Bog of the Ring

Groundwater Source Protection Zones

Prepared by:

Natalya Hunter Williams
Geological Survey of Ireland

Assisted by:

Coran Kelly, Geological Survey of Ireland
Donal Daly, Geological Survey of Ireland
Geoff Wright, Geological Survey of Ireland
Monica Lee, Geological Survey of Ireland
Paul Johnston, Trinity College, Dublin
David Ball, David Ball Associates

In collaboration with:

Fingal County Council

March 2005

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Bog of the Ring Public Water Supply Wells: Groundwater Protection Zones

1: Introduction

The objectives of the report are as follows:

- To delineate source protection zones for the four Bog of the Ring public supply wells.
- To outline the principal hydrogeological characteristics of the Bog of the Ring area.
- To assist Fingal County Council in protecting the water supply from contamination.
- To assist Fingal County Council in estimating groundwater resources.

2: Location, Site Description and Well Head Protection

Four boreholes are used for the Bog of the Ring Public Water Supply. The boreholes are located in a roughly WNW-ESE line along the Bog Road, in the Townlands of Ring Commons and Killougher. Three of the boreholes are within 1 km of each other, with the fourth borehole about 1.5 km further to the west. Currently, all four boreholes are active, and supply a combined volume of around 3,500 m^3/d. Table 1 provides a summary of the wells, including the name, drilled date and their general location. In addition to the wells listed in Table 1, another production borehole, PW1, was drilled just to the east of the M1. However, this has been omitted from the network due to silting.

Table 1: Summary of the locations of the wells at Bog of the Ring

Borehole	Date Drilled	General Location
PW2	2000	Bog road, at junction with road to Balrickard
PW3	2000	Bog road, at junction with road to Curragh Bridge
PW4	2000	Bog road, west of PW3
PW5	2000	Sharp bend in road in Killougher Townland

The sanitary protection of the boreholes appears satisfactory. They are located on concrete platforms approximately 5 m x 5 m that are elevated above the surrounding ground, and securely fenced-off behind 2 m railings (Figure 1). The boreholes are fully covered by small (1.2 m high) ‘cabins’, while the pump control equipment is housed in a separate cabinet. Pressure transducers record water levels automatically, and these data, together with pumping rate data, are transmitted continuously to the pumping station computer. The pumping station is situated on the Bog Road, just to the east of the M1.

At least one observation borehole is located near every well. Production wells 2 and 4 have two observation wells. The observation boreholes are generally between 80-400 m from the production wells, although the one next to PW4 is only 10 m away.

Figure 1: Production well 2 (PW2), showing the concrete platform, railings, well-head protection cabin and pump-control housing.

3: Summary of Well Details

Available pumping test and abstraction data include:

- 48-144 hour pumping tests on 8 trial wells (TWs 1, 4, 7, 8, 9, 10, 12 and 13) was carried out in 1984 and in 1993/94 (K.T. Cullen, 1985; K.T. Cullen & Co., 1994);
- 72-hour pumping tests carried out at Production wells (PWs 2, 3 and 5) in June 2000 (K.T. Cullen & Co., 2000);
- 7 day combined abstraction tests from PWs 1, 2 and 3, and then from PWs 4 and 5 in July 2000. The tests were sequential (K.T. Cullen & Co., 2000). The well groups were pumped simultaneously and water levels were monitored in these and the associated observation wells, as well as in shallow piezometers installed in the bog;
- Daily pumping volumes from Fingal Co. Co. for PWs 2, 3, 4 and 5 from 13/10/2003 to present. The wells have been pumped since July 2004, but these data are not available. Water level data are available from May 2004.

The locations of the production wells (PWs) are shown on all the maps in this report. The locations of the trial wells, observation wells and bog standpipes are shown in Figure A.1 (in the Appendix).

Table 2, below, provides a summary of the wells' details.

Table 2: Summary of well details

	Well Name				
Well Details	**PW1[1]**	**PW2**	**PW3**	**PW4**	**PW5**
GSI Well Number	-	2925NE W090	2925NE W091	2925NE W092	2925NE W093
Grid Reference	318659, 260160	317758, 260160	317429, 260377	317007, 260696	315685, 261356
Location	Ring	Ring Commons	Ring Commons	Ring Commons	Killougher
Well type	Bored	Bored	Bored	Bored	Bored
Owner	Fingal Co. Co.	Fingal Co. Co.	Fingal Co. Co.	Fingal Co. Co.	Fingal Co. Co.
Elevation (ground level) (mAOD)	32.5	34.261	35.507	37.089	55.085
Depth of borehole (m)	75	52	53	91.4	79.3
Diameter of hole (mm)	600/375	600/425	600/425	600/425	600/425
Diameter of casing/ screen (mm)	250	300	300	250	300
Screened interval (mbgl)	27-73	16-52	14-53	36-89	32-75
Screened length (m)	46	36	39	53	43
Depth to rock (m)	36.6	13.4	18.3	24.4	24.0
Bedrock Unit	Mullaghfin Fmn	Loughshinny Fmn	Loughshinny Fmn	Loughshinny Fmn	Loughshinny Fmn
Static water level (mbgl)[2]	N/A	0 (artesian)	0.37	2.85	7.86
Static water level (mAOD)[2]	N/A	34.26	34.96	33.23	46.62
Pumping water level (mbgl)[3]	-	13.26	14.56	16.13	16.32
Pumping water level (mAOD)[3]	-	21	20.4	17.1	30.3
Average Current Abstraction (m^3/d)[4]	0	1051	1048	336	1043
Maximum Drawdown[a] (m)[5]	0	>13.26	>14.56	>16.13	>16.32
Specific Capacity [6, b] (m^3/d/m)	N/A	285	195	N/A	253

Notes:

1. PW1 is not in use as a production well.
2. Static water levels refer to June 2000 measurements.
3. Pumping water level refers to 31st July 2004.
4. Pumping rates since April 2004.
5. Pumping water level is still declining slightly (summer 2004).
6. Specific capacities during 24-hour tests in June 2000.

4: Methodology

4.1 Desk Study

Trial, Production and Observation borehole details such as depth, depth to bedrock, construction, abstraction figures, along with geological and hydrogeological information were obtained from GSI records, County Council personnel and hydrogeological reports by KTC/ WYG (K.T. Cullen & Co., now part of White Young Green) and P.H. McCarthy. Data from the IGSL report for RPS-MCOS were also assessed (IGSL, 2004).

[a] drawdown = static water level – pumping water level
[b] specific capacity = abstraction divided by the drawdown. It is an indicator of both the efficiency of the well under varying pumping rates, and indirectly of the capacity of an aquifer to transmit water to the well.

4.2 Site visits and fieldwork

The fieldwork undertaken for this project included carrying out depth-to-rock augering, subsoil sampling and vulnerability mapping. Two rotary-cored drill holes were drilled to try to establish the presence/ absence of gravel deposits along the Matt River and in the area east of Gibbonstown Reservoir. Elevations above sea level were computed at selected borehole and surface water locations by static GPS surveying using a Leica System 5000. Some basic surface water chemistry data were collected. Field walkovers were also carried out to investigate the subsoil geology, the hydrogeology and vulnerability to contamination.

4.3 Assessment

Analyses incorporated field studies, data collected previously, and numerical modelling to delineate protection zones around the public supply wells.

5: Topography, Surface Water Hydrology and Land Use

The locations of the Bog of the Ring boreholes are shown on Figure 2 (and subsequent maps). PWs 2, 3 and 4 are situated in the centre of the very flat-lying Bog of the Ring, at elevations ranging from 34.26 mAOD to 37.09 mAOD. PW5 is located about 1500 m further WNW on slightly higher ground (55.09 mAOD). As can be seen, the boreholes lie along the Bog road in a WNW-ESE trending line. This orientation is determined by the bedrock geology; more resistant Namurian Sandstones occupy the hills to the south of the valley and bog area, and Ordovician Volcanics occupy the slightly higher ground to the north of the Bog. Underlying the valley and the Bog are softer and more easily eroded and weathered shaly limestones.

As described, the topography has a WNW-ESE 'grain' owing to the underlying geology. The topography to the southwest of the boreholes is hilly, and ground elevation rises steeply to 176 mAOD at Knockbrack Hill. Many streams emerge at springs on the flanks of Knockbrack Hill, flowing generally northwards to the stream that drains through the Bog, westwards to the Delvin River, or eastwards to the Matt River. The Bog of the Ring is situated in a very low gradient (0.003-0.006), flat-bottomed valley. Streams drain from west-northwest to east-southeast along the valley, through the bog, to the Matt River. Gradients are similarly gentle along the Matt River, with the ground sloping northwards at gradients of <0.003. The Matt River flows northwards from around Hedgestown, to Stephenstown. It then flows northeast to the coast at Balbriggan. Approximately 2 km east of the Matt River, the ground rises to just under 100 mAOD at Salmon. Streams drain westwards to the Matt River. Northeast of the valley, the ground rises gently and is flat to gently undulating, with elevations ranging from 50-70 mAOD. In this area, streams generally emerge as seeps and drainage ditches and flow eastwards along a shallow valley which slopes eastwards at about 0.008 to join the Matt River near Folkstown Little. Just west of Killougher, streams drain westwards to the Delvin River, which flows through Naul. Along the Delvin River, ground elevation decreases in a northeasterly direction at about 1:200.

Agriculture is the main activity in the area. The bog area around the boreholes is used (in summer) for grazing cattle. Sheep are also grazed nearby. On higher ground away from the bog, the land use is a mixture of pasture and tillage. In Hazardstown, there are orchards. Main summer crops in the area are wheat and root vegetables. Although the entire area has mains drinking water, houses near the wells are serviced by individual septic tank systems.

6: Geology

6.1 Introduction

This section briefly describes the relevant characteristics of the geological materials that underlie the Bog of the Ring and surrounding area. This provides a framework for the assessment of groundwater flow and source protection zones that will follow in later sections.

Bedrock information was taken from a variety of sources including:

- GSI publication on the bedrock geology of the region (McConnell *et al.*, 2001)
- Hydrogeological reports and borehole logs from KTC/ WYG (1985, 1994, 2000).

Subsoils information derives from

- Quaternary mapping undertaken by the GSI (O'Connor, 1998);
- Teagasc subsoils mapping (Meehan, 2004);
- Permeability mapping by GSI field personnel in July and August 2004;
- Sixty auger holes and two rotary holes drilled by the GSI (July and August 2004);
- Site investigation data, including geotechnical descriptions and tests (e.g., particle size analyses, triaxial permeability, falling head) (IGSL, 2004; Benson & Partners, 2001; OCSC, 2003, Glover Site Investigations Ltd, 2000).

6.2 Bedrock Geology

The Bog of the Ring production wells (PWs 2-5) are located in the Loughshinny Formation, which is a shaly limestone, with bands of brown limestone (which is presumed to be dolomitised) recorded in some of the boreholes. The non-pumping PW1 penetrates the Mullaghfin Formation, which is a pure, well-bedded limestone.

The shaly limestone rocks that the majority of the boreholes are drilled into are commonly known as 'Calp' limestones. They are laterally interbedded with pure limestones, and underlie younger (Namurian age) rocks that are generally non-calcareous shales and sandstones.

In this part of Co. Dublin, the Carboniferous rock units (see Table 3) are folded into a gentle syncline (bowl-shaped fold), whose axis is roughly WNW-ESE. The Namurian shales and sandstones occupy the core of the fold, and are found in the south of the study area under the higher ground of Knockbrack Hill. The Calp Limestones are found under the low-lying ground in the centre of the study area in a WNW-ESE band about 500-800 m wide.

Significantly older Lower Palaeozoic rocks are faulted against the Loughshinny Formation to the north of the Bog area. The WNW-ESE trending fault zone is not a continuous line, but is cross-cut and offset by roughly N-S faults that also cut across the younger limestones and Namurian rocks.

Descriptions of rock units and details of the overall relationship between the Lower Palaeozoic and Carboniferous rocks are derived from a GSI report on the area (McConnell *et al.*, 2001).

The individual bedrock units are described in Table 3, and their distribution is shown in Figure 2 and Map 1. A cross-section is shown in Figure 3.

Table 3: Bedrock Geology of the Bog of the Ring area

Age		Geological Name	Geological Description	Maximum thickness (m)
CARBONIFEROUS	*Upper*	**Walshestown Formation (WL)**	Shales, thin sandstones/ siltstones, occasional thin limestones	>200
		Balrickard Formation (BC)	Coarse micaceous sandstone with shale interbeds	75-100
	Lower	**Loughshinny Formation (LO)**	Layered dark grey micrite and calcarenite (fine – coarse-grained limestone) and shale	100-150
		Naul Formation (NA)	Calcarenite and calcisilitite (coarse – medium-grained limestone) with minor chert and thin shales	100
		Mullaghfin Formation (MF)	Layered, pale grey peloidal calcarenite (coarse-grained limestone)	210
		Holmpatrick Formation (HO)	Well-bedded grainstone-packstone and micrite (coarse – fine-grained limestone)	80-90
		Malahide Formation (ML)	Layered argillaceous bioclastic (muddy and fossiliferous) limestone	300-1200
		mudbank limestone (mk)	Unbedded grey micritic (fine-grained) limestone	?
SILURIAN - ORDOVICIAN (LOWER PALAEOZOIC)		**Denhamstown Formation (DD)**	Greywacke (layered and poorly-sorted) sandstone and siltstone	?
		Skerries Formation (SS)	Laminated blue-grey siltstone, sandstone	>350
		Balbriggan Formation (GG)	Variably-coloured mudstone	~500
		Belcamp Formation (BP)	Andesite (volcanic rock), pillow breccia, mudstone and tuff	>1600
		Clashford Formation (CF)	Mudstone and siltstone, andesite	>100
		Herbertstown Formation (HB)	Andesite, tuff and mudstone	>300
		Snowtown Formation (SW)	Banded grey mudstone and siltstone	200
		Fourknocks Formation (FK)	Banded red and green mudstone and siltstone	?

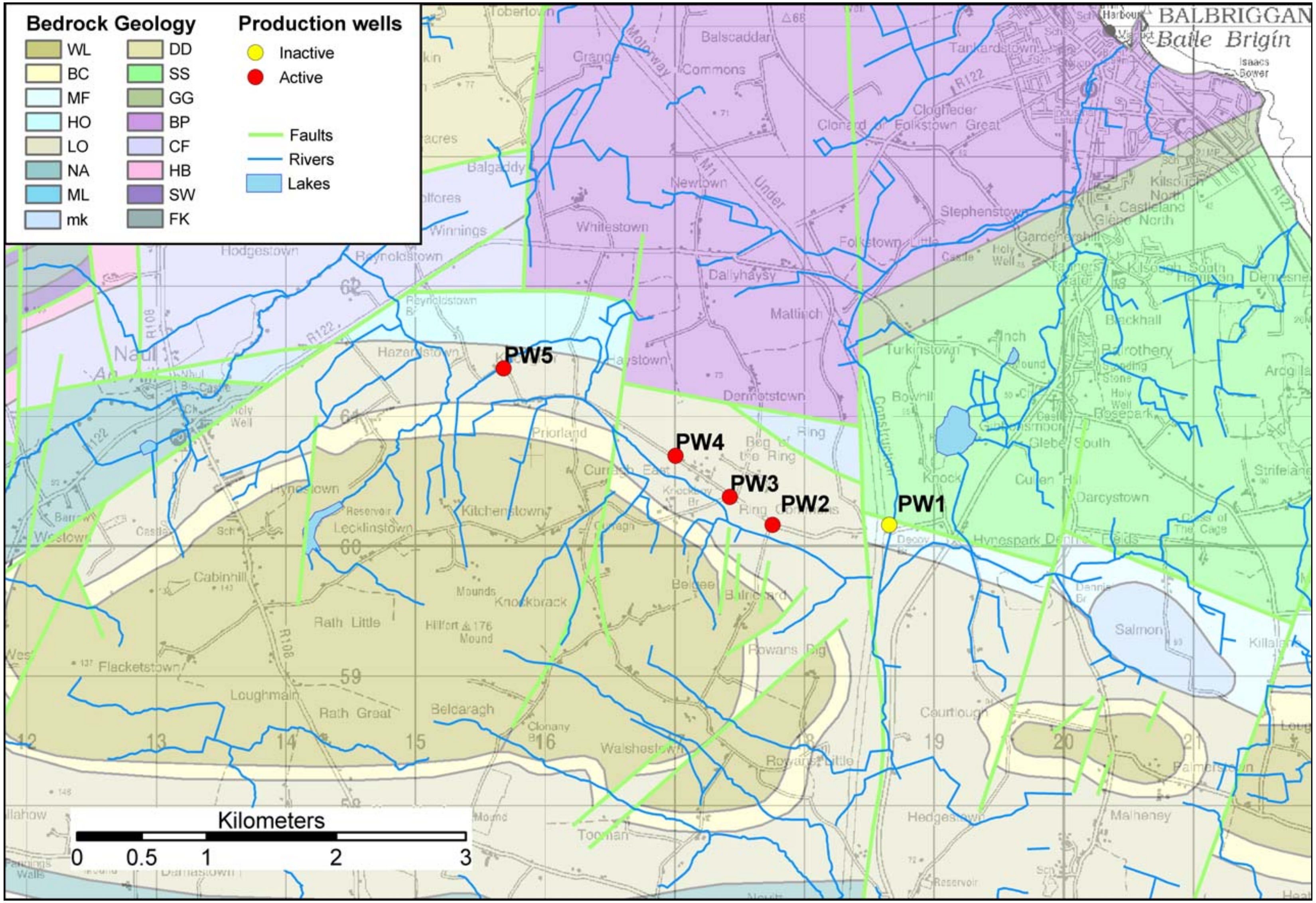

Figure 2: Bedrock Geology in the Bog of the Ring area. See Table 3 for bedrock geology codes and descriptions.

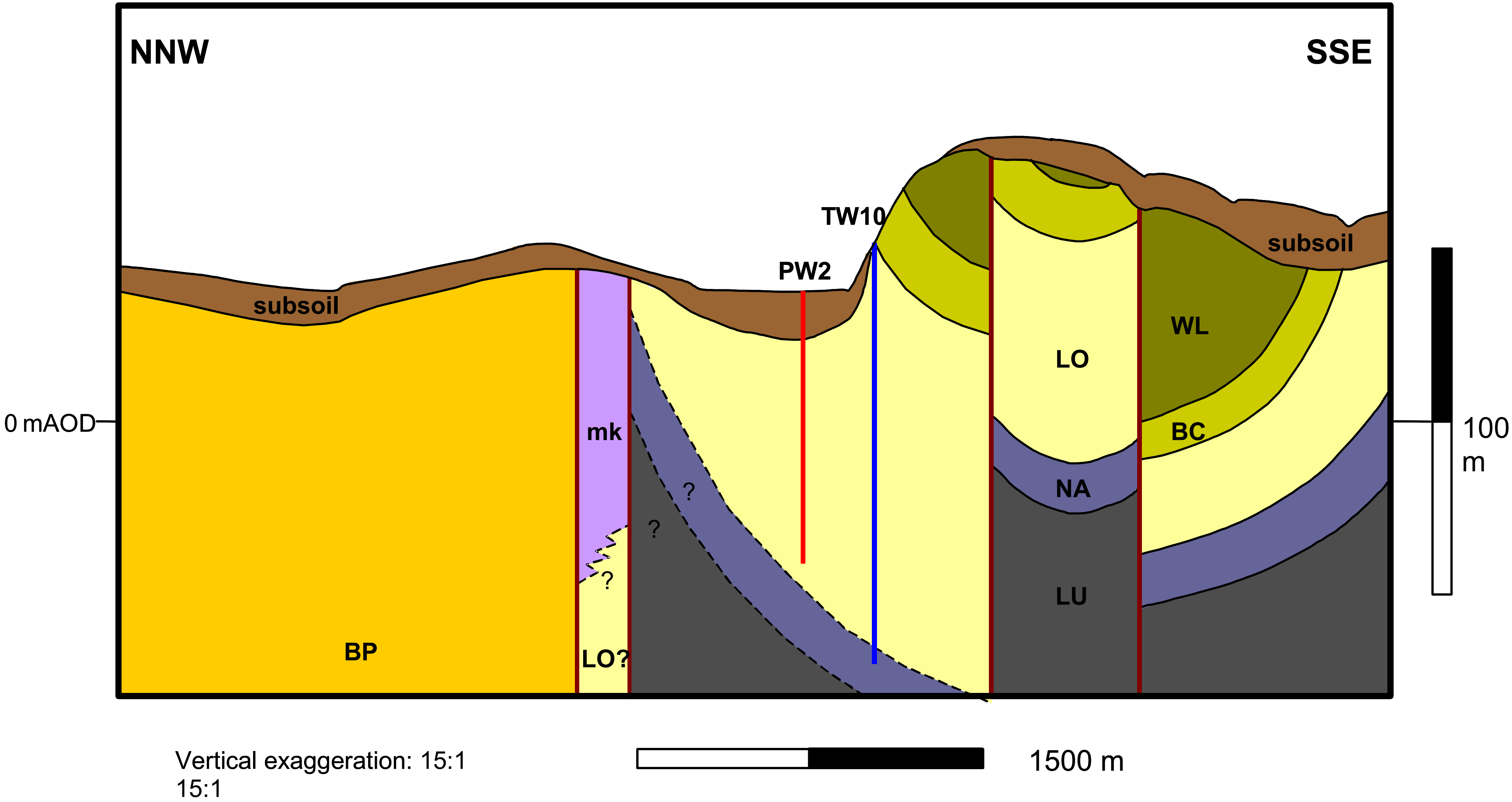

Figure 3: Cross-section.

6.3 Subsoil Geology

The subsoils in North Co. Dublin were mapped in the 1990's by the Quaternary Section of the GSI. This information has been incorporated in the Teagasc subsoil mapping (Meehan, 2004), on which the following categories and descriptions are based. Drilling and permeability mapping carried out for this project by the GSI provided additional information on the subsoils.

The subsoils comprise a mixture of fine-and coarse-grained materials, specifically, tills, lacustrine clays, alluvium and gravel. The characteristics of each category are described briefly in the following sections. The subsoil map is shown in Figure 4 and Map 2.

6.3.1 Till

Till is a poorly sorted sediment comprising a wide range of particle sizes. Tills are often overconsolidated, or tightly packed, unsorted, unbedded, possessing many different particle and clast (stone) sizes, and commonly have sharp, angular clasts (Meehan, 2004). Tills are often termed 'boulder clays' by engineers. There are three main types in the area, categorised according to their dominant lithological component, which are described below.

- **Sandstone and shale till (Lower Palaeozoic) with matrix of Irish Sea Basin origin (IrSTLPSsS)**
  Dominating the area to the north, east and west of the pumping wells the till is predominantly 'clayey' in texture (Meehan, 2004). Thirty seven auger holes were drilled by GSI into this till unit. The subsoil is classed as "**CLAY**" using BS 5930 (1999), in 49% of the available subsoil samples, and as "**SILT/CLAY**" in 40% .

- **Sandstone and shale till (Lower Palaeozoic) (TLPSsS)**
  This 'clayey' till unit is predominant in areas where rock is relatively close to the surface, which tend to be the higher relief areas. It generally comprises relatively small areas surrounded by the Sandstone and Shale till (IrSTLPSsS) unit in the northern half of the area. Furthermore, the till is distributed to the northeast and east of the rock outcrops, for example at Dermotstown and Stephenstown. Seven auger holes were drilled by GSI into this till unit. The texture is variable, with three samples classed as "**CLAY**", two samples as "**SILT/CLAY"**, and two samples classed as **"SAND/GRAVEL"**, using BS 5930.

- **Shales and sandstones till (Namurian) (TNSSs)**
  This 'clayey' till unit dominates the area to the south of the pumping wells. Fourteen auger holes were drilled by GSI into this unit. The subsoil is classed as **"CLAY"** using BS 5930, in 71% of the available subsoil samples (14).

6.3.2 Lacustrine Deposits (L)

Lacustrine deposits consist of sorted gravel, sand, silt and clay, occupying low-lying flat areas: in the vicinity of Ring Commons (where the pumping wells are situated) and along part of the Matt River, and at Gibbonsmoor. Sand and gravel is present beneath the lacustrine deposits. The thickness of the deposits overlying the sand and gravel in the area of the pumping wells is recorded in the borehole logs to be in the range of 9-12 m thick.

6.3.3 Alluvium (A)

Alluvium is a post-glacial deposit and may consist of gravel, sand, silt or clay in a variety of mixes and usually includes a high percentage of organic carbon (10%-30%). Alluvium is mapped only on modern day river floodplains. The alluvial deposits are usually bedded, consisting of many complex strata of waterlain material left both by rivers flooding over their floodplains and the meandering of rivers across their valleys. Alluvium is found primarily in lowlands along the Matt River and its tributaries, and along tributaries of the River Delvin. One borehole from the area is located in alluvium. Based on the gradient and energy regime of the Matt River, the deposits are expected to be primarily sands and silts with minor clay bands.

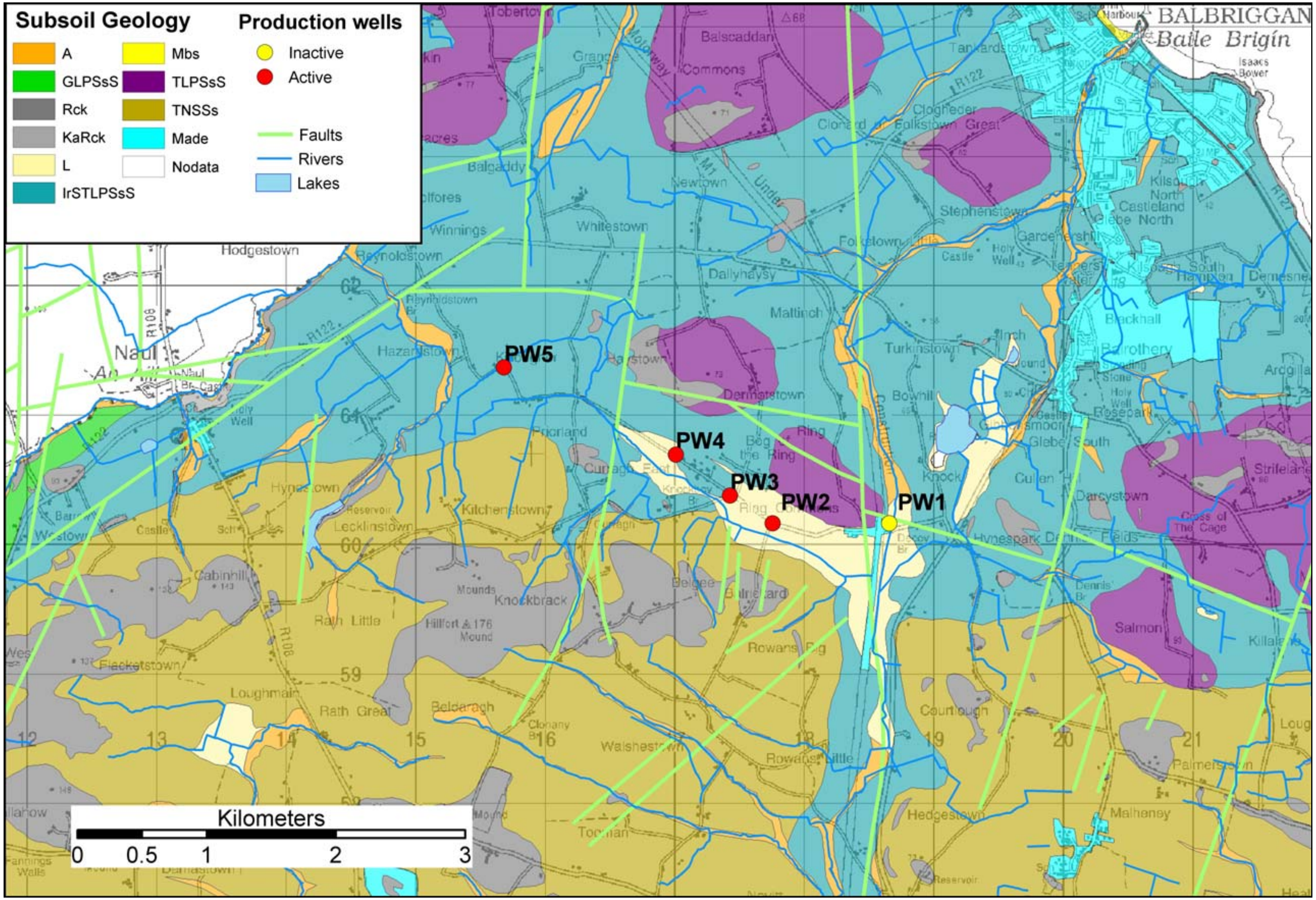

Figure 4: Subsoil Geology mapped by Teagasc in the Bog of the Ring area (Meehan, 2004). See Section 6.3 for descriptions and codes, excepting:
Mbs - Beach/raised beach sand; Rck - Bedrock at surface; KaRck - Karstified limestone bedrock at surface; Made - Made ground

6.3.4 Sand and Gravel

Glaciofluvial sands and gravels are different from tills in that they are deposited by running water only. The gravels usually have rounded edges, and the deposits are generally stratified (layered). As these deposits were lain by the water from melting glaciers, they represent the stagnation and decay of the ice sheets. The deposits are categorised according to dominant lithology (Meehan, 2004). The principal category in the area are Sandstone and shale sands and gravels (Lower Palaeozoic) (GLPSsS) and are located in the vicinity of the Delvin River, south of Naul and in the north of the area in the vicinity of Gormanstown. Approximately 5 m of sand and gravel is present beneath the Lacustrine deposits in the vicinity of PW2 and PW3, and up to 12 m is present at PW4. This gravel deposit is thought to be mostly clean and well bedded. A borehole drilled adjacent to PW7 by the GSI indicated 'GRAVEL' with 'sandy SILT' interbeds. A separate subsoil exposure to the north of the borehole was described as 'SAND' with thin gravel lenses. A few other, smaller areas of gravel are mapped within the source area; these are expected to be less clean, clayey gravel.

6.3.5 Depth to Bedrock

Sixty auger holes were drilled by the GSI in the vicinity of the production wells to ascertain the depth, thickness and permeability of the subsoils. Using this information, knowledge of sites that have rock cropping out, and areas indicated by Teagasc mapping as having rock close to surface, the depth to rock is estimated across the area. Over most areas, the depth to bedrock is generally greater than 10 m, and in the Bog area typically exceeds 15 m. Areas where the top of the bedrock is ≤ 5 m from ground surface occur towards the top of Knockbrack Hill (in the south of the study area), along parts of the Delvin River (in the west), around Dermotstown (just north of the Bog), and around Courtlough and Palmerstown (in the east).

7: Hydrogeology

7.1 Introduction

This section presents our current understanding of groundwater flow around the Bog of the Ring boreholes. These interpretations and conceptualisations of flow are used to delineate the source protection zones around the wells.

Hydrogeological and hydrochemical information for the study was obtained from the following sources:

- 48-144 hour pumping tests on trial wells (TWs 1, 4, 7, 8, 9, 10, 12 and 13) performed by KTC (K.T. Cullen & Co.) in 1984 and in 1993/94;
- 72-hour pumping tests carried out by KTC at Production wells (PWs 2, 3 and 5) in June 2000;
- Seven-day simultaneous pumping tests conducted sequentially, firstly at PWs 1, 2 and 3, and then at PWs 4 and 5 performed by KTC in July 2000;
- Monitoring of observation wells and shallow standpipes during the seven day tests on the production wells;
- Packer test data collected by IGSL on behalf of RPS-MCOS (IGSL, 2004);
- Local hydrogeological mapping carried out by the GSI;
- Drilling and permeability mapping carried out by GSI to ascertain depth to bedrock and subsoil permeability;
- Geotechnical assessments of subsoil permeability and particle size distribution in selected sites (IGSL, 2004);
- GSI files and Fingal County Council data;
- Water quality test results from samples collected during the various pumping tests at selected trial wells and all the production wells (K.T. Cullen & Co., 1994, 2000(a), 2000(c));
- Water quality results from local streams, collected by Fingal Co. Co. and by K.T. Cullen (2000(c));
- Numerical modelling by the GSI to estimate the ZOC and 100-day time of travel.

7.2 Meteorology and Recharge

The term 'recharge' refers to the amount of water replenishing the groundwater flow system. For the purposes of this report, the recharge rate is estimated on an annual basis, and is assumed to consist of the input (i.e. annual rainfall) less water losses prior to entry into the groundwater system (i.e. annual evapotranspiration and runoff). The estimation of a realistic recharge rate is critical in source protection zone delineation, as it dictates the size of the zone of contribution to the source.

The main parameters involved in recharge rate estimation are annual rainfall, annual evapotranspiration, and annual runoff. For this source report, the estimated parameters are outlined in the following sections.

7.2.1 Average Annual Rainfall

The average annual rainfall for the period 1971-2000 is 808 mm/yr over the majority of the area (rainfall data are from Met Éireann average annual rainfall values).

7.2.2 Annual Evapotranspiration

Annual evapotranspiration (A.E.) is approximately 445 mm/yr (Met Éireann average annual evapotranspiration data).

7.2.3 Potential Recharge

Potential recharge is calculated at 358 mm/yr. This is calculated by subtracting the estimated evapotranspiration from the average annual rainfall.

7.2.4 Estimated Actual Recharge

Estimated Actual Recharge represents the amount of water that will infiltrate to groundwater. Recharge is likely to vary according to subsoil permeability and subsoil thickness, for example recharge is likely to be greater in areas dominated by higher permeability subsoils and shallower depths to bedrock. Thus, recharge coefficients are applied to the potential recharge estimation to arrive at the actual recharge value. The recharge coefficients are derived from ranges suggested by the Working Group on Groundwater (in prep.). Table 4 presents the recharge coefficients used for the different permeability and vulnerability settings. The actual estimated recharge ranges from approximately 0 mm/yr in the areas where artesian conditions occur to 322 mm/yr where the subsoil is thin (less than 3 m thick) or absent. Over most of the area (dominated by low permeability thick subsoils) the recharge is estimated to be approximately 57 mm/yr.

Table 4: Recharge coefficients (rc) for different subsoil permeabilities and thicknesses

Subsoil thickness	Subsoil Permeability	Vulnerability	recharge coefficient (rc)
Rock close to surface	-	Extreme	90%
1-3 m	-	Extreme	80%
3-10 m	Moderate	High	35%
3-5 m	Low	High	30%
5-10 m	Low	Moderate	20%
>10 m	Moderate	Moderate	25%
>10 m	Low	Low	15%
	Moderate*	Low	20%

* The variability of the till categorised as **Sandstone and shale till (Lower Palaeozoic) (TLPSsS)** is such that the recharge is likely to be greater than that through the other till types.

7.3 Groundwater Levels, Flow Directions and Gradients

As part of the investigations by K.T. Cullen/ White Young Green, water levels in the vicinity of the production wells were recorded at various stages over the 20-year investigations:

- Water levels in the trial wells were recorded shortly after drilling in TW1 and TW4 (December 1984); TWs 6, 7 and 8 (April-May 1993); TWs 9, 10, 11, 12 and 13 (December 1993-March 1994).
- Water levels in some of the trial wells (TWs 7, 10, 12, 13 and 14) and nearby Co. Co. handpumps (PS1, 2 and 3) were also monitored over a longer period:
  - Once or twice a month from 27/7/99 to 15/12/99 and then from 4/1/00 to 14/9/00 (handpumps monitored only to 12/6/00);
  - Once to four times a month from 29/9/03 to 26/03/04 (trial wells and PS3 only).
- Water levels in the seventeen 'standpipes' (shallow piezometers) installed in the bog, six of which have two-depth sampling, were monitored over the periods:
  - Two measurements on 26/11/99 and 15/12/99 (all standpipes);
  - Once or twice a month from 4/1/00 to 12/6/00 (S10A & B only until 17/4/2000; S1A, S2A & B, S3, S8, S9A & B, S11, S15, S16A, S16B only until 17/7/00);
  - Once or twice a month from 29/9/03 to 26/3/04, then on 5/7/04 and 19/7/04 (S1B, S4, S5, S6, S7, S13, S14A & B, S17 only).

  (Many of the standpipes have been lost, since they are in areas grazed by cattle or may have been disturbed by other agricultural activities.)
- Water levels were monitored before, during and after the two sequential seven-day pumping tests on the production wells. Water levels were monitored in:
  - The five production wells during the 24 hour and 7 day tests in June and July 2000.
  - Eight observation wells (OBs 1 to 8), five of which also have piezometers in the subsoil. These were monitored at least daily over the period 26th June-27th July 2000, with a final measurement on 14th September 2000.
  - Eight standpipes (S1B, S4, S5, S6, S7, S13, S14A & B, S17), one of which has two-depth sampling. These were monitored almost daily from 26th June to 17th July 2000.
- Monitoring continued at seven observation wells (OBs 1 to 7) over the period 29/9/03 to 26/3/04, with two measurements on 5th and 19th July 2004.

Other data were collected by the GSI, and derived from other reports:

- GSI personnel measured water levels before (once on 24th and/ or 25th June 2004) and during the three-day production well shut-off (29th June – 1st July 2004) and for one day of pumping resumption (2nd July) at TWs 7, 10, 14; OBs 1, 3, 4, 5, 6, 7; standpipes S1B, 5, 6, 17. Water levels were monitored at frequencies ranging from 2-60 minutes on the first day of shut-off and on resumption of pumping, and between 2-6 times a day for the other two days. Water levels at the TWs and OBs were also measured on 19th July 2004.
- Water levels in twenty-one boreholes, dug wells and springs to the north of the Bog were also collected by GSI personnel on 10th- 13th August 2004.
- Water levels measured in domestic wells in October 2001 in the vicinity of Salmon (S.M. Bennet & Co., 2001).
- Water levels measured in trial wells in February 2003 in the vicinity of Loughbarn (OCSC, 2003).
- Water levels measured in boreholes drilled on behalf of RPS-MCOS (IGSL, 2004) at Salmon and Tooman in the summer of 2004.

In summary, there are numerous water level data, but the measurements derive from different times of year, different years, and different pumping conditions, so data in different locations cannot be related directly to one another, but used only as a guide to evaluating the "water table" map. There has been no continuous pre-pumping water level sampling across the monitoring network during the summer (non-recharge) months.

In areas of low transmissivity aquifers (e.g., Knockbrack Hill, formed by Namurian mudstones; and areas around Reynoldstown and Knock/ Balrothery, which are underlain by Lower Palaeozoic sandstones and siltstones), groundwater is likely to be close to the surface, particularly during winter. This is because the aquifers have generally low storage and cannot accept significant volumes of water, and low transmissivity, meaning that recharge cannot be transmitted quickly away from the waterlogged area. In contrast, in the higher transmissivity aquifers within the study area, the water table can be 5-10 m below ground level in elevated areas.

Groundwater is also close to ground level in low-lying areas and around areas where groundwater discharges (e.g., streams that are in hydraulic continuity with the aquifer). Underneath the Bog of the Ring and along parts of the Matt River south of Decoy Bridge, the groundwater is confined by low permeability Lacustrine subsoils. Because of this confinement, the groundwater pressure builds up to above ground level (due to groundwater flowing to these low-lying areas from elevations higher than the bog and river). This results in what is known as artesian conditions and, when boreholes penetrate the subsoil, groundwater overflows at the surface.

Where there is thick, low permeability subsoil, ‘perched’ groundwater conditions can develop. This situation arises when horizons within the subsoil become saturated due to very low permeability layers stopping further downward movement of recharging water. Beneath the low permeability layer, the subsoil is dry. These conditions are not reflected in the water level contour map, which shows bedrock water levels.

A contour map of “winter”, pre-pumping water level data is shown in Figure 5. The contours are based on an interpretation of water level data measured at boreholes, augmented with the elevations of streams in shallow rock areas, and springs. Overall, the water table is assumed to be a subdued reflection of topography. Where the subsoil is not too thick, the groundwater is likely to be unconfined (i.e., water table aquifers exist). In areas with thick, low permeability subsoil, the groundwater level is typically above the base of the subsoil, resulting in partially confined aquifer conditions. As discussed above, areas of the aquifer are artesian.

Groundwater contours show that groundwater flows northwards, NW and eastwards from Knockbrack Hill. Gradients are steep, reflecting both the steep topography and the low aquifer transmissivity, and range from 0.05 to 0.07. Some groundwater discharges to springs and to the streams that incise the hillside. The amount of groundwater discharging to the streams depends on the thickness and permeability of the subsoil. The thickness of the subsoil increases towards the base of the hill, reducing the contribution of groundwater to the stream flow in these areas. The remaining groundwater flows into the high transmissivity shaly limestone aquifer at the base of the hill.

In the east of the study area, groundwater flows westwards from the hills at Salmon, Palmerstown and Strifeland. Groundwater gradients range from 0.01 to 0.05, depending upon the topography and on the aquifer transmissivities (in general, high transmissivity aquifers have lower groundwater gradients than low transmissivity aquifers).

Groundwater flows southeastwards under the Bog. Groundwater gradients are very gentle (0.003), and groundwater is artesian under parts of the Bog. West of the Bog, groundwater gradients are slightly steeper (approximately 0.005). In general, the streams running through the Bog are not thought to be affected by groundwater levels, although water level data collected during the seven day pumping tests indicate that, in some areas of the Bog, surface water levels are affected by groundwater levels.

In the area of the Matt River, groundwater flows northwards (i.e., roughly parallel to the river) with similarly low gradients (0.003). Drilling has shown that artesian conditions exist underneath parts of the Matt River south of Decoy Bridge. However, the groundwater flow directions and contours indicate that groundwater discharges to the Matt River along parts of its length. This may be particularly the case north of Decoy Bridge. The groundwater divide south of Rowans Little is assumed to be coincident with the surface water divide.

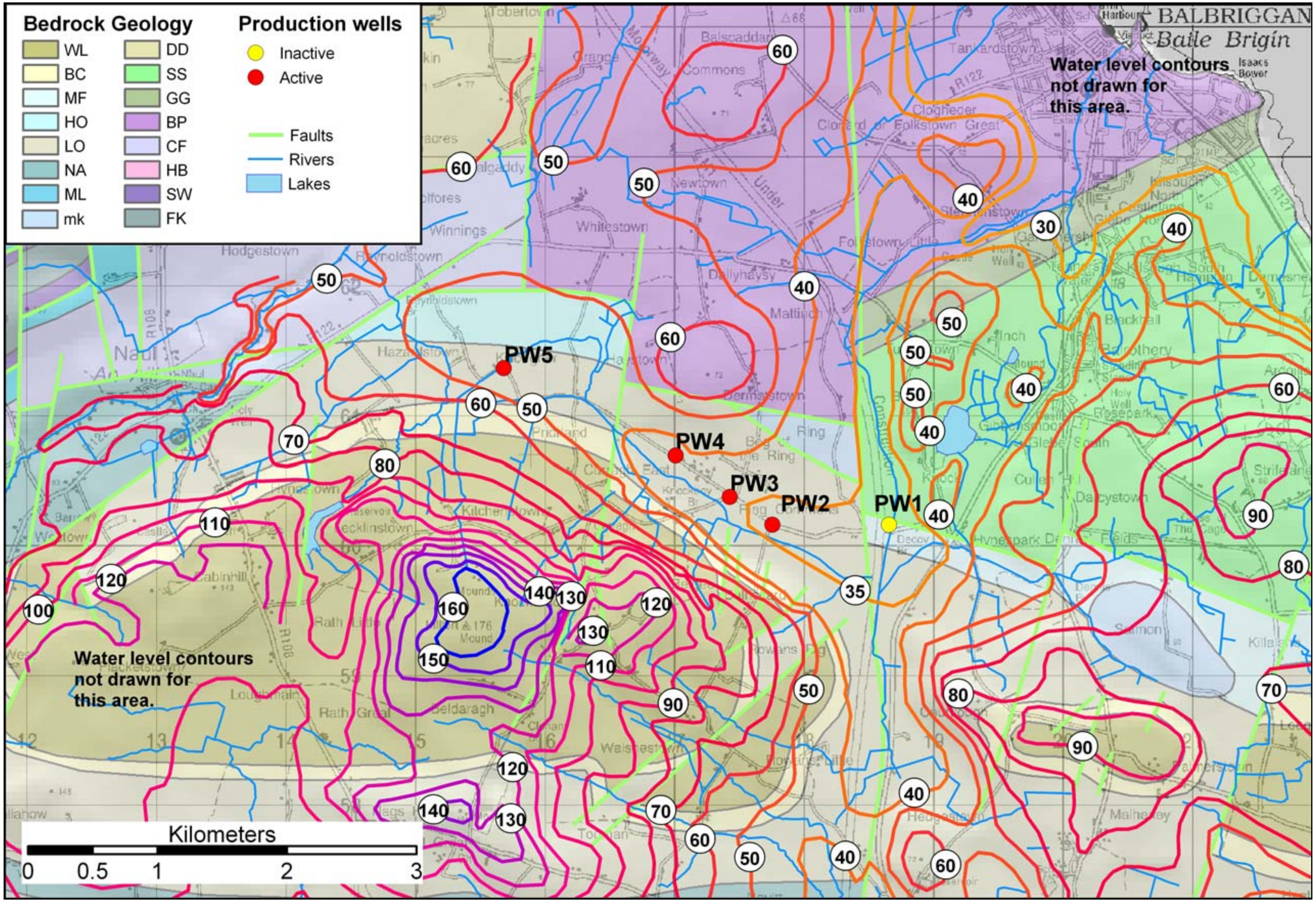

Figure 5: Groundwater level map in the Bog of the Ring area. Note that the contours are an interpretation based on well data, topography and surface water features. The groundwater heads are based primarily on winter data, and represent a non-pumping situation.

West of the Bog, in the vicinity of Hazardstown, there is a groundwater divide (a local groundwater high). To the east of the divide, groundwater flows southeastwards under the Bog and towards the Matt River. West of the divide, groundwater flows westwards to the Delvin River. The precise location of the groundwater divide is hard to determine, as the topography in this area is extremely subtle, and there are few borehole data to constrain its location. Available data and the distributions of high and low transmissivity aquifers indicate that it lies to the west of the surface water divide. It is likely that the position of the groundwater divide varies seasonally.

North of the Bog, the terrain is gently rolling, with elevations ranging from 50-70 mAOD. Groundwater mounds develop underneath the small hills, with groundwater flowing radially outwards. In the Whitestown to Dermotstown area, groundwater generally flows southwards. In the Newtown and Dallyhasy area, groundwater flows northeast/ east. In this area, groundwater appears to discharge to the streams and drainage ditches that flow eastwards to the Matt River along a shallow valley which slopes at about 0.008

The shape of the groundwater contours indicates that groundwater contributes to flow in the Delvin River, Matt River and the tributary to the Matt River that flows from Newtown to Folkstown. However, the amount of groundwater contributing to the river flows is difficult to determine since it depends upon the permeability of the river bottom. According to GSI records and the Teagasc subsoils maps, the Delvin River has rock outcropping along it course and/ or has high permeability sandy and gravelly subsoils adjacent to it. GSI drilling indicates that subsoils along the valley running from Newtown to Folkstown are gravelly and of at least moderate permeability (see section 6.3).

The nature of the subsoils and groundwater–surface water interaction along the Matt River is far less clear. Subsoil thicknesses range from 15 to more than 40 m, with low permeability tills overlying gravelly subsoils, which in turn overlie the bedrock aquifers. South of Decoy Bridge, artesian conditions in an area overlain by almost 10 m of clay were recorded (TW6). Between this well and Decoy Bridge, another borehole penetrated more than 30 m of low permeability clays before stopping in gravel (TW9). These thicknesses indicate that there is generally no interaction between groundwater and surface water systems in this area, although there may be local zones where the low permeability subsoil is sufficiently thin to permit this to occur. Further downstream (i.e. north of Decoy Bridge), the nature of the subsoils is less well known, but the general pattern of heads suggests that groundwater must discharge to the Matt River. As mentioned above, groundwater is not considered to contribute flow to the small rivers and streams crossing the area except in areas where subsoil is thin.

7.4 Aquifer Category

The distribution of aquifers is shown in Figure 6 and Map 3. The supply wells penetrate bedrock units that are hydrogeologically similar and hydraulically connected. Four of the wells (PWs 2, 3, 4 and 5) are located in the fractured shaly limestone of the Loughshinny Formation, which is classified as a **locally important aquifer that is generally moderately productive (Lm)**. Production well 1 (PW1) was drilled into the pure bedded limestone of the Mullaghfin Formation, into which the Loughshinny Formation grades northwards. This is classified as a **locally important karst aquifer (Lk)**. Further west, the Loughshinny Formation grades northwards into the pure limestone of the Holmpatrick Formation, which is also classified as an **Lk** aquifer. Westwards, it is faulted against the Naul Formation, which is similar to the Loughshinny Formation, but is more cherty and less shaly. The Naul Formation is also classified as a **locally important aquifer that is generally moderately productive (Lm)**. For the purposes of the report these limestone units are collectively referred to as the ‘Bog of the Ring aquifer’.

The ‘Bog of the Ring aquifer’ is bounded to the north by a WNW-ESE major fault (the North Dublin Fault) that juxtaposes the limestones of the aquifer against Lower Palaeozoic rocks. To the south, the limestones dip beneath younger layered shales and sandstones.

To the north of the Bog of the Ring, the Lower Palaeozoic aquifers comprise (a) fractured volcanic rocks (the Belcamp Formation) and (b) layered and metamorphosed sandstones, siltstones and mudstones (“greywackes”) (the Skerries and Clashford House formations). The fractured volcanic rocks are classified as a **locally important aquifer that is generally moderately productive (Lm)**.

The layered sandstone/ mudstone rock units, although highly deformed, are typically of low permeability and are therefore classified as an **aquifer which is generally unproductive except for local zones (Pl)**.

Low permeability Namurian rocks occur to the south of the Bog of the Ring. These comprise the Balrickard and Walshestown formations. Both these rock units are classified as **aquifers which are generally unproductive except for local zones (Pl)**. The Balrickard Formation consists of coarse sandstone interbedded with mudstones, and is therefore likely to have a slightly higher permeability (due to faulting and fracturing) than the overlying mudstones and siltstones of the Walshestown Formation. A borehole drilled by KTC into the Walshestown Formation (TW7) was test pumped at approximately 500 m^3/d. The drilling records indicate that nearly all this flow entered the well at about 72.5-74 mbgl in a layer of brittle siltstone.

Small, discontinuous areas of Mudbank limestone are mapped along the fault. This pure, unbedded limestone is classified as an **aquifer which is moderately productive only in local zones (Ll)**. More information regarding the specific well information used to arrive at the aquifer classifications is presented in the Draft National Aquifer Report (GSI, in prep.).

7.5 Aquifer Characteristics

Numerous north-south trending faults have been mapped cross-cutting the 'Bog of the Ring aquifer', offsetting it against itself, and staggering the boundary with the overlying shales and sandstones (to the south), and the boundary with the much older volcanic and layered sandstone/ shale rocks (to the north). Additionally, there are approximately east-west trending faults running close to the main North Dublin Fault. TW8 and TW14 record the effects of the intense faulting along the fault zones associated with the E-W North Dublin Fault and the major N-S that cross-cuts it near Decoy Bridge; the borehole log for TW8 describes 25 m of 'broken limestone conglomerate', whilst at TW14 the older green greywacke sandstones overlie broken limestone. Faults and additional fracturing associated with these faults are likely to increase the permeability of the aquifer. The numerous faults and fractures have resulted in a high transmissivity zone running WNW-ESE beneath the Bog. There is also a N-S trending fault zone running almost parallel to the M1 and the Matt River in the vicinity of Mattinch – Decoy Bridge and Courtlough (Matt River/M1 zone). The well field is located primarily in the WNW-ESE fault zone ('Central Zone').

Overall, the fracturing and faulting within and between the various rock units dominate permeability development within the rocks, thus controlling the overall transmissivity of the aquifer. Additionally, the borehole logs for some of the trial, production and observation wells (TWs 4, 10 and 13; PWs 2 and 4; OWs 4 and 6) indicate zones of dolomitised limestone. These zones, ranging from 0.5 to about 5 m, are associated with water inflows. Furthermore, where the limestones are purer (i.e. less clayey/ shaly), dissolution may occur along faults, fractures and bedding planes, widening them and enhancing the permeability. In some parts of the impure limestone aquifer, the permeability will be affected by low permeability fine-grained and shaly beds. However, due to the intense faulting and associated fracturing, the effect of the low permeability beds on the overall permeability of the Bog of the Ring limestone aquifer will be reduced, or even negated completely. Analyses of aquifer characteristics around the supply wells are based on test pumping undertaken by K.T. Cullen & Co. of trial wells (December 1984 to March 1994) and production wells (June 2000). Additionally, two sequential seven-day constant discharge tests were run in July 2000, simultaneously testing PWs 1, 2 and 3 and then PWs 4 and 5. Information gained from the pumping tests, such as average discharge, drawdown, specific capacity and transmissivities are summarised in Table 5. All data are from K. T. Cullen & Co. pumping tests, except where indicated as being from OCSC (OCSC, 2003).

The pumping tests assess a relatively large volume (10,000's m^3) of aquifer over a vertical interval of metres to 10's metres. Therefore, the pumping tests should be representative of the bulk aquifer characteristics. Note that, in some cases, considerably higher transmissivities are derived from recovery data. This is thought to be due to the fact that well losses influence the drawdown during pumping and because, during pumping, the high permeability zone at the top of the aquifer is dewatered. Note also that the transmissivity and permeability values have a wide range. This reflects the heterogeneity of fractured and faulted aquifers such as this. Productivity classes are also used to assess the aquifers. They are based on the specific capacity (well yield divided by water level drawdown) of a well, I the context of its discharge rate, and range from I (highest) to V (lowest). They provide a consistent and objective measure of an aquifer's ability to yield water (Wright, 2000).

Within the Loughshinny and Mullaghfin Formations, transmissivities and permeabilities calculated from 24- to 72-hour constant rate pumping tests, and from step tests, range from 23-290 m^2/d and 0.65-13.9 m/d, respectively. Specific capacities range from 35 – 285 m^3/d/m; and productivity values for these wells are in classes I and II, indicating that these wells are located in a productive, permeable aquifer. The test in the Mullaghfin limestone (TW8) indicated a lower than expected transmissivity. This may be due to the proximity of the borehole to low permeability Lower Palaeozoic rocks, or due to high well losses during testing (the borehole log indicates numerous cavities and fissures, which would induce turbulent flow).

The Lower Palaeozoic Volcanics (the Belcamp Formation) have transmissivities in the range 22-100 m^2/d, and permeabilities ranging from 1.3-5.9 m/d. The specific capacity of the trial borehole (TW1) is 40.3 m^3/d/m, giving a productivity index of II. Two wells used by Wavin have specific capacities of 14.1 and 19.1 m^3/d/m, and productivities of III and II respectively.

A pumping test in the Namurian mudstones of the Walshestown Formation (TW7) indicates transmissivities in the range 18-28 m^2/d, and permeabilities ranging from 0.3-0.5 m/d. The specific capacity of the trial borehole is 15.8 m^3/d/m, with a productivity index of III.

Pumping of the well completed in gravel (TW9) indicates a transmissivity in the range 58-66 m^2/d. However, these values are considered to be a considerable underestimate, since the construction of the well would induce enormous well losses (and therefore high drawdowns). A transmissivity of >100 m^2/d is given in Table 5, which equates roughly to permeabilities of >50 m/d. The specific capacity of this well was 41 m^3/d/m when it was tested.

Analysis of the 24 to 72 hour pumping tests on the production and trial wells shows that the shaly limestone aquifer is heterogeneous, with transmissivity varying at different locations by up to an order of magnitude (see Table 5). This is typical of fractured aquifers. The degree of heterogeneity is highlighted by the fact that the water level at OW4 was affected almost as much by pumping at PW3 (530 m to the east) as it was by pumping at PW4, approximately 10 m away. Additionally, water levels at OW5, 600 m from PW3 and only 7 m from PW4 were affected most by pumping at PW3. (However, it should be noted that the pumping rate at PW3 was more than five times greater than at PW4.)

Water levels measured during the two seven-day pumping tests show that the cone of depression from pumping PWs 1, 2 and 3 (at 1000, 2500 and 2500 m^3/d respectively) extends as far east as OW6, at least as far south as TW9 and at least as far west as OW5 and TW13. Measurement of water levels in available observation wells and trial wells indicates that OW3 (at Decoy Bridge) is within the cone of depression of PW6, but that OW6 further west is not. TW9 was not accessible for measurement.

Pumping PWs 4 and 5 simultaneously (at 480 and 2500 m^3/d respectively) impacted on TWs 12 and 3, and OWs 4, 5, 7 and 8. TW3 became non-artesian. The recovery of water levels drawn down at TW11 and OW2 during the first seven-day test was inhibited by pumping at PWs 4 and 5 during the second test.

Groundwater levels in the Bog and saturated subsoils near the Bog had varying responses to pumping in the production wells. During the seven day tests in July 2000, water levels at both PS1 and PS2 (Co. Co. handpumps which are assumed to draw water from the overburden) were affected. Water levels at PS1 are below the bottom of the well in 2004; water levels in PS2 cannot be measured. The impact of pumping was also experienced in the overburden at OWs 1, 2, 3 and 5 (and very slightly at OW5) and at standpipes S1, S9, S14 and S15. The seven day pumping tests did not appear to affect water levels in the other standpipes. This indicates that there is a degree of hydraulic continuity between the subsoil deposits and the bedrock aquifer, but that it is also quite variable.

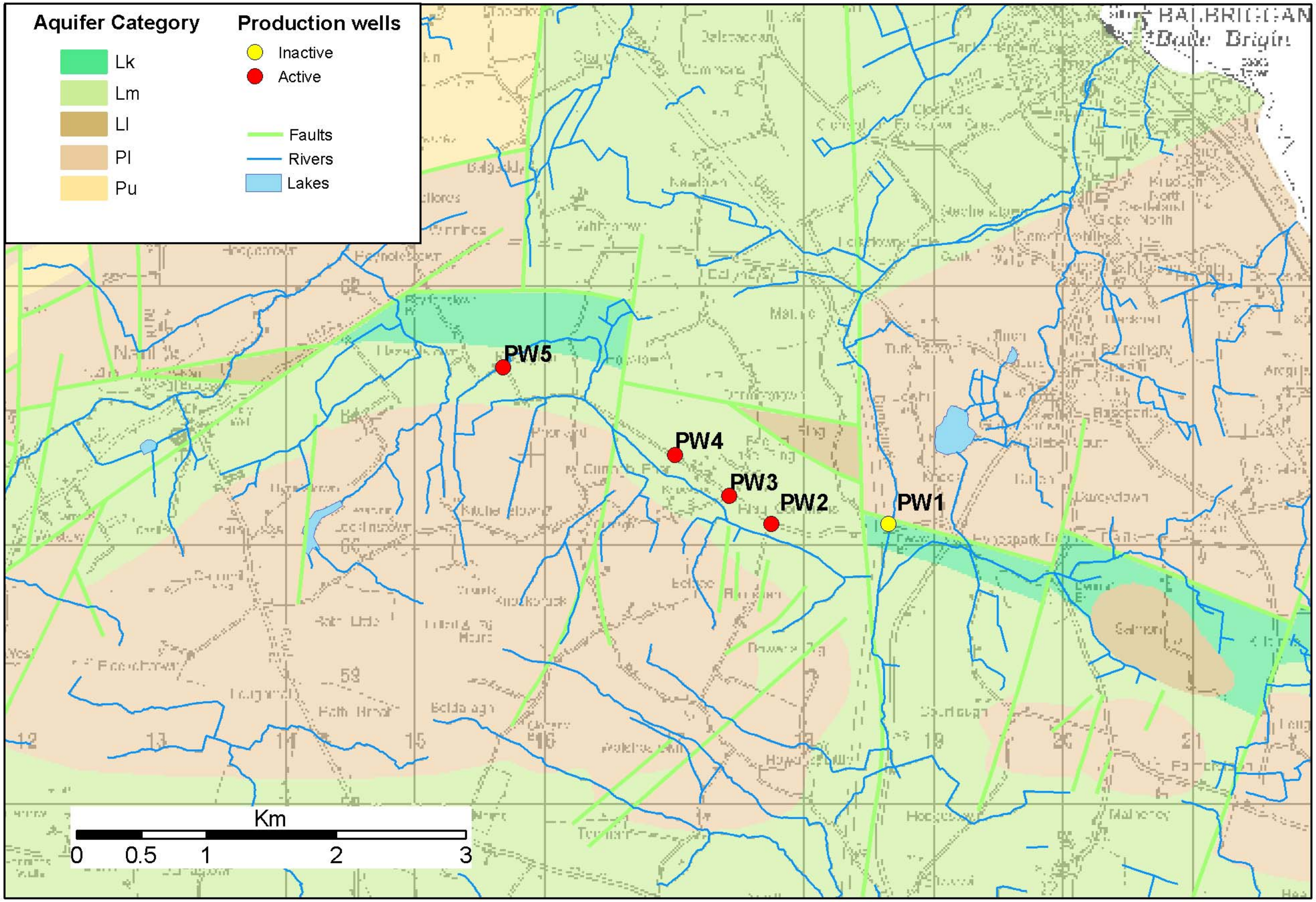

Figure 6: Aquifer Categories in the Bog of the Ring area (GSI, 2004). See Section 7.4 for descriptions and codes.

Table 5: Summary of aquifer characteristics

Well name	Test type [1]	Test date	Average Discharge (m^3/d)	Drawdown (m)	Specific Capacity ($m^3/d/m$)	Productivity Class	Transmissivity (m^2/d)	Saturated screened/ open interval (m)	Permeability (m/d)
Loughshinny Formation (shaly limestone)									
PW2	Constant rate [2]	June 2000	2654	9.42 (24hr)	282 (24hr)	I	139-152	36	3.9-4.2
	Recovery		2654				289	36	8.0
PW3	Constant rate [2]	June 2000	2730	13.63 (24hr)	200 (24hr)	I	141-149	39	3.6-3.8
	Recovery		2730				229	39	5.9
PW5	Constant rate [2]	June 2000	1945	7.7 (24hr)	253 (24hr)	I	133	43	3.1
	Recovery		1945				265	43	6.2
TW4	Constant rate [3]	15 Jan 1985	698	7.71 (40mins)	64.6 (84hr)	I/II	99-102	49	2-2.1
	Step test	15 Jan 1985	698, 785, 1056	7.71, 11.5, 15.27			79-188	49	1.6-3.8
TW10	Constant rate[3]	23 Feb 1994	505	7.28 (90mins)			111	76.5*	1.45
							111	30 ***	3.7
	Recovery		1145	30.85 (75hr)	37.2 (75hr)	II	173	76.5*	2.3
	Step test	23 Feb 1994	504, 785, 1180	7.28, 14.42, 27.68			65	76.5*	0.85
TW12	Constant rate	March 1994	2470	8.7	276 (48hr)	I	250	18	13.9
	Recovery		2470				240	18	13.3
TW13	Step test	8 March 1994	530, 969, 1283	7.84, 18.68, 29.58	42.6 (step 3, 270mins)	II	41-45	12	3.4-3.75
TW1 OCSC	"Constant rate"	8 Feb 2003	540	3.67	147 (120hrs)	I	60	24.4	2.5
Mullaghfin Formation (pure bedded limestones)									
TW8	Step test	5 Jan 1994	490, 870	7.64, 17.62	35.2 (75 hr) 4	II	23-33	8	2.9-4.1
Belcamp Formation (Lower Palaeozoic volcanics)									
TW1	Constant rate	4 Dec 1984	924	22.93 (72 hr)	40.3 (72hr)	II	22-24	17*	1.3-1.4
	Recovery		924				100	17*	5.9
Walshestown Formation (Namurian mudstones)									
TW7	Step test	May 1993	520, 655, 820, 1110	10.85, 17.38, 25.05, 37.12			18-21	54*	0.3-0.4
	CR recovery[5]		590	36.99 (72 hr)	15.8 (72hr)	III	28	54*	0.5
Gravels (overlying Loughshinny Formation)									
TW9	Constant rate[3]	17 Jan 1994	1330	28.57 (60mins)	>60**		>100**	2 **	>50**
	CR recovery		1180	28.45 (90hr)	41.6 (90hr)		>100**	2 **	>50**
	Step test	12 Jan 1994	492, 856, 1120, 1205	7.9, 16.5, 22.77, 25.68			66	2 **	33

Notes:

1) The constant rate pumping data were analysed using the Theis, Cooper-Jacob and Hantush methods; the recovery data were analysed using the Theis method; the step test data were analysed using the Eden-Hazel method.
2) Due to an initially variable pumping rate, the first 50-60 minutes of data were disregarded.
3) Due to variable pumping rates, only the first 40-90 minutes analysed.
4) Step test continued to constant rate of 980 m^3/d.
5) Pumping rate during pumping was too variable to analyse.

* indicates that saturated thickness taken (i.e., pumping water level is below the base of the solid casing).

** borehole was cased to bottom. Nominal saturated flowing interval of 2 m taken. Well losses significant due to construction.

*** the borehole log indicates that the majority of flow enters the borehole in the lowermost 30 m.

The high yields observed at the production wells are due to the presence of a high transmissivity zone supported by a significant gravel horizon. Despite the high transmissivity there are limiting factors which may affect the yield in the long term. The limiting factors are the low recharge and the presence of relatively poor bedrock aquifers. The high transmissivity zone and the gravels are surrounded almost wholly by relatively poor aquifers. Wells located in such zones may experience difficulty in maintaining yields during dry weather periods. The high transmissivity zones act as horizontal pathways, and maintenance of well yields is largely dependent on water feeding into them from the surrounding aquifers.

7.6 Hydrochemistry and Water Quality

Fingal Co. Co routinely collects water quality samples from the Bog of the Ring wells. Samples are collected after groundwater from all wells is mixed, and after chlorination. It is unknown whether, prior to sampling, the samples are filtered and have been treated for manganese and iron. Since the wells are in the same rock unit, the water quality results are considered to be representative of the aquifer. Data collected by the Co. Co. are tabulated in Table 6, and are summarised below.

Groundwater samples from the trial wells were collected by KTC at the end of the pumping tests (December 1984 – March 1994) carried out on the wells (K.T. Cullen & Co., 1994). Trial wells 4, 8, 11, 12 and 13 were sampled again in November 1999 (K.T. Cullen & Co., 2000(a)). The five production wells were sampled during the 7-day tests undertaken during July 2000 (K.T. Cullen & Co., 2000(c)). These data, which include analyses of water quality parameters, hydrochemical parameters and pesticides are presented in Table 7, and are summarised below.

- The groundwater is Hard. Total hardness in boreholes penetrating the impure limestone of the Loughshinny Formation ranges from 273-417 mg/l as $CaCO_3$, and averages 331 mg/l. Boreholes in the Mullaghfin Formation pure limestone record hardness in the range 256-271 mg/l as $CaCO_3$.
- Alkalinity (HCO_3) ranges from 245-344 mg/l as $CaCO_3$ (average 289 mg/l) in the Loughshinny Formation, and from 192-203 mg/l in the Mullaghfin Formation. Alkalinity is always less than hardness, indicating that no ion exchange has occurred and, therefore, that groundwater residence times are not excessively long.
- Electrical Conductivity (EC) values in the Loughshinny Formation range from 516-735 μS/cm (average 628 μS/cm). In the pure limestone Mullaghfin Formation, conductivity values range from 490-537 μS/cm.
- These values are typical of groundwater from a limestone source. Groundwater sampled from all wells has a calcium–bicarbonate type hydrochemical signature.
- Sulphate (SO_4) concentrations range from 22-82 mg/l (average 51 mg/l) in the Loughshinny Formation, and from 43-59 mg/l in the Mullaghfin Formation.
- In the Loughshinny Formation, chloride (Cl) concentrations range from 17-31 mg/l (average 27 mg/l), with all but one sample (at TW9) in the range 25-31 mg/l. Chloride concentrations range from 29-37 mg/l in the Mullaghfin Formation. Chloride levels in this aquifer are not considered to indicate contamination by organic wastes, but are related to chloride concentrations in the rainwater which recharges the aquifer, due to the proximity to the coast.
- Nitrate concentrations range from less than the method detection limit (MDL) to 2.7 mg/l (median 0.9 mg/l) in the Loughshinny Formation, and from 2.8-9.6 mg/l in the Mullaghfin Formation. Nitrite concentrations are generally below the MDL, or are very low (ranging from 0.007-0.023 mg/l).
- Ammonium (NH_4) concentrations in both the pure and shaly limestone aquifers range from below the MDL to 0.24 mg/l (average 0.15 mg/l). All concentrations are below the EU MAC. However, concentrations are above the GSI Guidelines in TW11 and PW3, and TW12 and PW5. The trial wells are adjacent to the present production well sites. New wells often have high ammonium

levels that typically drop during pumping. Samples collected by the Co. Co. since the production wells have been in service do not give cause for concern, and have been below both the EU MAC and the GSI Guidelines. However, these samples are a mixture of groundwater from PWs 2, 3, 4 and 5 and could, potentially, mask local problems.

- Potassium (K) concentrations in the shaly limestone (Loughshinny Formation) aquifer range from 0-7 mg/l, with average concentrations of 2.93 mg/l. Sodium (Na) concentrations range between 21 and 33 mg/l (average 26 mg/l). Potassium:sodium (K:Na) ratios range from 0-0.24. In the pure limestone (Mullaghfin Formation), potassium levels range from 1.6-2.1 mg/l, whilst sodium concentrations range from 16-21 mg/l. K:Na ratios range from 1.6-2.1. These values and ratios are within normal ranges.
- The GSI Guideline for potassium is 4 mg/l, which is exceeded twice; once at TW4 (7 mg/l) and once at TW6 (4.9 mg/l). This may indicate contamination by organic waste around the time the sample was collected. However, K:Na ratios are below the GSI Guideline of 0.3. Additionally, it appears that potassium and sodium concentrations may be naturally elevated in the shaly limestones compared with the pure limestones.
- Manganese (Mn) concentrations are consistently above the EU MAC value in all the samples. Concentrations range from 0.06-1.79 mg/l (median 0.4 mg/l). Concentrations of iron (Fe) are generally above the EU MAC value (14/18 samples). Iron concentrations range from 0.01-4.93 mg/l (median 0.61 mg/l). There is no obvious seasonal or spatial trend in the values. Manganese and iron originate in the shalier parts of the bedrock aquifer. The elevated levels most likely reflect natural conditions, and indicate low dissolved oxygen. However, they may also indicate contamination by organic waste.
- Aluminium at concentrations greater than the EU MAC has been recorded in PW1, TW8, TW12 and TW13 (up to 1.34 mg/l, at TW12). Limited data for the trial wells indicate that elevated concentrations are not sustained, since measurements at other times have been below the MDL. At PW1, frequent sampling over a 144 hour period in August 2000 showed aluminium concentrations varying from <MDL to 0.2 mg/l. Since routine testing began in January 2004, aluminium concentrations in mixed groundwater samples from PWs 2, 3, 4 and 5 have not exceeded the MAC.
- Initial turbidity problems were indicated by many of the samples collected during testing after drilling. Turbidities greater than the MAC were recorded during pumping tests after drilling at: TW3, TW8, TW9, TW10, TW11, TW12, TW13, PW1 and PW3. A series of samples while pumping were taken at the production wells in August 2000. At PW1, PW4 and PW5, turbidity decreased from during the 72-144 hour tests. At PW3, turbidity worsened before falling below the MAC, and at PW2, levels were consistently below the MAC. PW1 has remained so turbid since drilling that it has not been included in the production well network. Low turbidity levels in PW5 indicate that good construction mitigated problems indicated by turbidities recorded in TW12. At PW3, turbidity, although higher than the MAC, is considerably less than that recorded in the adjacent TW11. This again indicates that borehole construction can mitigate turbidity problems in this aquifer. Turbidity measurements recorded by the Co. Co. since January 2004 are below the EU MAC. It is not clear, however, if these samples have been filtered prior to sampling.
- In general, the bacteriological water quality is very good. No coliforms were detected in the trial wells during the testing after drilling. In the 1999 sampling round of selected trial wells, 1 E. coli per 100 ml was found in TW11, two in TW13, and three Faecal Streptococci per 100 ml in TW13. Well head protection in these wells is variable, so the results may reflect contamination reaching the groundwater via the borehole. Sampling of the production wells during the testing in June and July 2000 recorded >100 Total coliforms per 100 ml in PW1 and PW4, and 5 Total coli per 100 ml in PW5. No E. coli or Faecal Streptococci was detected. Total coliforms can result from organic materials in the soil, and alone do not indicate contamination by human activities. Faecal coliforms indicate contamination by organic waste. Since January 2004, Fingal Co. Co. has sampled mixed groundwater; however, these samples have been chlorinated prior to sampling. No

Total or E. Coli have been detected. This indicates that the disinfection system is working correctly, but no conclusion can be drawn regarding the aquifer conditions.

- Testing for numerous pesticides and halogenated hydrocarbons was undertaken on a selection of trial wells in 1999 and on the production wells in 2000 (K.T. Cullen & Co., 2000(a) and (c)). For the majority of determinands, concentrations were below the MDL, and any parameters detected were below the EU MAC. However, Diazinon (an insecticide) was detected in TWs 12 and 13; Phenols were detected in TW12; Aldrin (an insecticide) was found in PWs 1, 2 and 3 (0.01-0.03 μg/l; MAC 0.1 μg/l). Benzo compounds were determined in PW5 (0.004-0.007 μg/l; MACs 0.2-10 μg/l). Propyzamide (a funcgicide) was found in PWs 1 and 2 at concentrations of 0.03 μg/l (MAC 1000 μg/l; CEFAS, 2004), but retested a month later in August was <MDL. Trietazine (a herbicide) was detected in PW1 in July and August at concentrations of between 0.085 and 0.097 μg/l.

Overall, the samples from the trial and production wells do not indicate significant contamination or pollution of these wells. With the exception of Iron, Manganese, Aluminium and turbidity all non-biological parameters are below the EU MAC in the wells in all of the samples.

Concentrations of iron and manganese are elevated in all of the wells; this is due to bedrock conditions. Aluminium concentrations fluctuate and appear to be only locally elevated in the vicinity of PWs 1 and 5. Groundwater mixed from all wells complies with the EU MAC requirements (0.2 mg/l), although one measurement of 0.134 mg/l indicates that careful monitoring and assessment should continue.

The presence during testing of occasional faecal coliforms and of pesticides suggests that contamination events have occurred within the zone of contribution. Since this is a generally Low vulnerability area (see Section 9:), this is surprising. Contaminants may be arising from surface water and shallow groundwater that is entering the aquifer down the outside of the casing. Since the routine Co. Co. samples are chlorinated, an assessment of current natural conditions cannot be made.

Table 6: Summary of Hydrochemistry Data from Co. Co. sampling

Parameter	**Col**	**Turbidity**	**pH**	**Conductivity**	**Conductivity at 20°C**	**Temp.**	**Nitrate**	**Nitrite**	**Ammonium**	**Aluminium**	**Iron**	**Total Coliforms**	**E. Coli**
Units	(PFX)	Hazen	-	µS/cm	µS/cm	°C	NO_3 mg/l	NO_2 mg/l	NH_3 (mg/l)	Al (mg/l)	Fe (mg/l)	per 100ml	per 100ml
MAC *(GSI Threshold[1])*		4	6-9	1500	1500	-	50 *(25)*	0.1	0.3 *(0.15)*	0.2	0.2	0	0
6-Jan-04	8	0.39	7.4	737		10				<0.006	0.017	<1	<1
13-Jan-04	0	0.1	7.5	743		10	<1.6	<0.0165	0.072	0.147	0.011	<1	<1
20-Jan-04	1	0.12	7.4	740		11	<1.6	<0.0165	0.096	<0.006	0.01	<1	<1
27-Jan-04	0	0.15	7.3	742		10	<1.6	<0.0165	0.084	<0.006	0.009	<1	<1
5-Feb-04	0	0.15	7.4	736		10				<0.006	<0.006	<1	<1
5-Feb-04	0	0.15	7.2	736		11	<1.6	<0.0165	0.06	<0.006	<0.006	<1	<1
10-Feb-04	0	0.15	7.2	736		11	<1.6	<0.0165	0.06	<0.006	<0.006	<1	<1
17-Feb-04	7	0.38	7.3	737		11				<0.006	0.01	<1	<1
24-Feb-04	1	0.25	7.3	737		10	<1.6	<0.0165	0.048	0.134	0.053	<1	<1
4-Mar-04	1	0.66	7.3	731		10				<0.006	<0.006	<1	<1
9-Mar-04	3	0.29	7.3	740		11	<1.6	<0.0165	0.048	<0.006	0.008	<1	<1
18-Mar-04	0	0.1	7.4	732		11				<0.006	<0.006		
23-Mar-04	4	0.41	7.4	743		12.5	<1.6	<0.0165	0.06	0.018	0.021	<1	<1
30-Mar-04	3	0.53	7.3	740		12	<1.6	<0.0165	0.048	<0.006	<0.006	<1	<1
6-Apr-04	0	0.1	7.3	741		12	<1.6	<0.0165	0.048	0.016	0.021	<1	<1
20-Apr-04	1	0.3	7.3		664	11	<1.6	<0.0165	0.132	<0.006	0.008	<1	<1
27-Apr-04	6	0.52	7.4		664	11	<1.6	<0.0165	0.084	<0.006	<0.006	<1	<1
4-May-04	3	0.22	7.4		658	11				<0.006	<0.006	<1	<1
11-May-04	1	0.12	7.4		664	12				<0.006	<0.006	<1	<1
18-May-04	0	<0.1	7.2		661	12	<1.6	<0.0165	0.084	<0.006	<0.006	<1	<1
20-May-04	0	0.1	7.3		662	12	<1.6	<0.0165	0.096	0.018	<0.006	<1	<1
25-May-04	0	0.1	7.3		662	12	<1.6	<0.0165	0.096	0.018	<0.006	<1	<1

1. GSI Thresholds are used to assess where appreciable impacts to water quality are occurring. Samples that exceed the threshold, but not the EU MAC, are indicated by *italics*. MAC exceedances are indicated by **bold** type.

Continued, Summary of Hydrochemistry Data from Co. Co. sampling

Parameter	**Col**	**Turbidity**	**pH**	**Conductivity**	**Conductivity at 20^{o}C**	**Temp.**	**Nitrate**	**Nitrite**	**Ammonium**	**Aluminium**	**Iron**	**Tot_Coli**	**E_Coli**
Units	(PFX)	Hazen	-	μS/cm	μS/cm	^{o}C	NO_3 mg/l	NO_2 mg/l	NH_3 (mg/l)	Al (mg/l)	Fe (mg/l)	per 100ml	per 100ml
MAC *(GSI Threshold[1])*		4	6-9	1500	1500	-	50 *(25)*	0.1	0.3 *(0.15)*	0.2	0.2	0	0
1-Jun-04	0	0.1	7.3		663	12	<1.6	<0.0165	0.06	<0.006	<0.006	<1	<1
8-Jun-04	0	0.21	7.3		659	11				<0.006	<0.006	<1	<1
15-Jun-04	1		7.4		659	12	<1.6	<0.0165	0.06	<0.006	0.011	<1	<1
22-Jun-04	0		7.3		661	12	<1.6	0.0165	0.072	<0.006	<0.006	<1	<1
29-Jun-04	1	0.14	7.4		659	12				<0.006	0.012	<1	<1
6-Jul-04	0	0.11	7		657	12	4.3	<0.0165		<0.006	0.016	<1	<1
8-Jul-04	1	<0.1	7.4		664	12	<1.6	<0.0165	0.084	0.006	0.007	<1	<1
13-Jul-04	1	<0.1	7.4		664	12	<1.6	<0.0165	0.084	0.006	<0.006	<1	<1
15-Jul-04	1	<0.1	7.3		659	13	<1.6	<0.0165	0.072	<0.006	<0.006	<1	<1
20-Jul-04	1	<0.1	7.3		659	13	<1.6	<0.0165	0.072	<0.006	<0.006	<1	<1
20-Jul-04	0	0.11	7.4		659	13				<0.006	<0.006	<1	<1
27-Jul-04	0	0.11	7.4		659	13				<0.006	<0.006	<1	<1
27-Jul-04	3	0.1	7.3		657	12				<0.006	<0.006	<1	<1
3-Aug-04	3	0.1	7.3		657	12				<0.006	<0.006	<1	<1
5-Aug-04	0	0.11	7.2		659	12				0.03	<0.006	<1	<1
10-Aug-04	0	0.11	7.2		659	12				0.03	<0.006	<1	<1
17-Aug-04	1	0.3	7.3		659	12	<1.6	<0.0165	0.072		<0.006	<1	<1
24-Aug-04	0	<0.1	7.3		660	12	<1.6	<0.0165	0.096	<0.006	<0.006	<1	<1

1. GSI Thresholds are used to assess where appreciable impacts to water quality are occurring. Samples that exceed the threshold, but not the EU MAC, are indicated by *italics*. MAC exceedances are indicated by **bold** type.

Table 7: Summary of Hydrochemistry Data from the trial wells at Bog of the Ring. Data from K.T. Cullen & Co. (1994, 2000(a))

Parameter	Units	MAC Value (*GSI Threshold*[1])	TW1 Dec 1984	TW3 Jan 1985	TW4 Jan 1985	TW4 Nov 1999	TW6 1993/ 94	TW7 1993/ 94	TW8 1993/ 94	TW8 Nov 1999	TW9 1993/ 94	TW10 1993/ 94	TW11 Nov 1999	TW12 Nov 1999	TW12 1993/ 94	TW13 Nov 1999	TW13 1993/ 94
Colour	Hazen	20	5	5	10	<2	<5	<5	<5	<2	<5	<5	5	7	<5	<2	<5
Turbidity	Formazin U	4	0.6	**4.4**	3.2	0.6	0.25	**38**	**44**	0.3	**8.7**	**25**	**31**	**>20**	**16**	**26.7**	**25**
pH	Units	6-9	7.4	7.6	7.2	7.08	7	7.2	7.4	7.35	7.2	7.2	7.36	7.68	7.3	7.46	7.6
Conductivity	µS/cm	1500	496	582	698	617	720	670	490	537	735	670	615	620	690	516	565
Hardness	$CaCO_3$ mg/l		242	312	328	316	417	403	265	279	370	320	333	275	378	273	306
Alkalinity	$CaCO_3$ mg/l		216	324	290	245	338	346	203	192	256	260	288	268	344	266	282
Sulphate	SO_4 mg/l	250	2.6	43.6	68	57	82	40	43	59	63	61	70	30	41	22	25
Chloride	Cl mg/l	250 (*30*)	*37*	29.5	*30*	29	29	23	29	*37*	17	*31*	25	25	*31*	25	27
Nitrate	NO_3 mg/l	50 (*25*)	2.04		2.7	0.8	<0.5	<0.5	2.8	9.61	0.9	<0.5	<0.22	<0.22	<0.5	<0.22	<0.5
Nitrite	NO_2 mg/l	0.1		<0.001	<0.001	<0.007	<0.01	<0.01	<0.01	0.0098	<0.01	<0.01	<0.007	0.0066	<0.01	<0.007	<0.01
Tot. Ammonium	NH_4 mg/l	0.3 (*0.15*)	0.11	0.2		0.065	0.23	0.15	<0.05	0.026	0.1	0.24	*0.182*	*0.208*	0.24	0.026	<0.05
Magnesium	Mg mg/l	50	13	19.5	23.3	20.9	20	13	14	14.9	25	20	21.2	18.8	22	14.9	18
Calcium	Ca mg/l	200	75	101	112	92.1	134	140	83	87	107	95	98.4	79.3	115	81.9	93
Copper	Cu mg/l	0.5	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.011	<0.01	<0.01	<0.01
Iron	Fe mg/l	0.2	0.07	0.17	**0.28**	0.075	**2.3**	**2.6**	**1.6**	0.011	**0.62**	**1.7**	**3.79**	**4.93**	**0.61**	**3.09**	**0.39**
Manganese	Mn mg/l	0.05	**0.19**	**1.79**	**0.48**	**0.397**	**0.28**	**0.13**	**0.19**	**0.063**	**0.16**	**0.07**	**0.88**	**1.52**	**1.2**	**0.153**	**0.08**
Aluminium	Al mg/l	0.2				<0.02	<0.05	<0.05	**0.38**	<0.02	<0.05	0.07	<0.02	**1.34**	<0.05	<0.02	**0.26**
Phosphorous	P_2O_5 mg/l	5				<0.115				0.115			<0.115	<0.115		<0.115	
Fluoride	F mg/l	1.0				0.290				0.143			0.228	0.174		0.117	
Sodium	Na mg/l	150	25	32.8	28.8	22.9	22	13	16	16.7	33	22	26.8	22.9	31	21.3	21
Potassium	K mg/l	12 (*4*)	2	2.31	*7.0*	0.0	*4.9*	*4.1*	1.6	1.76	3.1	3.9	3.22	1.79	1.7	2.05	2.3
K:Na Ratio	K:Na	(*0.3*)	0.08	0.07	0.24	0.00	0.22	*0.32*	0.10	0.11	0.09	0.18	0.12	0.08	0.05	0.10	0.11
Susp. Solids	mg at 105 ^oC	No Visible				4				<2			5	31		6	
Lead	Pb mg/l	0.05				<0.001				<0.001			<0.001	0.003		<0.001	
Zinc	Zn mg/l	1.0				<0.01				<0.01			<0.01	0.015		<0.01	
Odour	Dilution No.					0				0			2	2		0	
Tot. Coliforms	no./100 ml	0				Nil				Nil			Nil			Nil	
Faecal Strep.	no./100 ml	0	Nil		Nil	Nil		Nil	Nil	Nil	Nil	Nil	Nil		Nil	3	Nil
E. Coliforms	no./100 ml	0	Nil		Nil	Nil		Nil	Nil	Nil	Nil	Nil	1		Nil	2	Nil
Rock Unit [2]			BC	LO	LO	LO	LO	WL	MF	MF	gravel	LO	LO	LO	LO	LO	LO

1. GSI Thresholds are used to assess where appreciable impacts to water quality are occurring. Samples that exceed the threshold, but not the EU MAC, are indicated by *italics*. MAC exceedances are indicated by **bold** type.
2. See Table 3 for rock unit (Geological Formation) codes.

Table 7, continued Summary of Hydrochemistry Data from the trial wells at Bog of the Ring. Data from K.T. Cullen & Co. (1994, 2000(a))

Parameter	**Units**	**MAC Value (*GSI Threshold*[1])**	**PW1** July 2000	**PW2** July 2000	**PW3** July 2000	**PW4** July 2000	**PW5** July 2000
Colour	Hazen	20	<2	<2	<2	<2	<2
Turbidity	Formazin U	4	**>20**	0.9	**4.6**	1	1.6
pH	Units	6-9	7.43	7.18	7.18	7.11	7.22
Conductivity	µS/cm	1500	479	550	585	623	679
Hardness	$CaCO_3$ mg/l		271	322	329	304	373
Alkalinity	$CaCO_3$ mg/l		192	270	275	280	315
Sulphate	SO_4 mg/l	250	53	57	67	47	44
Chloride	Cl mg/l	250 (*30*)	*34*	29	25	25	28
Nitrate	NO_3 mg/l	50 (*25*)	4.25	2.17	0.27	<0.22	<0.22
Nitrite	NO_2 mg/l	0.1	0.013	0.023	<0.007	0.010	0.010
Tot. Ammonium	NH_4 mg/l	0.3 (*0.15*)	<0.013	0.052	*0.156*	0.091	*0.182*
Magnesium	Mg mg/l	50	14.6	21	21.4	18.7	23.2
Calcium	Ca mg/l	200	84.4	94.5	96.6	90.9	111
Copper	Cu mg/l	0.5	0.022	<0.01	<0.01	<0.01	<0.01
Iron	Fe mg/l	0.2	**2.79**	0.066	**0.699**	**0.396**	**0.522**
Manganese	Mn mg/l	0.05	**0.51**	**0.295**	**0.33**	**0.7**	**0.96**
Aluminium	Al mg/l	0.2	**0.643**	<0.02	<0.02	<0.02	<0.02
Phosphorous	P_20_5 mg/l	5	<0.23	<0.23	<0.23	<0.23	<0.23
Fluoride	F mg/l	1.0	0.122	0.265	0.249	0.294	0.162
Sodium	Na mg/l	150	20.9	21.8	25.2	24.2	27.6
Potassium	K mg/l	12 (*4*)	2.1	3.31	3.35	3.29	1.79
K:Na Ratio	K:Na	(*0.3*)	0.10	0.15	0.13	0.14	0.06
Susp. Solids	mg at 105 ^{o}C	No Visible	81	7	5	<2	<2
Lead	Pb mg/l	0.05	0.003	<0.001	<0.001	<0.001	<0.001
Zinc	Zn mg/l	1.0	0.023	0.01	0.012	<0.01	0.017
Odour	Dilution No.		0	0	0	1	0
Tot. Coliforms	no./100 ml	0	>100	Nil	Nil	>100	10
Faecal Strep.	no./100 ml	0	Nil	Nil	Nil	Nil	Nil
E. Coliforms	no./100 ml	0	Nil	Nil	Nil	Nil	Nil
Rock Unit			MF	LO	LO	LO	LO

1. GSI Thresholds are used to assess where appreciable impacts to water quality are occurring. Samples that exceed the threshold, but not the EU MAC, are indicated by *italics*. MAC exceedances are indicated by **bold** type.
2. See Table 3 for rock unit (Geological Formation) codes.

7.7 Conceptual Model

The conceptual model is based on the mapped geology and on hydrogeological data such as water levels, pumping tests, subsoil thicknesses and permeabilities, surface water features, topography, etc. The conceptual model represents our current understanding of groundwater flow around the Bog of the Ring boreholes. The groundwater regime in the area is complex due to the structural and glacial history of the area. The available hydrogeological information does not allow a definitive understanding of the hydrogeology.

- The wells are drilled in impure (shaly) limestones. Four of the wells (PWs 2, 3, 4 and 5) are located in the fractured shaly limestone of the Loughshinny Formation, which is classified as a **locally important aquifer that is generally moderately productive (Lm)**. Production well 1 (PW1) was drilled into the pure bedded limestone of the Mullaghfin Formation, into which the Loughshinny Formation grades northwards. This is classified as a **locally important karst (Lk) aquifer**.
- Groundwater flow is primarily along faults and fractures in the bedrock, evidenced by discrete inflow zones recorded in the well logs. Dolomitised zones may exist, further enhancing permeability. Dissolution of the limestone along fracture planes should also have further increased permeability.
- The limestones have high transmissivity, which is believed to arise from extensive faulting and fracturing of the limestones in this area. A high transmissivity zone runs WNW-ESE, (Central Zone), beneath the Bog. In the area where the production wells are drilled, the limestone area beneath the surface is 500-1000 m wide (i.e., in a north-south direction). The well field is primarily located in the Central Zone.
- Underneath the Bog, the limestone bedrock aquifer is overlain by 5-15 m of saturated gravels, which is in turn overlain by about 10 m of clays. The gravels are likely a more or less continuous layer. The saturated gravels are considered to contribute extra transmissivity to the groundwater system and also to provide extra groundwater storage. Gravelly deposits overlain by clays were recorded at PW1, PW2, PW3 and PW4. They are absent further west in the vicinity of PW5, and to the north and south of the Bog.
- The fractured limestones are bounded to the north by the North Dublin Fault, which juxtaposes older rocks against the limestone. At the southern margin of the limestone, it disappears underneath the overlying younger shales and sandstones that form Knockbrack Hill. This change occurs roughly where the ground slope increases. The older (Ordovician) Volcanic rocks immediately to the north of the Production Wells have moderately good transmissivity. Groundwater gradients indicate that hilly parts of the Volcanic aquifer have lower transmissivity. This is attributed to their being less fractured and hence more resistant to erosion. The older (Ordovician and Silurian) sandstones and shales to the northwest and northeast of the boreholes, and the younger (Namurian) rocks to the south of the boreholes, have low transmissivities.
- There is also a N-S trending fault zone running almost parallel to the M1 and the Matt River in the vicinity of Mattinch – Decoy Bridge and Courtlough (Matt River/M1 zone). High transmissivity is indicated by a low groundwater gradient. Saturated gravel deposits (>10 m) next to the M1 and the Matt River are known south of Decoy Bridge, and appear to generate high transmissivities. A pumping test in gravel subsoils indicates permeabilities >50 m/d. There are no permeability data for the bedrock in this area.
- Higher groundwater gradients indicate that the shaly limestones to the east of the Matt River have lower permeabilities than those under the Bog.
- Much of the area is covered by thick, low permeability subsoils, which inhibit recharge of the bedrock aquifers by rainfall but give good aquifer protection. Exceptions are on the upper areas of Knockbrack Hill and around Dermotstown, where rock is close to the surface.
- Recharge is approximately 322 mm/yr in the areas where subsoil is thin (<3 m) or absent. Recharge is zero in the areas where the aquifer is confined by thick subsoils and is artesian. Over

much of the area (where subsoils are thick and low permeability), recharge is estimated to be approximately 57 mm/yr.

- In the natural (non-pumping state), the aquifer is confined by low permeability clays or tills, and is generally artesian from Priorland (between PW4 and PW5) in the west to Decoy Bridge (PW1) in the east. The aquifer is also artesian at least as far south as Courtlough. In the vicinity of PW5 and further west, the bedrock aquifer is also confined, but not artesian. Water levels in boreholes and spring elevations indicate that, in general, the groundwater piezometric surface follows topography. Away from the Bog area, the bedrock aquifers are generally unconfined. Locally, subsoil thicknesses may be such that confined conditions exist.
- In the valley area that the Bog occupies, groundwater gradients are very gentle (0.003). Groundwater flow is to the east. From Knockbrack Hill, groundwater (and ground surface) gradients are steep (>0.05) and directed northwards to the Bog. From the north, groundwater flows southwards through the Ordovician volcanic aquifer into the fractured limestone aquifer at the Bog of the Ring. The topography is gently rolling and groundwater gradients relatively gentle (<0.03).
- Measured groundwater levels indicate that to the west of PW5, in the vicinity of Hazardstown, groundwater flow directions do not coincide with topography. The groundwater divide is believed to lie about 750 m further to the west than the surface water catchment boundary.
- At current pumping rates (total 3,500 m^3/d), water levels are between about 13.5 and 25.5 mbgl (approximately 15 to 29 mAOD). This equates to drawdowns of between about 13.5 and 18 m.
- At the wells, the water levels are below the base of the gravel layer (probably due to well losses). However, water levels in the observation wells show that the water level is generally above the top of the gravels.
- Under natural (non-pumping) conditions, it is believed that groundwater flows eastwards to the area of Decoy Bridge, then northwards out of the high-transmissivity Bog of the Ring limestone aquifer along a north-trending zone near the Matt River.
- Evidence for this flow direction comes from groundwater gradients estimated from measured water levels and from topographic considerations; a northwards flow towards Decoy Bridge from the Courtlough area is indicated by groundwater levels in boreholes. A westward groundwater flow from the Salmon area to Decoy Bridge is also indicated by measured groundwater levels and also by the steeper topography.
- The nature of the zone conducting groundwater northwards from Decoy Bridge along the Matt River valley is poorly constrained. From limited borehole data, it is thought that gravelly deposits capable of transmitting significant quantities of groundwater overlie the generally low transmissivity bedrock aquifer. The bedrock aquifer transmissivity may also be enhanced in this local zone due to the presence of a major fault zone.
- In the area north of the Bog of the Ring, groundwater is thought to discharge to streams and ditches that coalesce to form an eastward-flowing tributary to the Matt River.
- West of the groundwater divide near Hazardstown, groundwater flows to the River Delvin.
- At current rates of pumping, the eastern edge of the cone of depression is near to Decoy Bridge (during the 3-day shut-off in July, water level recovery at this location (OW3) was about 25 cm). The cone of depression does not appear to extend as far as the crossroads 500 m further east (OW6).
- Pumping shifts the natural groundwater divide near Hazardstown further to the west. The pumping water level contour map suggests that the groundwater divide is very close to the Delvin River.
- The high yields observed at the production wells are due to the presence of a high transmissivity zone supported by a significant gravel horizon, but the limiting factors on the long term yields are the low recharge and presence of relatively poor bedrock aquifers. The high transmissivity zone and the gravels are surrounded almost wholly either by **locally important aquifers that are generally moderately productive (Lm)** or **poor aquifers which are generally unproductive except for local zones (Pl)**. The high transmissivity zones act as horizontal pathways, and maintenance of well yields is largely dependent on water feeding into them from the surrounding

aquifers. The continued monitoring will allow further investigation into the long term yields of the wells.

7.8 Numerical Model

A numerical model based on the conceptual model outlined above was developed using MODFLOW 3.1. The modelling objectives and scope were to:

- calibrate aquifer transmissivities and their distribution;
- calibrate aquifer recharge and its distribution;
- gain an insight into the groundwater system and to help understand better the outflows from the groundwater system;
- help define the extent of the Zone of Contribution (ZOC) and 100-day time of travel for the four production wells.

It was not the intention of the modelling exercise that the model reproduce exactly the groundwater system, but rather that it would give a ‘broad picture’ of the hydrogeology of the area.

7.8.1 Model configuration

Model Framework

- The model is oriented parallel to the main geological and permeability trends. The grid cells are approximately 500 m in the *x* direction and 450 m in the *y* direction.
- The model is one layer thick. This layer represents both the bedrock aquifer, the weathered layer at the top of the bedrock aquifer, and overlying high-permeability subsoils (gravels). Vertical cell thickness varies depending upon the geology and the aquifer characteristics of the bedrock. This is discussed further below. The low permeability subsoil deposits are not modelled.

Model Boundaries

- The lateral extent of the model was based on the conceptual model and defined using geological and hydrogeological boundaries. The boundary conditions are shown on Figure 7, and are described below:
  - The **southwest** boundary is a **NO FLOW** boundary. It is defined mainly by surface water catchment boundaries, with which groundwater divides are considered to correspond.
    - Along the western part of this boundary, the model boundary is defined by an approximate groundwater flow path. A groundwater flow path is a line which groundwater cannot cross, but can only run parallel to (unless some external stress changes its direction and/ or location). This area is considered to be too far away from the pumping wells to be significantly influenced by pumping.
    - Most of the boundary occurs along a significant topographic feature in low transmissivity rocks; its location will be unaffected by pumping.
    - Along the southernmost part of this boundary, the groundwater divide is in a low-relief area. The location of the groundwater divide is presumed to coincide with the surface water catchment divide. It is defined on this basis and with few data, and therefore its exact location is uncertain. Note that the location of the divide is indicated by modelling (see sections 7.8.3 and 7.8.4) to move southwards due to pumping.
  - The **southeast** boundary is a **NO FLOW** boundary. It is defined by a groundwater divide which was mapped as described in Section 7.3. This boundary is considered to be far enough away and topographically significant enough for its location to be largely unaffected by pumping at the Bog of the Ring well field.
  - The **northwest** boundary is a **RIVER** boundary. It is defined by the River Delvin, which is the main discharge zone in the west of the study area. The river head is derived along its length from the OSi 1:50,000 map and falls from 61–41 mAOD. The river conductance is derived using the

MODFLOW default formula from an assumed river bottom permeability of 0.01 m/d, and assumed river width of 5 m and depth of 3 m. Conductance controls the ease with which groundwater can enter the river (or vice versa) and values estimated for each cell depend on the river length crossing each cell and on the dimensions of the cell. Values in this model range from 834-2917 m^2/d.

- The **NNW/ north** boundary is a **NO FLOW** boundary. It is defined in part by the relatively impermeable Lower Palaeozoic rocks of the Clashford House Formation, and in part by a northeast trending groundwater divide.
- The **northeast** boundary is a **NO FLOW** boundary. It is the approximate location of a groundwater divide.
- The **east** boundary is a **mixed** boundary. Most of the boundary is **NO FLOW**, but there are also **RIVER** and **CONSTANT HEAD** boundary cells.
  - The CONSTANT HEAD cell at Decoy Bridge is set to known groundwater head values. Using a constant head boundary (CHB) simulates the effect that the Matt River have on the groundwater flow, but avoids modelling the river explicitly. The winter 1994 (pre-pumping) groundwater head was 34 mAOD, and the summer 2004 (post-pumping) groundwater head is 32 mAOD. The summer head value used is based on 2004 water level data at OW3 and likely includes the effect of pumping.
  - The RIVER cell at Stephenstown simulates the tributary to the Matt River. The river head specified at this cell is 30 mAOD. The properties of this boundary are described further below.
  - East of Matt River to north of Salmon, the NO FLOW boundary is defined by the relatively impermeable Lower Palaeozoic rocks of the Skerries Formation.
  - Between Decoy Bridge and Stephenstown, the boundary between the Ordovician Volcanics and low transmissivity Skerries Formation is simulated using a NO FLOW boundary. Again, this is an approximation. In reality, this is the approximate location of the Matt River. However, little is known about the behaviour of the Matt River and its interaction with the groundwater system in this locality. Therefore a no flow boundary avoids making assumptions about the river behaviour. It is considered that the CHB simulating the groundwater outlet at Decoy Bridge, and river cells simulating the Matt River tributary are sufficient to replicate the groundwater system behaviour.

- There are two boundary types *within* the model domain:
  - A **RIVER** boundary, which simulates the ditches and streams that flow eastwards from Newtown to join the Matt River near Stephenstown. The network of drainage channels is represented by a single channel that widens and deepens downstream. Cell conductances accordingly range from 93-296 m^2/d. The river head is derived along its length from the OSi 1:50,000 map, and falls from 49–30 mAOD.
  - The **RECHARGE** boundary, which simulates the proportion of rainfall that enters the bedrock aquifer. As described in Section 7.2.4 and summarised in Table 4, recharge is estimated based on the subsoil thickness and permeability. There are sixteen recharge classes (zones) defined in the model, which are based on the proportions of different subsoil vulnerabilities and permeabilities in a grid cell. The zone distribution and actual recharge values are shown in Figure A.2 (in Appendix).

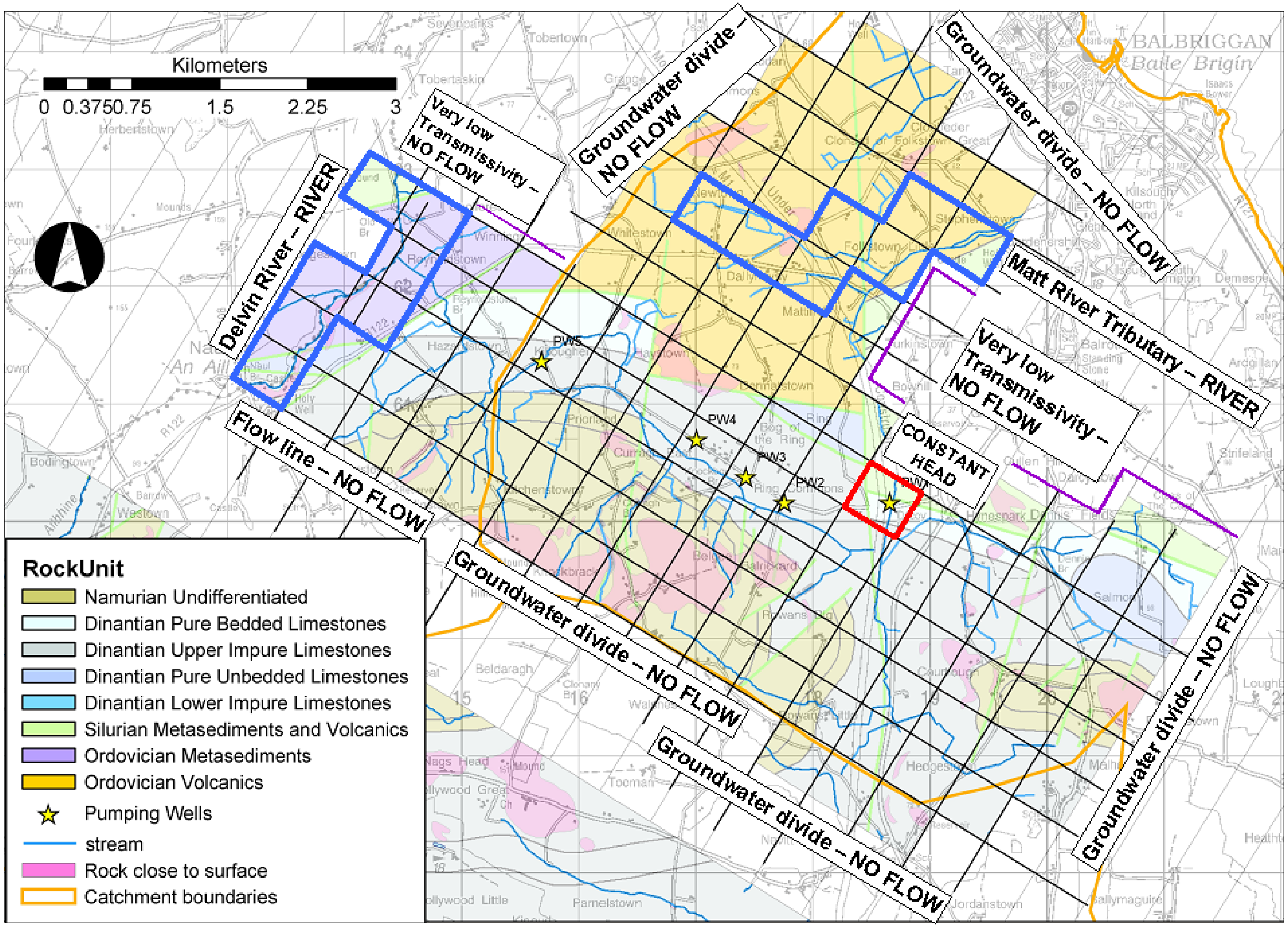

Figure 7: Diagram showing the numerical model boundaries. See text for discussion.

Model Aquifer Transmissivities

The model is divided into different aquifer units, as outlined below. The higher permeability weathered layer or, in some locations, gravel layer at the top of the bedrock is not modelled separately; the transmissivity assigned to the grid cell accounts for this implicitly. The permeability map and the resulting transmissivity map are shown in Figure A.3. The transmissivities used for each unit are summarised in Table 8 and were delineated as follows:

- 'Impure Limestones'
  - *Central zone*: represents the fractured Loughshinny Formation aquifer combined with the permeability contribution from the overlying saturated gravels. With the exception of the unused PW1, the production wells lie in this aquifer unit.
  - *Peripheral zone*: represents the fractured Loughshinny Formation aquifer in the vicinity of the Bog but in areas where there is no/ little gravel overlying the bedrock.
  - *Eastern zone*: represents the Loughshinny Formation aquifer to the east of the Matt River and M1.
  - *Matt River/ M1 zone*: represents the Loughshinny Formation aquifer along a major N-S fault zone combined with the permeability contribution from the overlying saturated gravels.
- 'Ordovician Volcanics', which lie to the north of the Bog area.
  - *Main zone*: represents the bulk of this aquifer.
  - *Hill zone*: represents the aquifer properties of areas that are hillier and are therefore presumed to be less fractured, more resistant to the effects of erosive processes, and less permeable.
- 'Lower Palaeozoic Metasediments', which lie to the northwest of the Bog area.
- 'Namurian mudstones and sandstones', which lie to the south of the Bog area, and in the very east of the study area.
  - The transmissivities in the eastern part of the study area are approximately half those in the vicinity of Knockbrack Hill.

Table 8: Summary of the aquifer properties used in the numerical model

Aquifer unit	Sub-area	Horizontal permeability (m/d) [1]	Transmissivity (m^2/d) [2]
Impure Limestones	Central zone	9	630
	Peripheral zone	5	350
	Eastern zone	0.7	49
	Matt River/ M1 zone	12	840
Ordovician Volcanics	Main zone	0.6	24
	Hill zone	0.25	10
Lower Palaeozoic Metasediments	N/A	0.25	7.5
Namurian Mudstones and Sandstones [2]	Knockbrack Hill	0.0625–0.125	3.1-4.6
	Eastern zone	0.0313-0.0625	2-3.75

1) Transmissivity within an aquifer unit in the model varies slightly due to varying cell thickness. The value given represents the average, based on the target cell thickness.
2) Note that for reasons of model numerical stability, cell thicknesses in the Namurian aquifer vary widely. Therefore, permeabilities are adjusted to maintain similar transmissivities.

Since the model was run in steady state conditions, aquifer storativities were not defined. Aquifer effective porosities are discussed in Sections 7.4 and 8.2.

Abstraction

Current total abstraction at the public supply is approximately 3500 m^3/d. The abstraction rates for the supply wells, recorded by Fingal Co. Co., are listed below in Table 9. Abstraction increased by 50% is also listed to reach an approximate 5000 m^3/d target in case of future scheme expansion.

Table 9: Abstractions at the Bog of the Ring Public Supply Wells.

Well Name	Abstraction (m^3/d)	Abstraction + 50% increase (m^3/d)
PW2	1052	1578
PW3	1050	1575
PW4	337	340 *
PW5	1044	1566
Total	*3483*	*5059*

* an abstraction increase at PW4 is not factored in, as results from the June 2000 pumping tests indicate that the pumping water level should be maintained, if possible, within 24 m of the ground surface (>13.2 mAOD).

7.8.2 Model calibration

The groundwater level contour map based on winter pre-pumping water levels was used to calibrate the model. The model was run in steady-state mode for non-pumping conditions.

The values of transmissivity were varied within ranges indicated by pumping tests, groundwater gradients and recharge rates to converge on the values outlined in Section 7.8.1. Recharge was computed as described in Sections 7.2 and 7.8.1.

The calibration criteria were:

- Predicted groundwater gradients and flow directions in different areas of the model match those derived from the hand-drawn groundwater head map.
- Less than 10 m absolute error in the predicted heads at key points in the model (e.g. pumping and observation wells, heads on Knockbrack Hill and in the north (around Newtown), east (around west Palmerstown) and south (south of Rowans Little).

The results are shown in the Appendix Figure A.4

7.8.3 Model validation

Once the model was calibrated, it was validated against groundwater heads that have been contoured on the basis of current (August 2004) water levels at the production wells and observation wells (July 2004). The model was run in steady state using current pumping rates (see Section 7.8.1 above).

Overall, predicted groundwater levels are similar to known and interpolated groundwater heads. At PWs 2, 3, 4 and 5, an exact match was not expected, since the grid cells are not refined around the pumping wells, and head values in the cells are averages across approximately 500 x 450 m areas. Additionally, well losses at the pumping wells increase drawdown beyond that predicted by general groundwater flow equations. Furthermore, aquifer heterogeneity on an inter-well scale was not modelled.

The results are shown in Figure A.5.

The modelling suggests that the groundwater divide may move approximately 200 m southwestwards in the area of Rowans Little and Hedgestown, and approximately 900 m westwards in the area of Hazardstown, when the abstraction rate is 3500 m^3/d.

Sensitivity analyses were performed independently on the values of recharge across the whole model, and on the Central zone and Matt River zone limestone permeabilities. The results indicate that:

- A 10% increase or decrease in recharge results in an approximately 0.7 m increase or decrease in groundwater heads. This relationship is approximately linear (e.g., a 20% increase would cause a 1.4 m increase), except in the areas near to the constant head or river boundary cells. The variation in head is only weakly dependent on pumping rate.
- A 10% increase or decrease in permeability results in an approximately 0.1-0.7 m increase or decrease in groundwater heads. The relationship is strongly dependent on pumping rate, with the smallest increase/ decrease observed at the highest pumping rates. For the non-pumping scenario, the effects of varying permeability are very similar to varying overall recharge.

7.8.4 Model predictions of additional scenarios

Finally, conditions were modelled for two scenarios with abstraction rates greater than 3,500 m^3/d:

1. 5,000 m^3/d from existing wells (PW2, PW3, PW4 and PW5);
2. 4,000 m^3/d, with the additional 500 m^3/d abstracted from a new well located 250 m south of PW1, to assess the possible impact of a well along the N-S fault.

For both scenarios, the model predicts that further expansion of the zone of contribution (ZOC) occurs along both the high transmissivity Central zone and the Matt River/M1 zone.

For Scenario 1, the boundary of the zone is predicted to migrate westwards by approximately 200 m in the Hazardstown area and approximately 40 m southwards in the Rowans Little–Hedgestown area.

For Scenario 2, the boundary migrates westwards by approximately 70 m in the Hazardstown area and approximately 80 m southwards in the Rowans Little–Hedgestown area.

The predicted boundaries cannot be taken as definitive; neither the available data nor the conceptual model on which the numerical model is based nor the model grid allow precise delineation of the ZOC boundaries. However, the numerical modelling provides useful guidance on the groundwater flow regime in the area. It highlights the importance of the high transmissivity zones and the sensitivity of the aquifer to abstraction rate.

The model predictions indicate the need for further assessment of the available groundwater resources in this aquifer, prior to decisions on increasing the abstraction beyond 3,500 m^3/d.

8: Delineation of Source Protection Areas

This section delineates the areas around the wells that are believed to contribute groundwater to the wells, and that therefore require protection. The areas are delineated based on the conceptualisation and numerical modelling of the groundwater flow system, as described in Sections 7.7 and 7.8, and are presented in Figure 8 and on Map 5.

Two source protection areas are delineated:

- *Inner Protection Area (SI)*, designed to give protection from microbial pollution;
- *Outer Protection Area (SO)*, encompassing the remainder of the ZOC of the well.

8.1 Outer Protection Area

The Outer Protection Area (SO) is bounded by the complete catchment area to the source, i.e. the zone of contribution (ZOC), which is defined as the area required to support abstraction from long-term recharge. The ZOC is controlled primarily by a) the total discharge, b) groundwater flow directions and gradients, c) bedrock aquifer permeabilities and d) the recharge in the area. The current combined abstraction rate at the Bog of the Ring boreholes is about 3480 m^3/d. The ZOC is delineated for the current abstraction rate.

The ZOC for the Bog of the Ring production wells is delineated by both hydrogeological mapping techniques and numerical modelling (using MODFLOW). This is constrained by an estimate of the area required to support the abstraction obtained by using the average recharge and the abstraction rates. The ZOCs are shown in Map 5 and the boundaries are described below.

The **Eastern Boundary** is based on hydrogeological mapping which indicates that there is a groundwater divide in Killalane.

The **Southern Boundary** is delineated using topography and numerical modelling.

The **Southwestern Boundary** is constrained by topography. The groundwater divide coincides with the topographic divide. It is conservative boundary as groundwater within this area of low transmissivity rocks is likely to have short flow paths, quickly discharging to the small streams draining the Knockbrack hill. Thus the boundary allows for some flow that may get to the wells, particularly toward the boundary with the limestones.

The **Western Boundary** is delineated using topography and numerical modelling, extending between Cabinhill and Naul.

The **Northwestern Boundary** is constrained by geological boundary between the Carboniferous Limestones and the Ordovician Metasediments. It is assumed that the Ordovician Metasediments do not yield significant quantities of water. Accordingly, an arbitrary 200 m buffer beyond the geological boundary is used to delineate the boundary.

The **Northern Boundary** is based on hydrogeological mapping which indicates that there is a groundwater divide between Dermotstown and Whitestown, which almost coincides with the topographic divide.

The **Northeastern Boundary** (between Dermotstown and Dennis Fields) is constrained by topography and the geological boundary of the Carboniferous Limestones with the Silurian Metasediments. An arbitrary buffer of 200 m beyond the geological boundary is used to delineate the boundary. Further west toward Decoy Bridge, the boundary is delineated using topography. In the vicinity of Decoy Bridge and Knock there is an area of higher permeability to allow groundwater to discharge from the area. To account for this the boundary of the ZOC is based on the boundary of the higher permeability subsoil in this area.

8.2 Inner Protection Area

The Inner Protection Area (SI) is the area defined by a 100-day time of travel (ToT) to the source. It is delineated to protect against the effects of potentially contaminating activities that may have an immediate influence on water quality at the source, in particular microbial contamination. By using the aquifer parameters for permeability and hydraulic gradient, 100-day ToT estimations are made. Estimations of the extent of this area are done by using Darcy's Law, which can be used to estimate groundwater velocities.

Velocity = (gradient x permeability) ÷ porosity

The pumping water gradient is estimated downgradient and upgradient of PW2, PW4 and PW5. Thus velocities are estimated to the southeast, southwest, northwest and northeast of the wells.

Velocities are estimated to be approximately 3 m/d to the southeast and northwest, parallel to the main high transmissivity zone. Accordingly the boundary of the SI is 300 m southeast and northwest of the wells. To the southwest due the steeper gradients the velocity is estimated to be approximately 9.5 m/d and to the northeast 4 m/d. However, to the southwest the velocities are such that the 100-day ToT boundary extends beyond the boundary between the Carboniferous Limestones and the Namurian rocks. Thus a permeability of (0.125 m/d) and a porosity (0.01) of the Namurian rocks are taken into account. Accordingly the boundary of the SI is approximately 450m southwest of the wells. To the northeast of the wells the boundary of the SI is approximately 400 m. The SI area is shown in Figure 8 and Map 5.

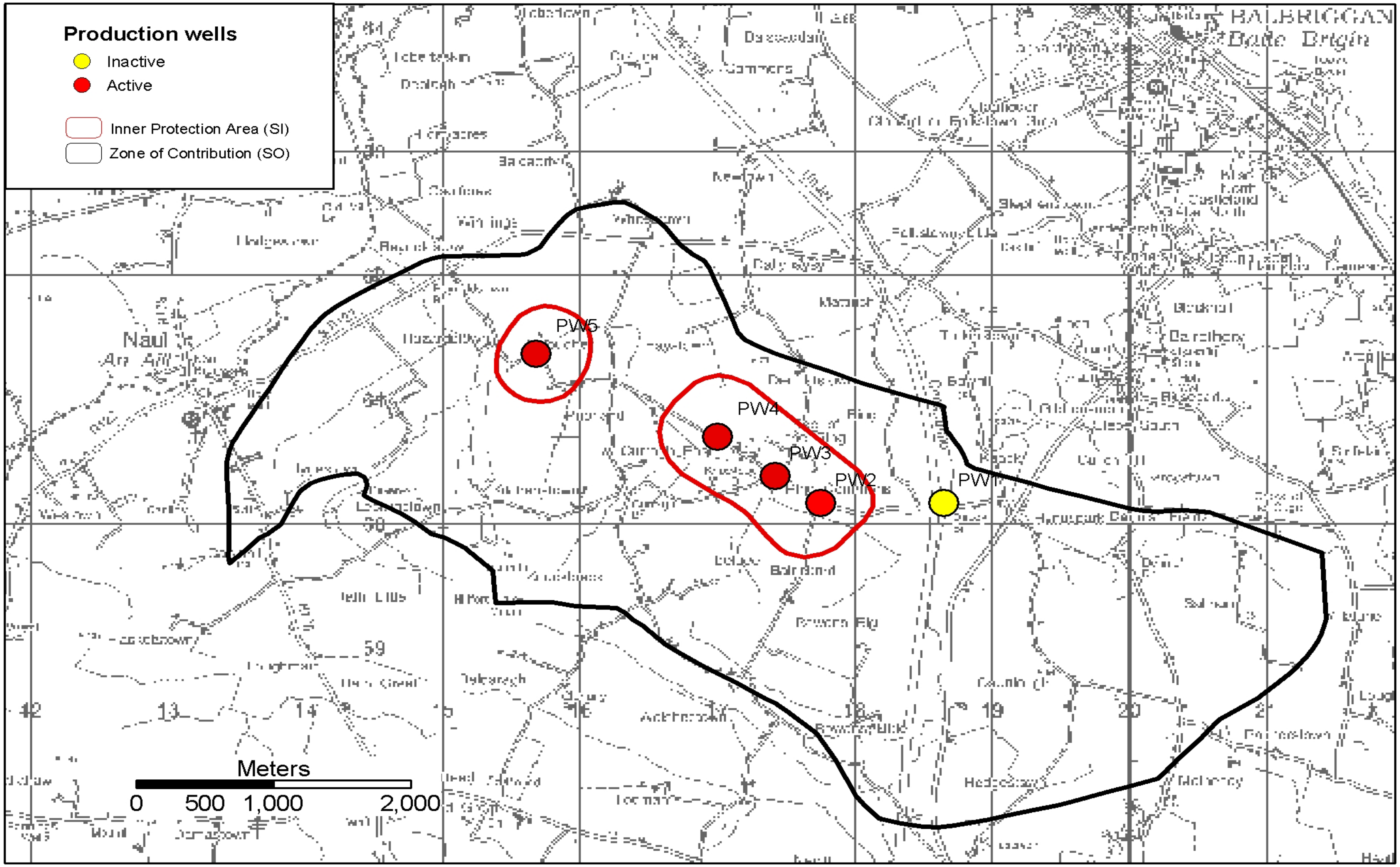

Figure 8: Zone of contribution (ZOC) to the Bog of the Ring wells, showing the Inner (SI) and Outer (SO) protection zones. See text and Table 10 for explanation

9: Vulnerability

Groundwater vulnerability is dictated by the nature and thickness of the material overlying the uppermost groundwater 'target'. Consequently, vulnerability relates to the thickness of the unsaturated zone in the sand/gravel aquifer, and the permeability and thickness of the subsoil in areas where the sand/gravel aquifer is absent. A detailed description of the vulnerability categories can be found in the Groundwater Protection Schemes document (DELG/EPA/GSI, 1999) and in the draft GSI Guidelines for Assessment and Mapping of Groundwater Vulnerability to Contamination (Fitzsimons *et al.*, 2003).

- For the purposes of vulnerability mapping, the source of the groundwater is the bedrock, therefore the "**top of the rock**" is the target.
- The permeability of the sand and gravel is classified as "**high**," the permeability of the till is "**low**" to "**moderate**", the permeability of the alluvium is "**moderate**", and the permeability of the lacustrine deposits is "**low**".
- Depth to bedrock is described in Section 6.3.5.
- The distribution of interpreted groundwater vulnerability in the ZOC is presented on Map 4. The area around the source is generally classified as "**low**" and "**moderate**" vulnerability. Areas of "**extreme**" and "**high**" vulnerabilities tend to be confined to the locally elevated areas, for example on Knockbrack Hill. Rock is also close to the surface in otherwise "**low**" vulnerability areas along some of the streams that drain Knockbrack.

Depth to bedrock can vary over short distances. As such, the vulnerability mapping provided will not be able to anticipate all the natural variation that occurs in an area. The mapping is intended as a guide to land use planning and hazard surveys, and is not a substitute for site investigation for specific developments. Classifications may change as a result of investigations such as trial hole assessments for on-site domestic wastewater treatment systems. The potential for discrepancies between large-scale vulnerability mapping and site-specific data has been anticipated and addressed in the development of groundwater protection responses (site suitability guidelines) for specific hazards. More detail can be found in 'Groundwater Protection Schemes' (DELG/EPA/GSI, 1999).

9.1 Groundwater Protection Zones

The groundwater protection zones are obtained by integrating the two elements of land surface zoning (source protection areas and vulnerability categories) – there are eight possible source protection zones. In practice, the source protection zones are obtained by superimposing the vulnerability map on the source protection area map. Each zone is represented by a code (e.g. **SI/H**, which represents an Inner Protection area where the groundwater is highly vulnerable to contamination). These are on the final source protection map, which is presented as Map 5. Eight groundwater protection zones are present around the Bog of the Ring public supply wells as shown below in Table 10.

Table 10: Matrix of Source Protection Zones for the Bog of the Ring public supply

VULNERABILITY RATING	SOURCE PROTECTION	
	Inner	***Outer***
Extreme (E)	SI/E	SO/E
High (H)	SI/H	SO/H
Moderate (M)	SI/M	SO/M
Low (L)	SI/L	SO/L

9.2 Potential Pollution Sources

The lands around the wells are primarily used for crop growing, grazing and tillage. Agricultural activities and the houses in the ZOC are the principal hazards to the supply wells. Near PW2, issues such as runoff associated with the M1 motorway is also a potential sources of pollution. Overall, the main potential sources of pollution within the ZOC are pesticides, livestock, septic tank systems and runoff from roads. The main potential pollutants are faecal bacteria, viruses, Cryptosporidium, and nitrogen.

10: Conclusions and Recommendations

- The boreholes at Bog of the Ring are excellent yielding wells, which are located in a fractured zone in a **locally important aquifer which is moderately productive (Lm)**.
- The high yields observed at the production wells are due to the presence of a high transmissivity zone supported by a significant gravel horizon.
- The long-term yield is limited by the low recharge and presence of relatively poor bedrock aquifers bounding the main 'Bog of the Ring aquifer'. The high transmissivity zones act as horizontal pathways, and maintenance of well yields is largely dependent on water feeding into them from the surrounding aquifers.
- A comprehensive water level monitoring programme is recommended to enable further evaluation of the sustainable yields of the wells.
- The protection zones delineated in this report are based on our current understanding of groundwater conditions and on the available data. Due to the general complexity of Ireland's hydrogeology and limitations in data availability, uncertainty is an inherent element in drawing boundaries (see Section 3.5 in DoELG/EPA/GSI, 1999). The hydrogeology of the Bog of the Ring area is exceptionally complex. Therefore, drawing boundaries, particularly in the high transmissivity zones, is difficult and some uncertainty is inevitable. Detailed drilling and monitoring in these areas would be required before precise boundaries could be delineated.
- The ZOC is delineated for the current abstraction rate of 3,500 m^3/d. It shows extension of the ZOC westwards in the Hazardstown area and southwards in the Rowans Little/Hedgestown area beyond the pre-pumping groundwater divides.
- The model predictions highlight the need for further assessment of the available groundwater resources in this aquifer, prior to decisions on increasing the abstraction rate beyond 3,500 m^3/d. The predicted boundaries cannot be taken as definitive; neither the available data, nor the conceptual model on which the numerical model is based, nor the model grid allow precise delineation of the ZOC boundaries.
- Overall, the samples from the trial and production wells do not indicate significant contamination or pollution of these wells.
- The area around the source is generally classified as "**low**" and "**moderate**" vulnerability.
- Overall, our recommendations are as follows:

1. Continued monitoring of water levels in the pumping and observation wells.
2. Chemical and bacteriological analyses of raw water (rather than treated water) should be carried out approximately once a month to get baseline reference data. Following analysis of the data it may be decided to reduce the frequency to once every two or three months.
3. Particular care should be taken when assessing the location of any activities or developments within the inner protection area (SI) that might cause contamination at the boreholes.
4. The potential hazards in the ZOC should be identified, and a risk assessment of each hazard is recommended.

11: Acknowledgements

We wish to acknowledge the contributions to the study made by the following people:
Fingal Co. Co.: Pat Finn, Water Services Section; Keith Hanratty; Water Services Section; Janice Butler, Water Services Section; Michael Donoghue, Caretaker at Pumping Station; Joseph Mandolil, Resident Site Engineer.
RPS-MCOS: Eleanor Boland.
GSI: Kathryn Hill, Jenny Rush, Mairead Glennon, Silvia Caloca, Siobhan McLaughlin, Laurence Dempsey and David Broderick, Groundwater Section – map production and field work; Rosemarie Jordan, Seabed Survey Section – GPS field assistance.

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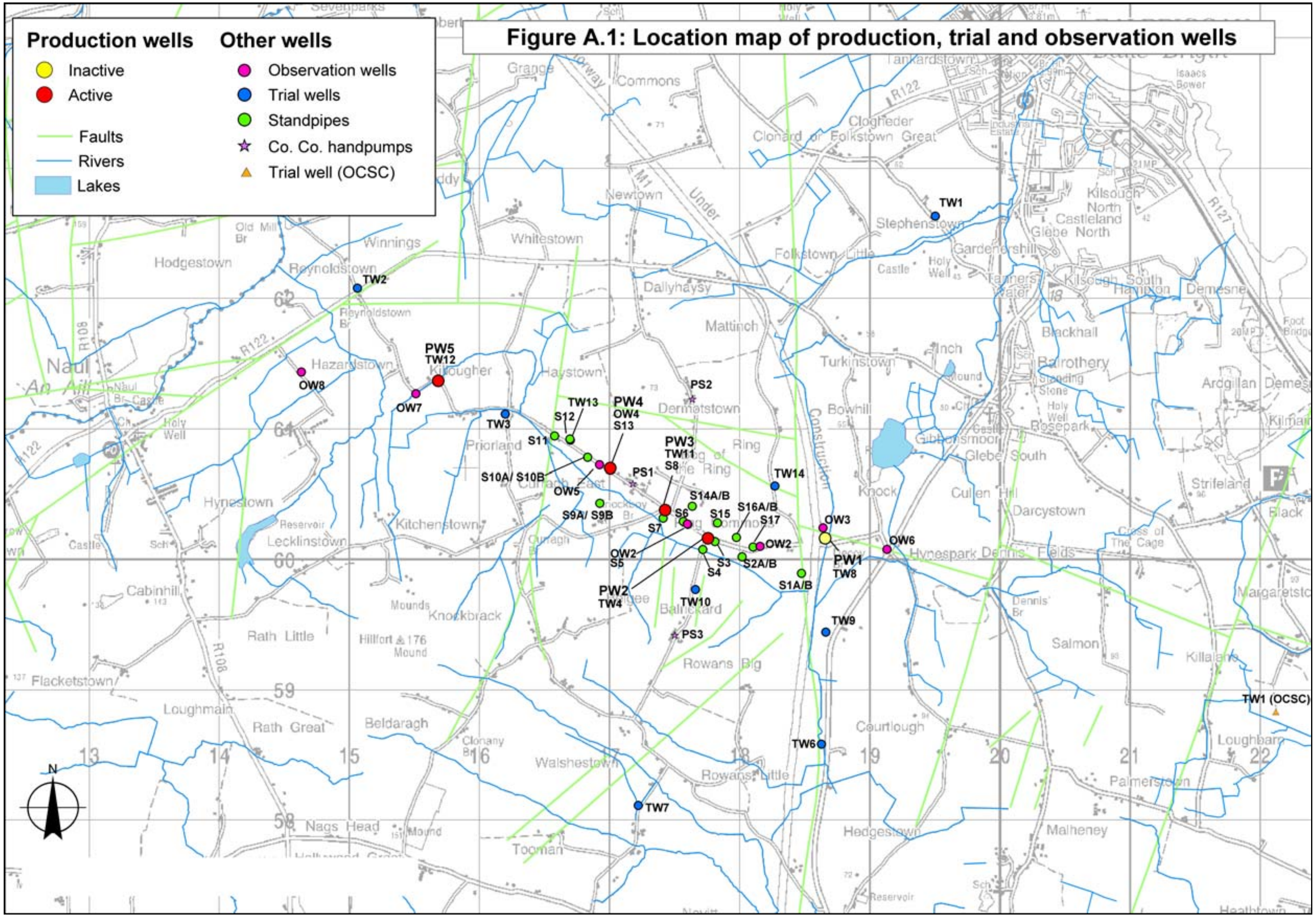

Figure A.1: Map showing the locations of wells discussed in the text.

(a) Recharge Zone Map

x	x	x	x	x	x	14	15	x	x	x	x	x	x	x	x
x	x	x	x	x	13	14	12	13	12	x	x	x	x	x	x
x	x	x	x	x	8	15	10	11	10	x	x	x	x	x	x
x	x	x	x	7	10	11	11	10	x	x	x	x	x	x	x
x	x	x	x	10	8	8	13	13	x	x	x	x	x	x	x
x	x	x	x	13	15	14	14	13	x	x	x	x	x	14	13
x	x	x	x	15	13	12	12	14	10	x	x	5	13	13	13
15	15	15	15	15	13	2	8	14	13	15	15	12	12	14	14
x	15	15	15	15	15	15	16/15	16/15	16/15	16/15	16/15	13	14	14	6
15	13	15	15	15	15	15	12	13	10	5	14	15	8	14	14
15	13	13	12	15	15	15	13	3	1	13	14	15	14	14	14
15	14	15	10	13	4	4	3	1	7	14	15	15	14	15	x
x	x	x	x	x	x	x	x	x	x	x	15	15	8	x	x

(b) Recharge Value (mm/yr) Map

x	x	x	x	x	x	68	57	x	x	x	x	x	x	x	x
x	x	x	x	x	79	68	90	79	90	x	x	x	x	x	x
x	x	x	x	x	143	57	115	104	115	x	x	x	x	x	x
x	x	x	x	179	115	104	104	115	x	x	x	x	x	x	x
x	x	x	x	115	143	143	79	79	x	x	x	x	x	x	x
x	x	x	x	79	57	68	68	79	x	x	x	x	x	68	79
x	x	x	x	57	79	90	90	68	115	x	x	222	79	79	79
57	57	57	57	57	79	304	143	68	79	57	57	90	90	68	68
x	57	57	57	57	57	57	0/57	0/57	0/57	0/57	0/57	79	68	68	197
57	79	57	57	57	57	57	90	79	115	222	68	57	143	68	68
57	79	79	90	57	57	57	79	269	322	79	68	57	68	68	68
57	68	57	115	79	251	251	269	322	179	68	57	57	68	57	x
x	x	x	x	x	x	x	x	x	x	x	57	57	143	x	x

Figure A.2: Maps showing (a) recharge zonation and (b) recharge values in mm/yr used in the numerical model. The 'x' represents inactive cells in the model. In the cells where there are two values (i.e. 16/15 or 0/57), recharge takes different values depending on whether the aquifer is artesian (natural conditions) or non-artesian (pumping conditions).

(a) Permeability Map (m/d)

x	x	x	x	x	x	0.6	0.6	x	x	x	x	x	x	x	x
x	x	x	x	x	0.25	0.6	0.6	0.25	0.6	x	x	x	x	x	x
x	x	x	x	x	0.25	0.6	0.6	0.6	0.6	x	x	x	x	x	x
x	x	x	x	0.25	0.25	0.6	0.6	0.6	x	x	x	x	x	x	x
x	x	x	x	0.6	0.6	0.6	0.6	0.6	x	x	x	x	x	x	x
x	x	x	x	0.6	0.6	0.6	0.6	0.6	x	x	x	x	x	0.7	0.7
x	x	x	x	0.6	0.6	0.25	0.25	0.6	5	x	x	0.7	0.7	0.7	0.7
0.25	0.25	0.25	5	5	5	9	9	9	9	12	12	0.7	0.7	0.7	0.7
x	0.25	0.25	5	5	9	9	9	9	9	9	12	0.7	0.7	0.0313	0.0625
0.25	0.25	5	5	5	0.125	0.125	0.125	5	5	5	12	12	0.0313	0.0313	0.0625
0.25	9	9	0.125	0.085	0.085	0.125	0.125	0.125	0.085	5	0.085	12	0.7	0.7	0.7
5	9	0.0625	0.085	0.085	0.085	0.125	0.0625	0.125	0.125	0.125	0.0625	12	0.7	0.7	x
x	x	x	x	x	x	x	x	x	x	x	0.0625	12	0.7	x	x

(b) Transmissivity Map (m^2/d)

x	x	x	x	x	x	24	24	x	x	x	x	x	x	x	x
x	x	x	x	x	10	24	24	10	19	x	x	x	x	x	x
x	x	x	x	x	10	24	22	18	13	x	x	x	x	x	x
x	x	x	x	10	10	24	21	14	x	x	x	x	x	x	x
x	x	x	x	24	24	24	23	16	x	x	x	x	x	x	x
x	x	x	x	24	24	25	25	21	x	x	x	x	x	46	45
x	x	x	x	23	25	11	11	24	236	x	x	45	45	46	45
8.9	10	10	187	192	205	668	653	625	602	815	798	49	51	50	49
x	7.9	10	231	348	606	607	610	652	617	614	841	52	50	2.0	2.5
5.6	6.9	352	343	355	4.6	3.6	3.0	345	337	337	809	833	2.2	2.0	3.8
9.1	632	637	3.7	3.5	3.6	4.3	4.6	3.9	3.5	348	3.6	843	49	49	47
282	614	3.5	3.6	3.6	3.6	4.1	3.1	4.3	4.2	4.3	3.7	837	49	49	x
x	x	x	x	x	x	x	x	x	x	x	4.2	840	49	x	x

Figure A.3: Maps showing (a) cell permeability (m/d) and (b) cell transmissivity (m^2/d) used in the numerical model. The 'x' represents inactive cells in the model.

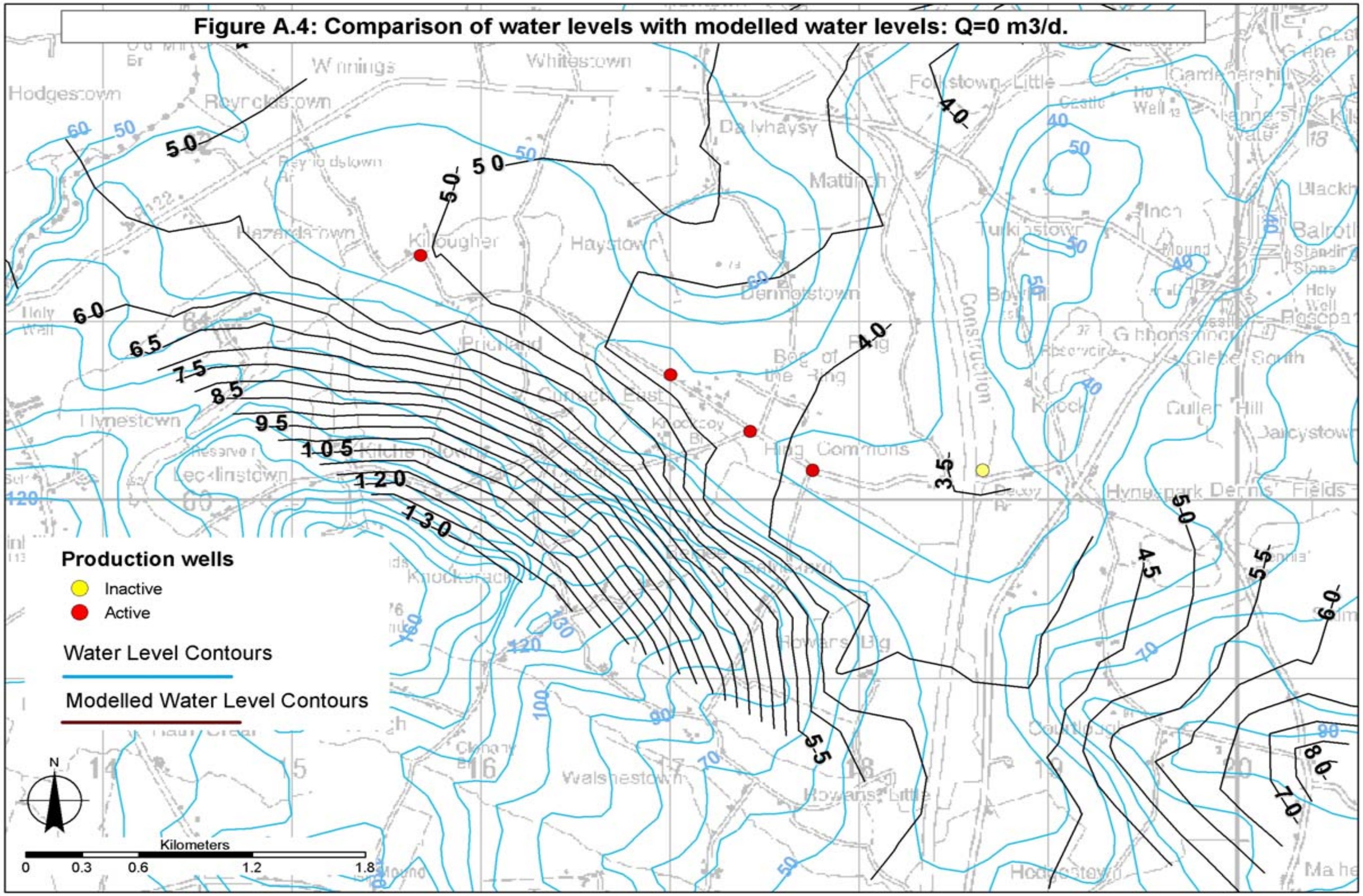

Figure A.4: Comparison of groundwater head values against modelled head values for the unpumped situation.

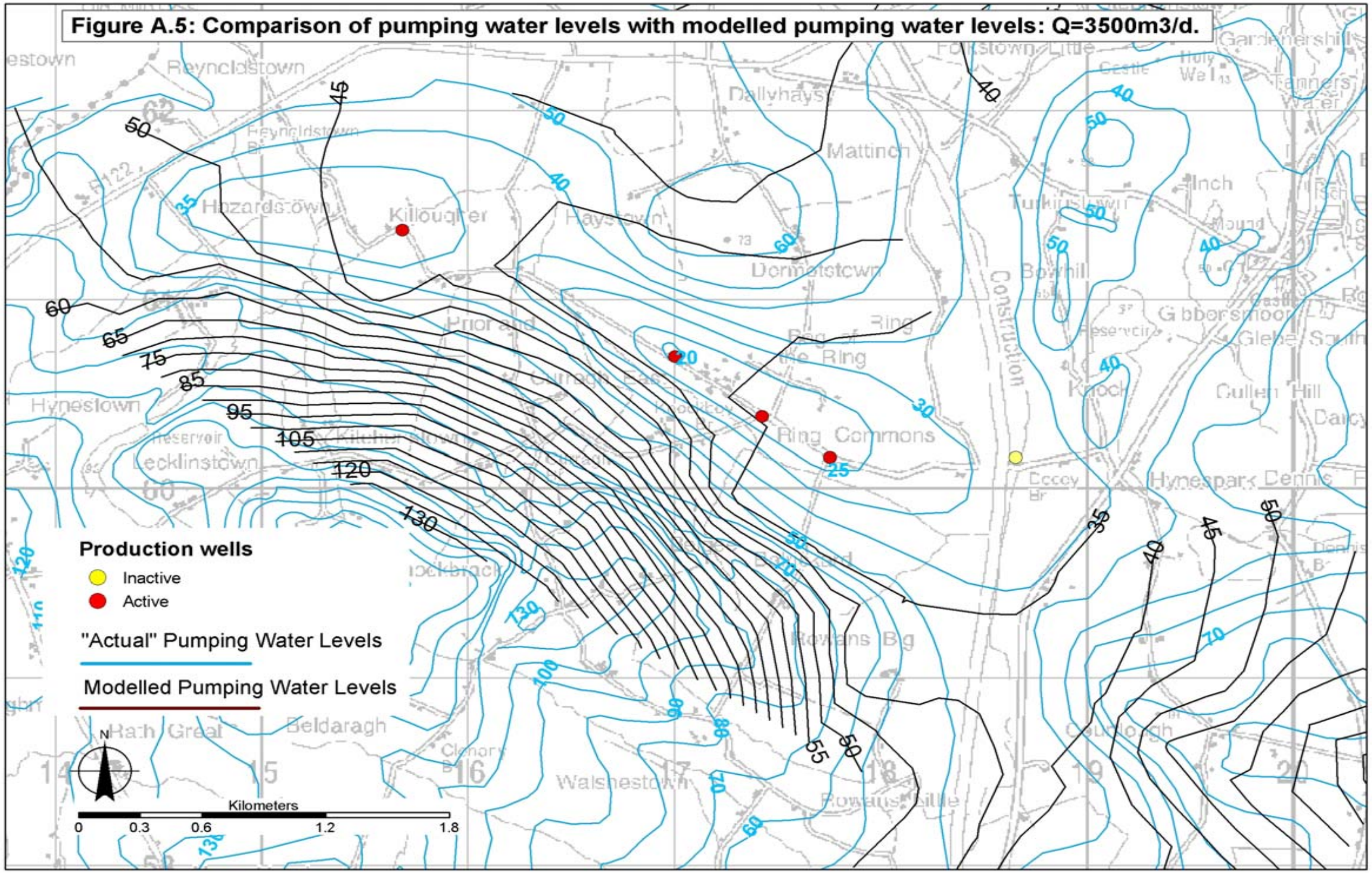

Figure A.5: Comparison of modelled and actual pumping water levels.