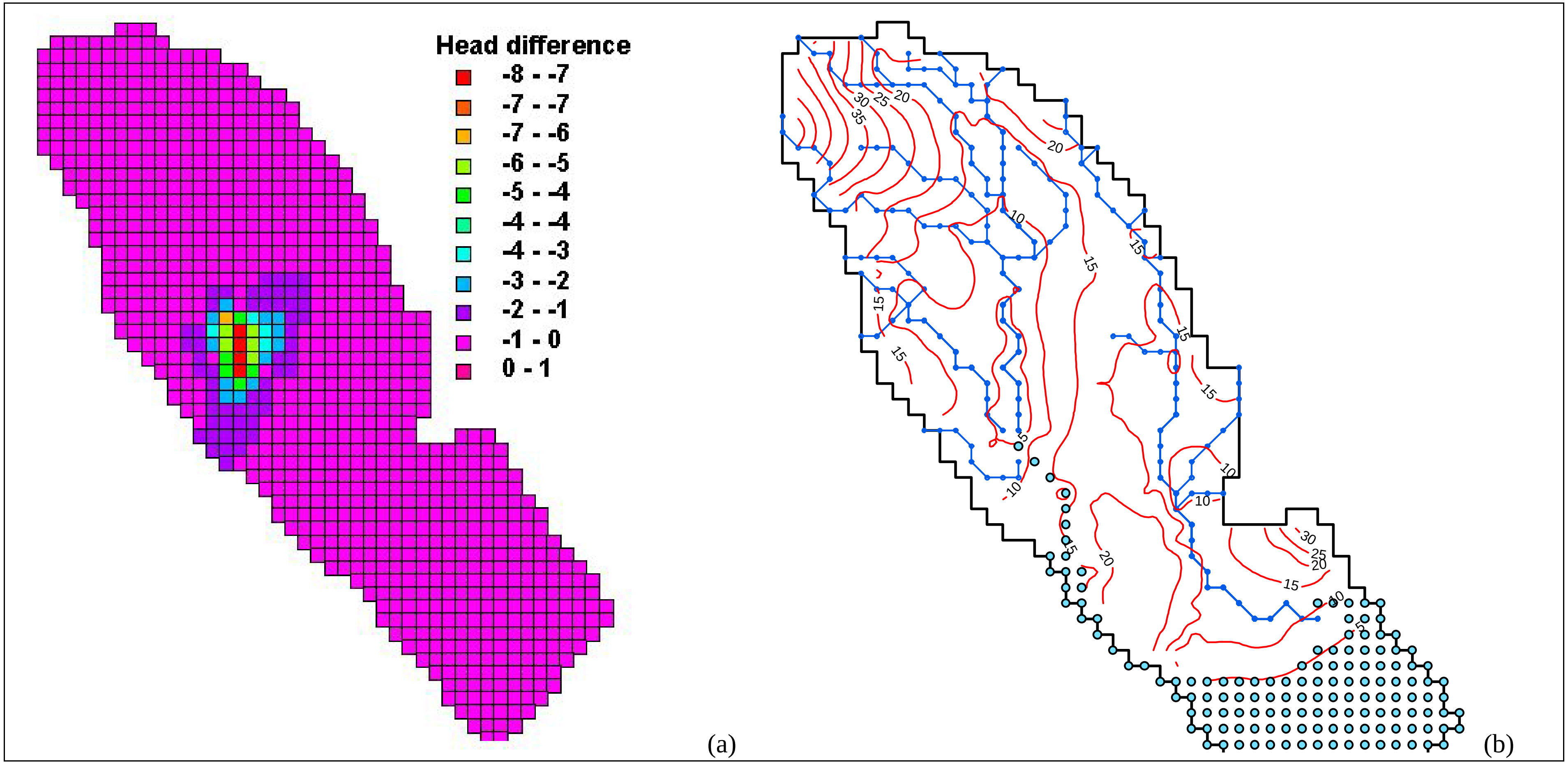


Figure 58 (a) Difference in groundwater head between sensitivity analysis Run 6 and initial steady-state model and (b) simulated groundwater head contours for sensitivity analysis Run 6

N.B. A reduction in groundwater head compared to the original model is plotted as a negative value.

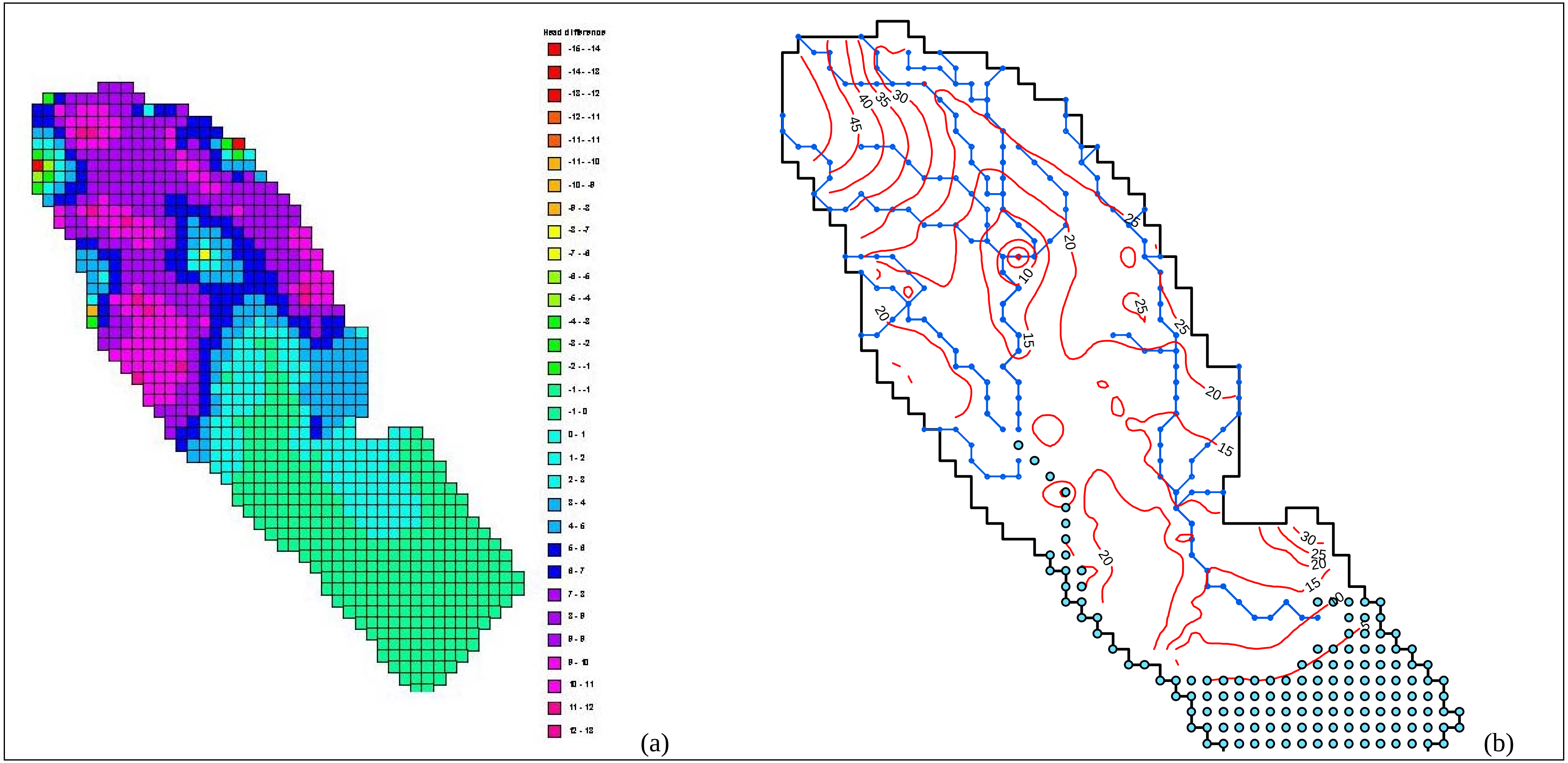
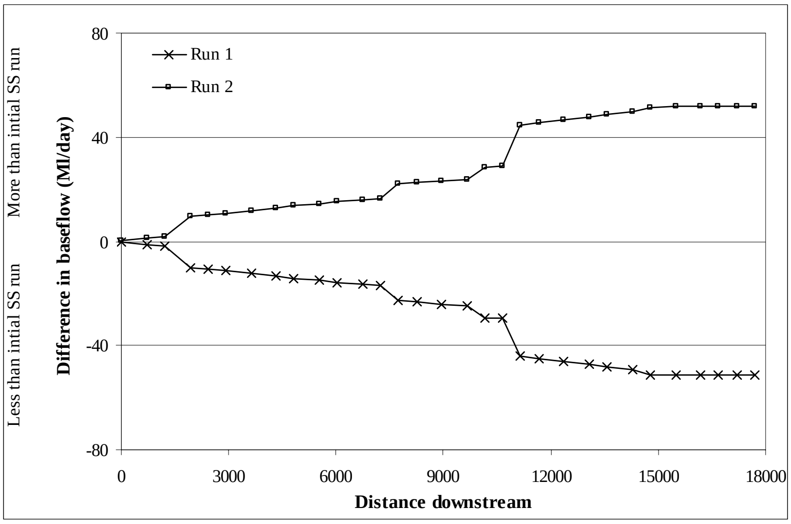
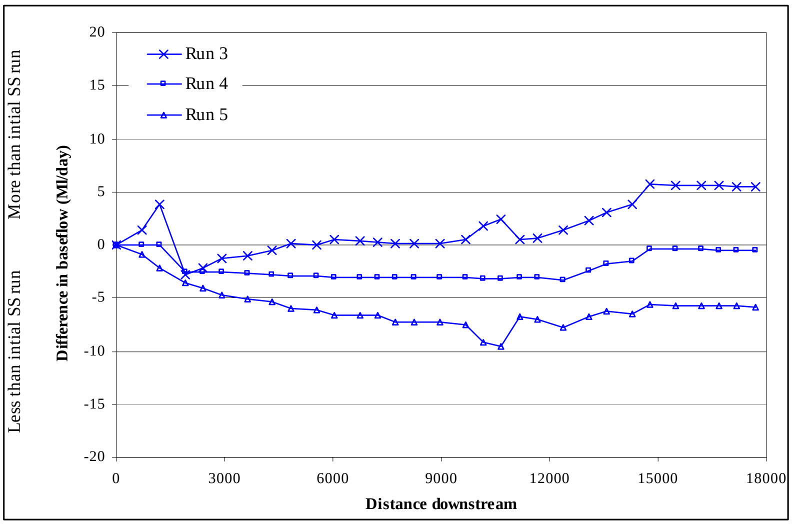


Figure 59 (a) Difference in groundwater head between sensitivity analysis Run 7 and initial steady-state model and (b) simulated groundwater head contours for sensitivity analysis Run 7

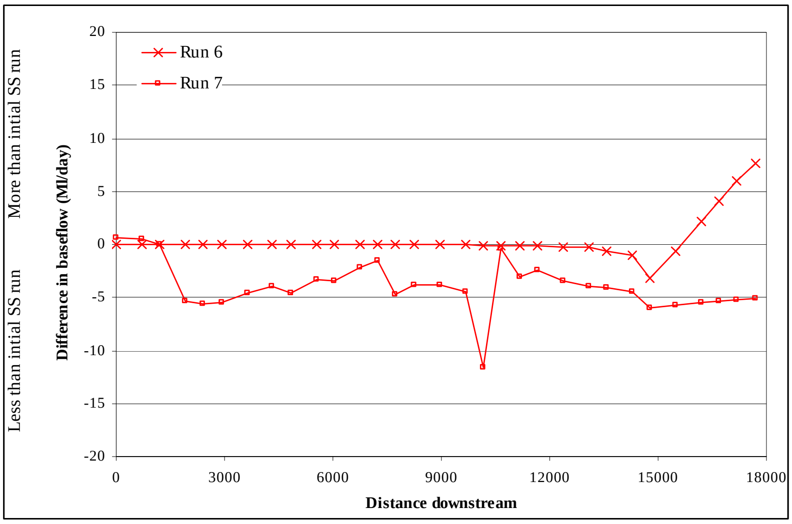
N.B. A reduction in groundwater head compared to the original model is plotted as a negative value.



(a)

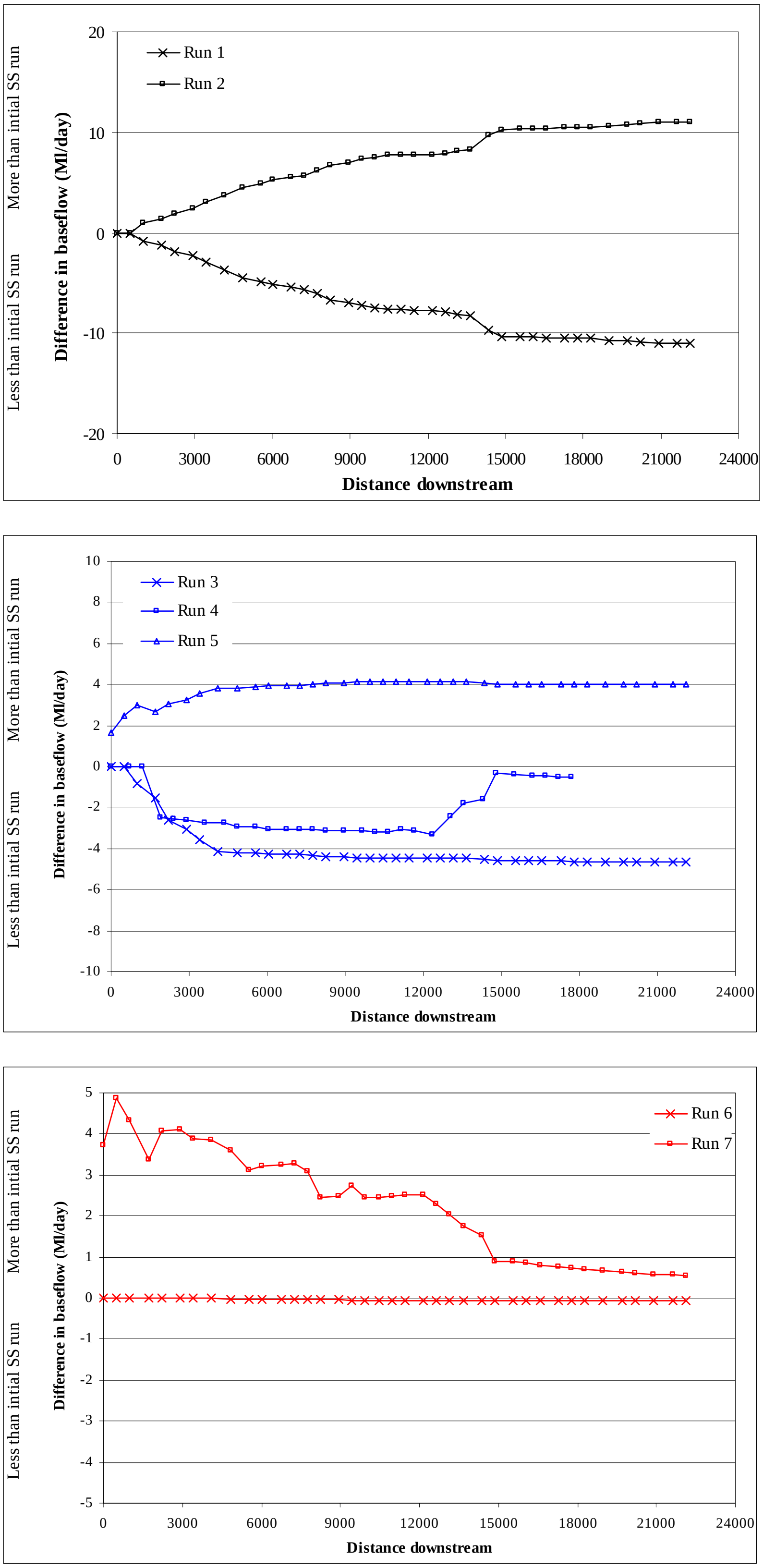


(b)



(c)

Figure 60 Difference in baseflow along River Nith between the initial steady-state simulation and (a) sensitivity analysis Runs 1 and 2, (b) sensitivity analysis Runs 3 to 5 and (c) sensitivity analysis Runs 6 and 7



(a) (b) (c)

Figure 61 Difference in baseflow along Lochar Water between the initial steady-state simulation and (a) sensitivity analysis Runs 1 and 2, (b) sensitivity analysis Runs 3 to 5 and (c) sensitivity analysis Runs 6 and 7

7 Summary and conclusions

7.1 SUMMARY

The aim of the groundwater flow modelling in the Dumfries basin is to both test the existing conceptual model and to determine the water resources of the basin. A conceptual model of groundwater flow in the Dumfries Basin has been developed from groundwater investigations carried out over a number of years. This conceptual understanding requires testing using numerical modelling techniques. To achieve these aims, the quantification of the groundwater flow processes has to be undertaken. This has been done by three tasks; recharge estimation, water balance and groundwater flow modelling. These tasks are complimentary and enable the conceptual model to be tested on a spatially distributed basis. This enables any deficiencies in the understanding of the groundwater flow to be assessed and recommendations for further work to be made.

The main thrust of the work reported here is the creation of a groundwater flow model of the Dumfries basin. This has involved the following:

- Conceptual model of groundwater flow developed.
- Rainfall recharge calculated on a distributed basis.
- Numerical groundwater flow modelling undertaken:
  - Time-variant water balance created.
  - Steady-state groundwater flow simulated.
  - Time-variant simulations undertaken.

Work has improved aspects of the conceptual understanding of groundwater flow and also identified various data deficiencies

7.2 CONCLUSIONS

Groundwater head measurements are concentrated in the centre of the basin, coverage needs to be widened to the rest of the basin. A limited number of groundwater levels are monitored regularly. To aid the understanding of the Dumfries basin, improved monitoring of groundwater heads, both spatially and temporarily, is required.

Uncertainties exist in both the understanding of river-aquifer interaction and in the water balance due to a lack of surface water flow data. The main omission is a flow record as close as possible to the tidal limit of the River Nith. Without these data, the difference in flow along the River Nith cannot be determined, hence the river-aquifer interaction, and a reasonable water balance for the Nith catchment cannot be created.

7.2.1 Conceptual model

- The Quaternary deposits are largely permeable allowing recharge to groundwater system.
- Limited recharge occurs under the mosses (peat overlying clays).
- Marine clays separate River Nith from the bedrock aquifer in the Nith estuary.
- Springs discharging on edge of Larchfield-Caerlaverock ridge were identified as an important part of groundwater system.

- Runoff processes and river-aquifer interaction are important controls on groundwater flow.
- Understanding of groundwater flow limited in north and south of basin due to lack of observation boreholes in these areas.

7.2.2 Recharge

- Recharge is highest in the north-west of the basin where rainfall is highest and grassland predominates.
- The long-term average recharge rate is higher in the River Nith catchmant than in the Lochar Water (434 mm/a vs 200 mm/a). This is due to higher rainfall in the Nith catchment and the peats reducing vertical recharge in the Lochar Water catchment.
- Comparison of time series of recharge with groundwater hydrographs shows a good relationship with little or no time difference between recharge and groundwater head response.

7.2.3 Water balance

- Flows in the River Nith dominate the water balance, however the flow at the tidal limit of the River Nith is not known and has had to be estimated.
- Abstraction has been increasing in basin since late 80s/early 90s.
- However, there is a potential for extra resource providing river flow data are collected to improve understanding of river-aquifer interaction and water balance.

7.2.4 Groundwater flow modelling

- Groundwater flow is simulated reasonably well, but groundwater head data are concentrated in centre of the basin.
- Baseflow along River Nith is simulated reasonably well but flow gauging close to the tidal limit of the River Nith is required.
- Modelling identified deficiencies in the understanding of groundwater flow in the Lochar Water catchment, regarding recharge and groundwater-surface water interaction.
- Sensitivity analysis shows that modelled heads in the valleys and particularly river baseflows are not sensitive to changes in transmissivity, but a good estimate of recharge is important.
- River-aquifer interaction is not fully understood and cannot be simulated successfully yet.

7.2.5 Rationale for the improvement of the model

- General water balance to be created which enables the groundwater resource to be assessed. Further development of the groundwater system can then be determined.
- Determining the best location for additional boreholes both in terms of aquifer potential and derogation of other sources and rivers.
- Examining the performance of the groundwater system during droughts, for both existing and planned boreholes can be undertaken.

- Climate change and its impacts on the operation of existing and planned boreholes can be assessed.
- Operational scenarios for the management of the wellfields can be examined, so that abstraction can be maximised when required, i.e. on a seasonal basis.

8 Recommendations

To improve the understanding of groundwater flow in the Dumfries basin and to enable an assessment of the groundwater resources of the basin, the following data and investigations are required:

- Groundwater heads
    - Determine groundwater levels in the following areas either by using existing boreholes or by drilling new boreholes. These are listed in order of priority:
        - In the north-west of the basin, for example near High Kilroy (292000, 582000) but more generally towards the top of the basin where there are currently no observation wells.
        - In the region of the high ground at Caerlaverock; preferably along the line between the co-ordinates 301500, 568000 and 299000, 573500.
        - In other areas of the basin where there are currently few observation boreholes for example near Locharbriggs (300000, 578000).
    - Continue to measure groundwater levels in the Holywood, Newbridge, Redbank and Racks Moss boreholes using loggers.
    - Identify a basin wide set of observation boreholes that will be dipped on a monthly basis. This should include all the boreholes listed in Table 3. If this is not realistic then identify a subset of these to have a logger installed. In the first instance it would be valuable to install loggers in the following four boreholes, which would be left there for as long a period as possible:
        1. Carnation No.1.
        2. Locharbriggs.
        3. Dundas Chemicals.
        4. Greenmerse.
    - A secondary objective would be to monitor the variation in groundwater head over time at:
        1. Terregles Obs 2.
        2. Workington Brewery.
        3. Kingholm Mill or Well Cottage.
        4. Golf Course.
        5. Larchfield.
- Surface water flows
    - As a priority establish a method of gauging flows on the River Nith at its lowest non-tidal point. If appropriate then a rating curve for the section of the River Nith at the site of the current flood level monitoring station should be undertaken. This will enable a long-term record of flows at the bottom of the Nith catchment to be created.
    - Undertake spot gaugings along the Nith, Cluden Water and Cargen Water with the aim of identifying losing and gaining stretches of the rivers. The Nith could be split into two sections upstream and downstream of Holywood

Production Borehole for this purpose. Carry out spot gauging on the Cluden Water, on the same day, at locations i) on the edge of the basin, ii) halfway between the edge of the basin and Fiddlers Ford, and iii) downstream of Fiddlers Ford. If possible identify a relationship between the flow in the Cluden Water as it comes onto the basin and the flow at Fiddlers Ford. The acquisition of flow data that could be used to identify accretion profiles along the Lochar Water would be worthwhile.

  - Continue with surface water gauging both for permanent gauges on the tributaries on the Rivers Nith and Lochar Water and undertake spot gauging campaigns at regular intervals during the year. Longer-term records are required to improve the water balance.

- Investigate surface water systems
  - Examine where the water flows and how much reaches the Lochar Water and its tributaries from the peat deposits, which are drained by numerous water courses.
  - Springs and drains have been identified on the edge of the ridge of high ground between the Nith and the Lochar Water to the south-east of Dumfries and these have been required in the model to reduce groundwater heads. The locations of these should be surveyed, their elevations estimated (from a DTM), and the flows at each measured at least on one day during both a dry period and a wet period.
  - Recharge, which has been modelled to the sandstone aquifer through the sand and gravels around Longbridge Muir, has resulted in high simulated groundwater heads. The 1:10 k OS map shows numerous ponds and streams in the area and this surface water system should be investigated further.
- Other tasks
  - An accurate historical record of abstractions should be developed so that the development of the exploitation of the groundwater system can be determined. The current groundwater abstraction should also be determined.
  - Examine borehole construction to enable the reason for different groundwater head hydrographs and impacts of pumping to be determined.

Once data has been collected, then a fully time variant groundwater flow model should be developed. Due to the importance of the surface water system, a recharge model with runoff routing should be used. The inclusion of runoff routing will enable the surface-groundwater interaction to be modelled appropriately.

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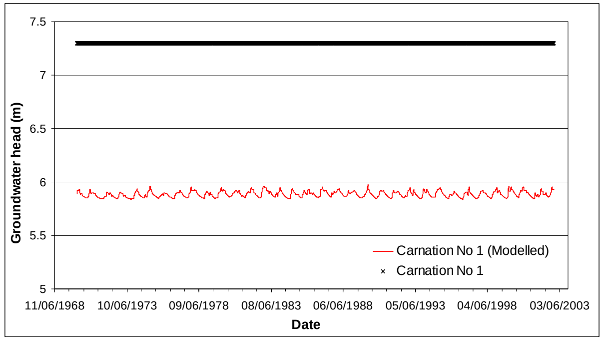
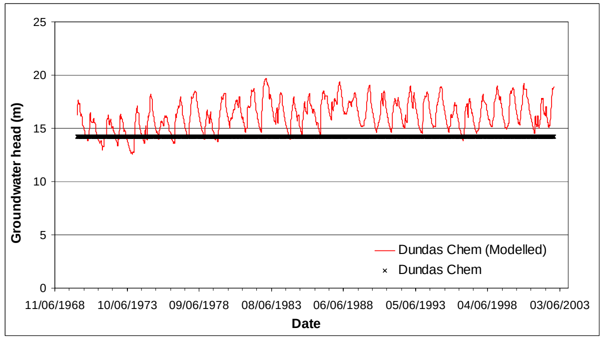
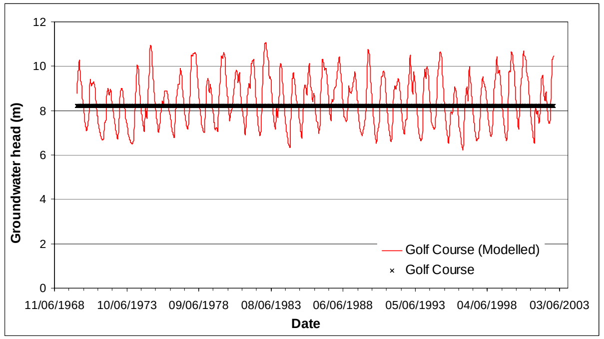
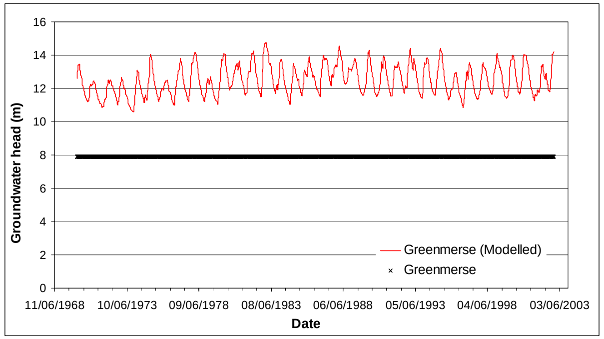
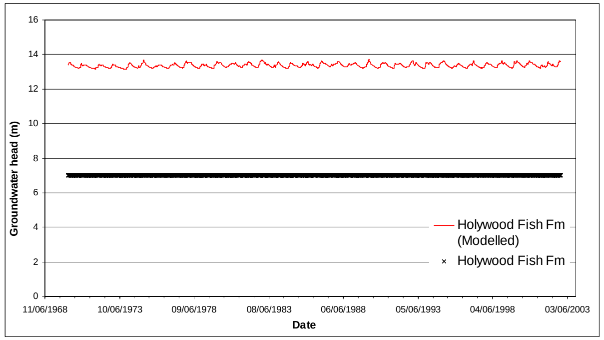
Appendix 1 Simulated groundwater head hydrographs: time-variant simulation

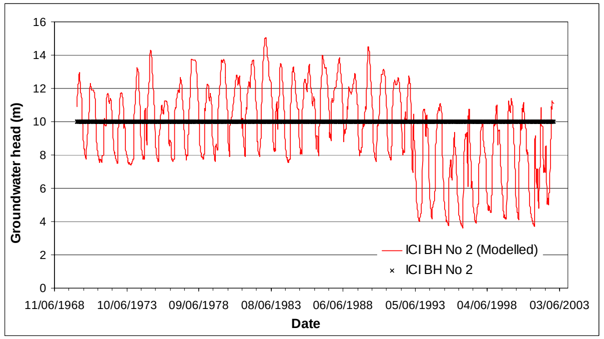


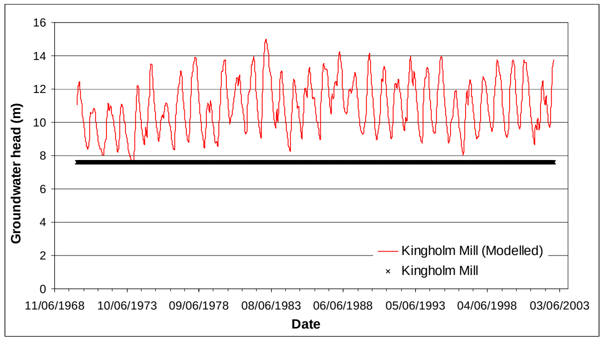


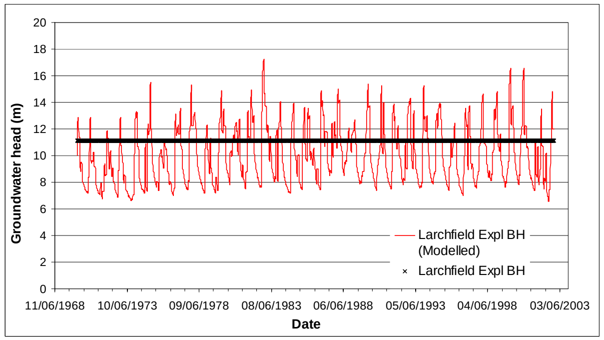


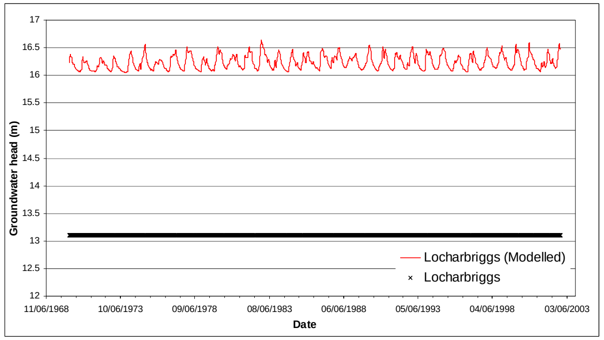


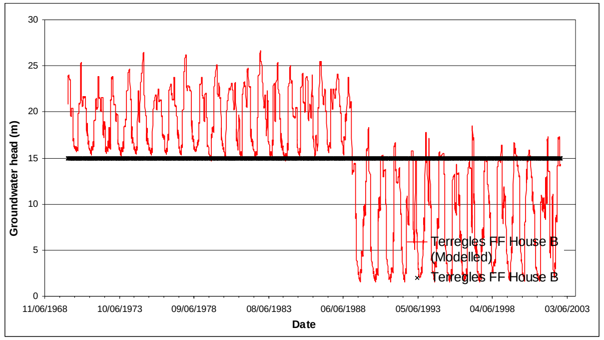








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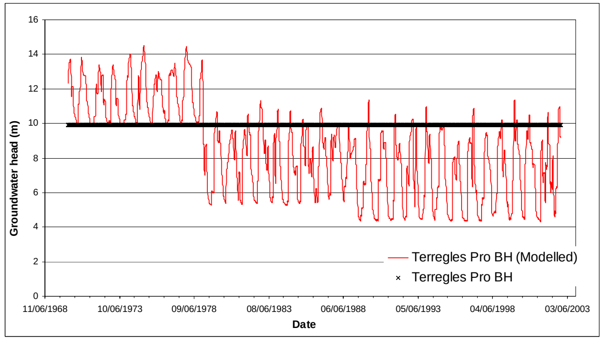
Terregles FF House B (Modelled)
Terregles FF House B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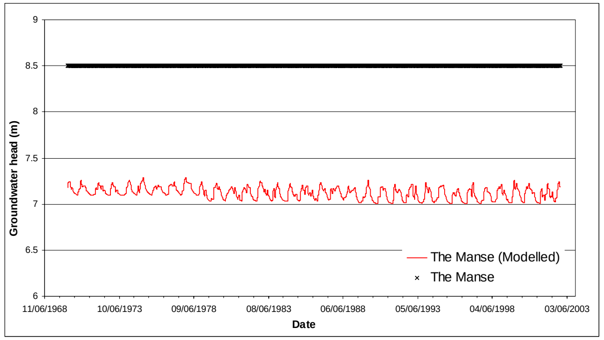
Groundwater head (m)
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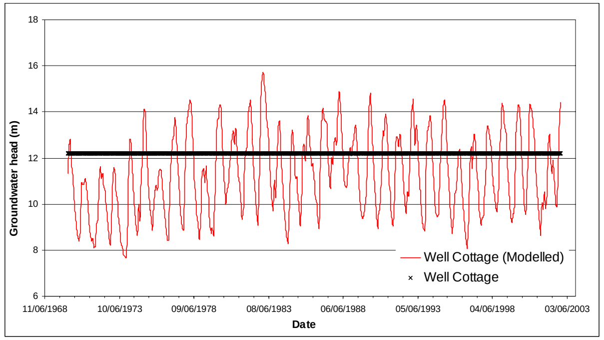
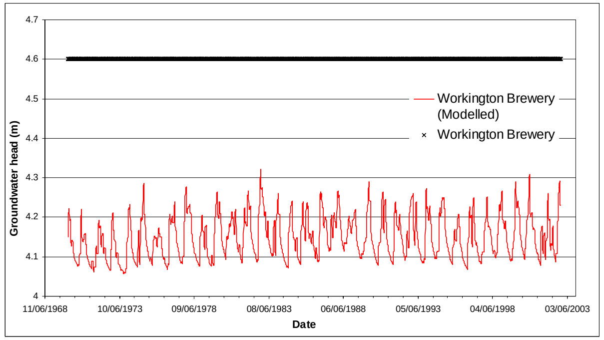
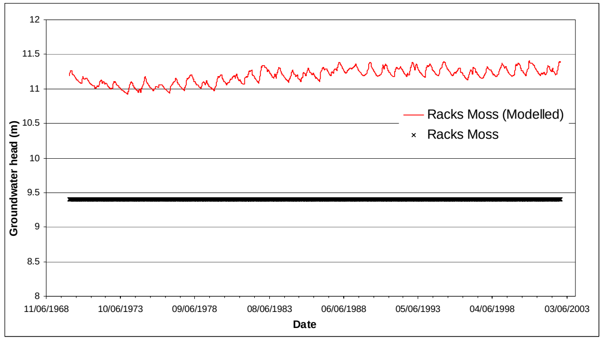
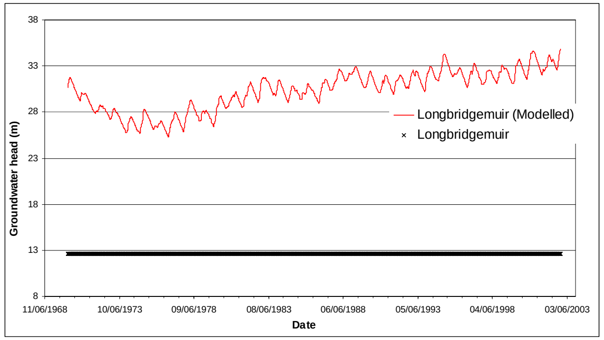

Groundwater head (m)
Date
Well Cottage (Modelled)
Well Cottage


Groundwater head (m)
Date
Workington Brewery (Modelled)
Workington Brewery


Groundwater head (m)
Date
Racks Moss (Modelled)
Racks Moss


Groundwater head (m)
Date
Longbridgemuir (Modelled)
Longbridgemuir

Appendix 2 Simulated river baseflow hydrographs: time-variant simulation