Louth County Council

Establishment of Groundwater Source Protection Zones

Drybridge Water Supply Scheme

Drybridge Borehole

October 2014

Revision: E

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PROJECT DESCRIPTION

Since the 1980's, the Geological Survey of Ireland (GSI) has undertaken a considerable amount of work developing Groundwater Protection Schemes throughout the country. Groundwater Source Protection Zones are the surface and subsurface areas surrounding a groundwater source, i.e. a well, wellfield or spring, in which water and contaminants may enter groundwater and move towards the source. Knowledge of where the water is coming from is critical when trying to interpret water quality data at the groundwater source. The Source Protection Zone also provides an area in which to focus further investigation and is an area where protective measures can be introduced to maintain or improve the quality of groundwater.

Louth County Council contracted GSI to delineate source protection zones for eight groundwater public water supply sources in Co. Louth. The sources comprised Ardee, Cooley (Carlingford and Ardtullybeg), Collon, Greenore, Termonfeckin, Omeath, Drybridge and Killineer.

This report documents the delineation of the Drybridge source protection zones.

A suite of maps and digital GIS layers accompany this report and the reports and maps are hosted on the EPA and GSI websites (www.epa.ie; www.gsi.ie).

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1 INTRODUCTION

Groundwater Source Protection Zones are delineated for the Drybridge Borehole source according to the principles and methodologies set out in 'Groundwater Protection Schemes' (DELG/EPA/GSI, 1999) and in the GSI/EPA/IGI Training course on Groundwater Source Protection Zone Delineation.

The Drybridge borehole source supplies drinking water to the Tullyallen area to the northwest of Drogheda. In this report the source borehole is labelled borehole PWSBH01 (Figure 1).

The objectives of the report are as follows:

- To outline the principal hydrogeological characteristics of the area surrounding the source.
- To delineate source protection zones for the Drybridge borehole.
- To assist Louth County Council in protecting the water supply from contamination.

Groundwater protection zones are delineated to help prioritise the area around the source in terms of pollution risk to groundwater. This prioritisation is intended as a guide in evaluating the likely suitability of an area for a proposed activity prior to site investigations. The delineation and use of groundwater protection zones is further outlined in 'Groundwater Protection Schemes' (DELG/EPA/GSI, 1999).

The maps produced are based largely on the readily available information in the area, a field walkover and on mapping techniques which use inferences and judgements based on experience at other sites. As such, the maps cannot claim to be definitively accurate across the whole area covered, and should not be used as the sole basis for site-specific decisions, which will usually require the collection of additional site-specific data.

The locations of the groundwater and surface water point features investigated during the site visits and identified during the desk study are shown in Figure 2. A summary table of the point data collected is provided in Table A1.1 in Appendix No. 1.

2 METHODOLOGY

A desk study of existing data sources relevant to the source was carried out prior to a site visit. Site visits, site walk-overs and field mapping of the study area were conducted on 30/04/2010 and 13/06/2010. An interview with the source caretaker was carried out on 30/04/2010. A depth to bedrock drilling programme was carried out by the GSI during May 2007 to investigate the subsoil geology, the hydrogeology and the vulnerability to contamination of the study area. Karst mapping of the area was carried out in May 2008 and April and June 2010. Further karst mapping and a karst tracer test using fluorescent dye was undertaken in June 2013.

3 LOCATION, SITE DESCRIPTION AND WELL HEAD PROTECTION

Borehole PWSBH01 is located in a Louth County Council compound on the southwest side of the Dry Bridge in the townland of Tullyallen, as shown in Figures 1 and 2. The site is approximately 2 km west of Drogheda, 500 m north of the River Boyne and 240 m east of the M1 motorway.

The compound is fenced/walled and has a hardcore surface, a treatment/pump house, and three shallow underground chambers. The westernmost chamber contains borehole PWSBH01; the middle chamber contains a sampling tap and a scour valve; and the eastern chamber comprises a clearwater tank. The first two chambers have hinged lids at just above the ground surface, while the clearwater tank has a concrete roof with a manhole access point. The site layout can be seen in Photograph 1 below.

The mouth of the borehole is formed by concentric 130 mm, 200 mm and 250 mm diameter steel casings. These are cut off at a level 0.03 m above the floor of the borehole chamber and 1.2 mbgl. A small volume of ponded water was present on the floor of the chamber during the site visit of 30th April 2010. This water may derive from drainage out of service ducts which enter through the western face of the chamber. The borehole chamber can be seen in Photograph 2 below. There is no indication that a grout seal was installed in the upper borehole annulus during construction.

Photograph 1 View from southwest of PWSBH01 chamber

Photograph 2 View of borehole chamber and mouth of borehole

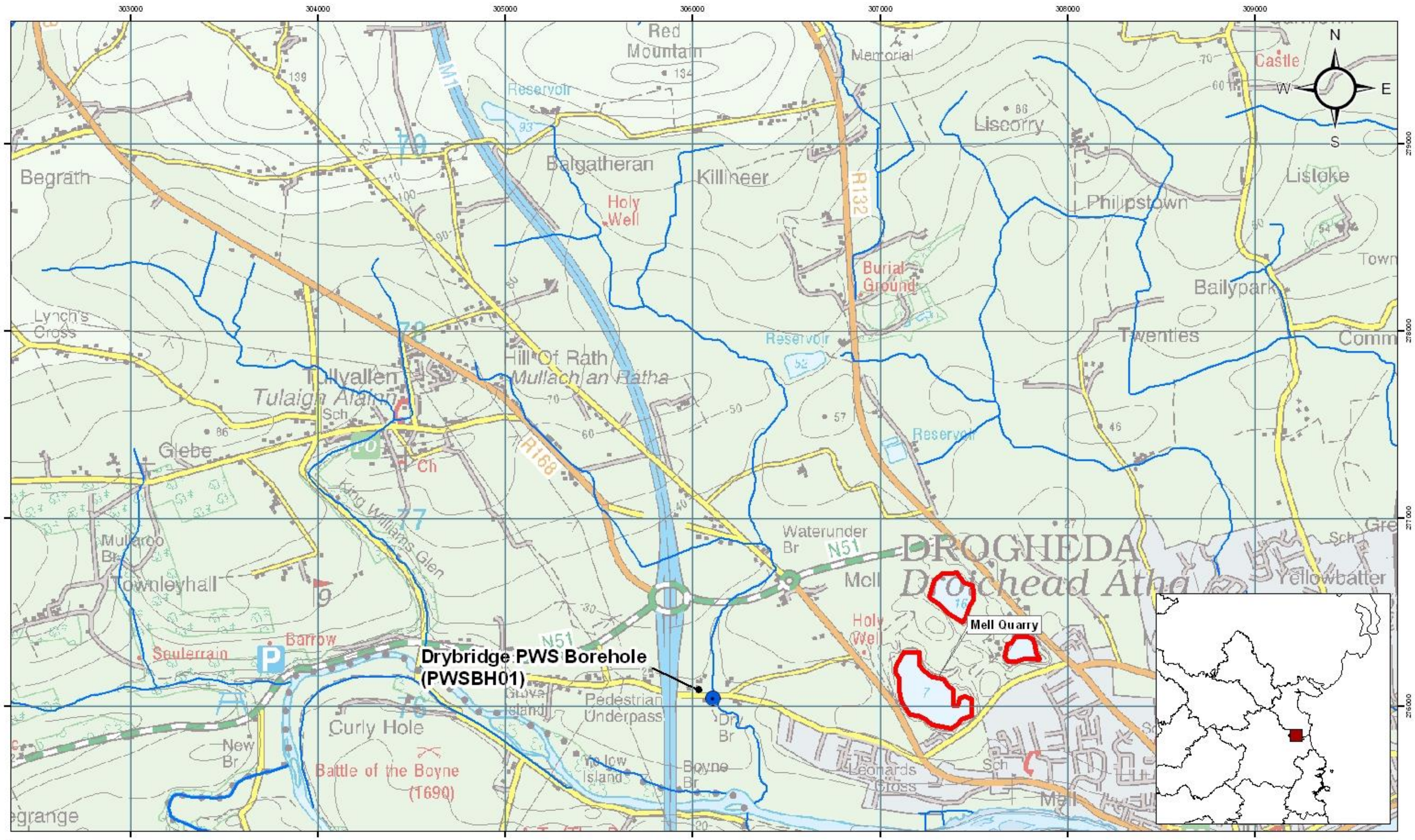

Figure 1 Drybridge Site Location Map

PWS Abstraction

Stream

Boundary of Mell Quarry Extraction Pits

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0 0.25 0.5 1 km

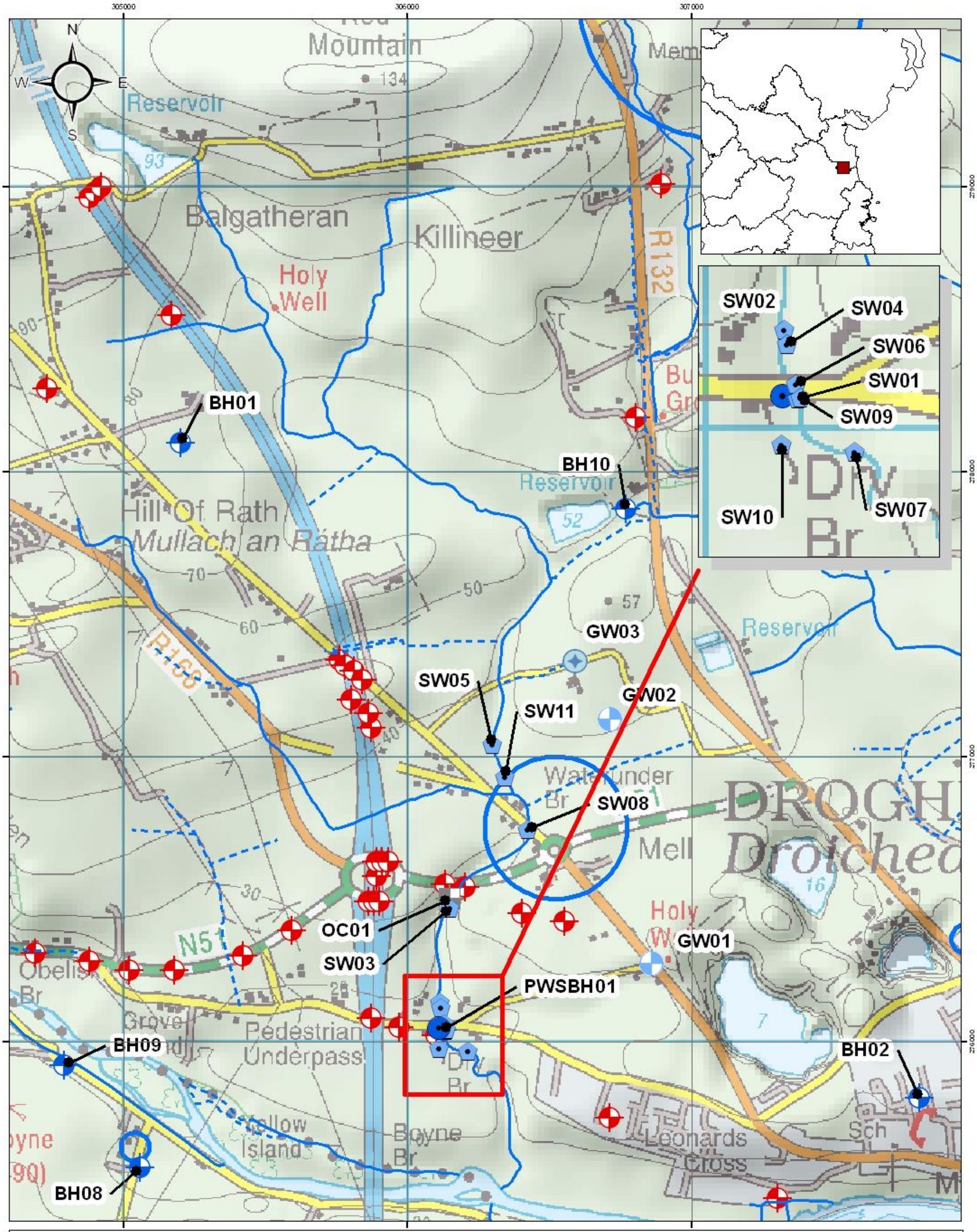

Figure 2 Data Points in the Vicinity of Drybridge PWS Site

PWS Abstraction
Stream
Groundwater Borehole
Groundwater Dug Well
GSI Well Database (50 m accuracy)
GSI Well Database (50 m to 1 km accuracy)
Groundwater, Spring
Surface Water Data Point
Bedrock, Outcrop
Stream / Drain digitised from 25-inch historical map
0 0.125 0.25 0.5 0.75 km

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4 SUMMARY OF BOREHOLE DETAILS

The borehole details have been collated from NERDO (1981), Atkins (2002), and Louth County Council records. The borehole was originally drilled in 1979 as part of the North East Regional Development Organisation (NERDO) groundwater resources investigation (NERDO, 1981). The borehole was refurbished in the period 2001 to 2003 by Louth County Council and commissioned in 2003 (Keith Hanratty, pers comm., 2010). A graphical borehole log of the original 1979 borehole from the NERDO (1981) report is included in Appendix 1. A new schematic diagram showing the original borehole, the rehabilitated borehole and water levels at various moments of interest between 1980 and 2010 is shown in Appendix 1 Figure A1.1. The water level in the Boyne River is also shown on the schematic for reference.

Borehole PWSBH01 was drilled to a depth of 43 m in 1979. The target depth of 45 m could not be reached due to collapse of the walls of the borehole. The borehole was rehabilitated in 2001-2003 by Louth County Council, by re-drilling at 250 mm diameter. The re-drilled well was cleaned out following problems of borehole collapse. Subsequently, a 130 mm stainless steel liner was installed to 39 mbgl. Six metres of 125 mm diameter Johnson well screen (304 stainless steel, 1.5 mm slot-aperture) and a base plate were installed below the liner between 39 m and 45 mbgl.

In 1979 and following commissioning in 2003, the source had problems of high turbidity following initial start-up. In the rehabilitated borehole this turbidity cleared up after approximately 2 minutes of pumping. As such the borehole was fitted with a timer controlled scour which directed the first 2 minutes of pumping after start-up to waste. During the site visit on 30th April 2010 the site caretaker advised that the scour option was no longer in use as the turbidity problems had abated, however a minor amount of fine particles continue to settle on the floor of the clearwater tank.

The scheme currently supplies 275 m^3/d, (with a capacity to produce 350 m^3/d) and serves an approximate population of 800 people. The pumping rate during the site visit of 30th April 2010 was 16.4 m^3/h (394 m^3/d). The system pumps intermittently to a clearwater tank adjacent to the source. The water is chlorinated in the clearwater tank and then pumped to a reservoir in the townland of Killineer. The source is pumped in general for 22 hours out of every 45 hours, i.e. approximately 50% of the time. The source was successfully pump tested for three days at 10.7 l/s (924 m^3/d) in February of 1980 (NERDO, 1981) and at 480 to 530 m^3/day during commissioning; as such, it appears that it is not currently used to its full capacity.

Table 1-1 Summary of Source Details

Monitoring Code	IE_EA_G_029_2100_005
GSI Well Database Reference No.	2927SEW059
Borehole Name	PWSBH01
Grid reference	E306109 N276045
Townland	Tullyallen
Source type	Borehole
Drilled	1979 / Rehabilitated 2001 – 2003
Owner	Louth County Council
Elevation (Ground Level)	approx. 13.3 mAOD (NERDO, 1981)
Depth	45 mbgl
Depth of casing	39 mbgl
Depth of Well Screen	125 mm diameter, 1.5 mm aperture slotted stainless steel well screen 39 to 45 mbgl attached to base of 130 mm stainless steel casing
Diameter	200 mm steel casing 0 to 19.5 mbgl 130 mm stainless steel casing 0 to 39mbgl 125 well screen from 39m to 45mbgl
Depth to rock	7.8 mbgl
Static water level (SWL)	1979 – 1996 Hydrograph SWL range = 4.53 to 12.11 mAOD; Average = 7.12 mAOD
Pumping water level (PWL)	4.7 mAOD or 7.38 mb top of 130 mm steel casing (mbtc) (9 am on 30/04/2010; Pumping Rate = 394 m^3/day)
Drawdown at current pumping rate	approx 2.42 m (Average SWL minus PWL)
Depth of pump	39 m
Consumption (Co.Co. records)	275 m^3/d at a rate of 16.4 m^3/h (Average for 2009)
Pumping test summary [(i)]:	
(i) abstraction rate m^3/d	924.5 m^3/d (10.7 l/s test pumping rate)
(ii) specific capacity	77 m^3/d/m @ 924.5 m^3/day 171 m^3/d/m @ 530 m^3/day (14 day test (Atkins, 2002)) Approx 163 m^3/d/m @ 394 m^3/day (April 30th, 2010)
(iii) transmissivity (T)	160 m^2/d
(iv) average permeability	5.3 m/d [(ii)]

Note (i): 3 day constant rate pumping test at 10.7 l/s (924 m3/day) started on 18/02/80 (NERDO, 1981).
Note (ii): Permeability based on T/b, where 'b' is the saturated aquifer thickness = 30.35 m (based on 12 m of drawdown after 2520 minutes of pumping test on 18/02/1980 (i.e. pumping water level at 0.65 mAOD) minus base of borehole in 1980 (-29.7 mAOD).

5 TOPOGRAPHY, SURFACE HYDROLOGY AND LANDUSE

The source is located on the northern flank of the Boyne River valley at approximately 13.3 mAOD (see Figure 1). The source is on the northern limit of the Boyne sand and gravel terraces, and the area around it has been deeply incised, resulting in a hummocky topography. To the north of the source the ground surface rises steadily to the bedrock-cored ridges of the Hill of Rath (approx. 70 mAOD) located 2 km to the northwest and Red Mountain (approx. 130 mAOD) located 3 km north. The topographic gradient to the north of the source is approximately 0.03.

Surface water in this area generally drains southwards from the high ground to the Boyne. A stream draining a small catchment west of the R132 regional road, south from Red Mountain and east from the Hill of Rath, runs north to south along the eastern side of the source compound. The stream (called the Drybridge Stream in this report) feeds into the Boyne 600 m south-southeast of the source. This stream sinks completely underground at Water Underbridge (850 m north-northeast of PWSBH01) in drought conditions. When measured in May 2008 it had an approximate flow of 0.009 m^3/s. Drainage density across the higher ground to the north and onto the lower land around the source is high[1]. There is a small drain on the road adjacent to the site compound, which drains through the compound wall into the site. The drain discharge infiltrates through the compound hardcore surface dressing.

The study area has a mixed land-use. Agricultural land-use dominates the area with both arable crops and livestock pasture surrounding, and occurring immediately up-slope of the source. The edge of Drogheda urban area lies less than 300 m east of PWSBH01. The M1 retail centre and car park lie approximately 350 m to the northeast, and the M1 motorway is located less than 250 m to the west of the source. A number of houses and farms lie within 100 m of the borehole. These houses are thought to be on the mains water and sewage systems, however an onsite wastewater treatment system was observed on the property immediately west of the source during the site visit of 30th April 2010 and such systems may also be present at other, more rural residences. Disused sand and gravel pits lie 100 m southwest of the supply borehole and Mell Quarry, a large disused rock quarry (approximately 1 km^2), is located between 1 km and 2 km east of the source.

6 HYDRO-METEOROLOGY

Establishing groundwater source protection zones requires an understanding of general meteorological patterns across the area of interest. The data source is Met Éireann.

Annual rainfall: 800 mm. The closest meteorological station to the Drybridge Source is Drogheda (Killineer) at Killineer Reservoir, 1.2 km to the south where the average rainfall between 1970[2] and 1990 was 800 mm/yr (Fitzgerald and Forrestal, 1996).

Annual evapotranspiration losses: 532 mm. The closest synoptic weather station to the study area is Dublin Airport 35 km to the south. Average potential evapotranspiration (P.E.) at Dublin Airport between 1961 and 1990 was 560 mm, based on Met Eireann data. Actual evapotranspiration (A.E.) is then estimated as 95% of P.E., to allow for seasonal soil moisture deficits giving an Actual Evapotranspiration of 532 mm.

Annual Effective Rainfall: 268 mm. This is calculated by subtracting actual evapotranspiration from rainfall. Potential groundwater recharge is equivalent to this.

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[1] High drainage density equates to > 1 km length of surface water courses per 1 km^2 of surface area

[2] Note: Drogheda (Drybridge) rainfall station opened in 1970.

7 GEOLOGY

This section briefly describes the relevant characteristics of the geological materials that underlie the Drybridge source. It provides a framework for the assessment of groundwater flow and source protection zones that will follow in later sections. The geological information is based on the bedrock geological map of Meath, Sheet 13, 1:100,000 Series (Geological Survey of Ireland (GSI), 2005) and accompanying memoir (McConnell *et al,* 2005); historical geological mapping by the GSI at the 6-inch to 1 mile scale; the GSI Well and Borehole Databases; and on bedrock outcrop and subsoil exposures encountered during site visits. The bedrock geology of the area is shown in Figure 3.

7.1 BEDROCK GEOLOGY

The bedrock map indicates that the area surrounding the source is underlain by limestone bedrock of Lower Carboniferous age with older Silurian aged rocks to the north. Regionally the limestones extend southwards from a line joining Old Bridge (4 km west of Drogheda) and Termonfeckin and continue under the Boyne River to the south of Drogheda. The bedrock types in the area are summarised in stratigraphic order in Table 7-1.

Table 7-1: Bedrock Descriptions

Bedrock Formation	Generalised Rock Unit Classification	Geological Description	Max thickness[3] (m)
Platin Formation (PT)	Dinantian pure bedded limestones (DPBL)	Limestone: crinoidal peloidal grainstone-packstone. Local dolomitisation common	700
Tullyallen Formation (TA)	Dinantian pure bedded limestones (DPBL)	Limestone: pale micritised grainstone-wackestone	500
Glaspistol Formation (GP)	Silurian Metasediments and Volcanics (SMV)	Black mudstone and quartzose greywacke	unknown
Little Harbour Formation (LT)	Silurian Metasediments and Volcanics (SMV)	Calcareous greywacke and mudstone	>100

The limestones are described as strongly jointed, vertically fissured karstified limestones which have had their fractures infilled by a variety of sands, silts and clays (as encountered during the drilling of PWSBH01 in 1979; NERDO, 1981). The limestones have been dolomitised and decalcified locally along major joint and bedding planes (NERDO, 1981).

Approximately 850 m north of the source, the Dinantian limestones are juxtaposed against the Silurian Metasediments by the Slane fault which runs east-northeast to west-southwest between the two units. Within the limestone formations, cross faults run north-northwest to south-southeast, perpendicular to the Slane fault. The source borehole is located immediately west of one such mapped cross fault.

The limestones are folded at their western end into a shallow syncline with a gentle plunge to the south west (NERDO, 1981). The historical GSI mapping for the area indicates that the limestone strata in the vicinity of the source dip between 5 and 20^{O} in a generally southerly direction. The Silurian strata are indicated as dipping south southeast at between 20^{O} and 40^{O} in the area north of the source.

A cross-section of the geology of the study area is shown in Figure 9. The line of the cross-section in Figure 9 is shown in Figure 3.

[3] Maximum thickness values from McConnell *et* al (2005)

7.2 KARSTIFICATION

Hydrogeological mapping (May 2008 and April and June 2010) included mapping karst features in the vicinity of the source. Karst features can be seen in Mell Quarry where karst landforms were noted during a site visit to the quarry by the GSI in 2008. These included enclosed depressions, infilled collapses and solution cavities and caves. Swallow holes and solutional openings in the rock were mapped in May 2008 and April 2010 in the bed of the Drybridge Stream at Waterunder Bridge, approximately 800 m northeast of the borehole. These features were subsequently investigated using fluorescent dye to determine their connectivity with the borehole.

The dye trace was conducted on 13 June 2013 at 2.15pm. 400 grammes of sodium fluorescein dye was injected into the swallow hole in the bed of the river (Photograph 3). The river then ran dry downstream of this swallow hole and re-emerged approximately 250 m downstream at a spring area (ING E306385 276562). The stream running past the borehole was less than the amount rising at the spring, indicating that the stream lost water through its bed downstream of the spring.

Photograph 3 swallow hole in river upstream of the pumphouse

Daily water samples were taken from the borehole by Denis Grimes, the Caretaker. The dye was first detected in the sample taken two days after the injection. This indicates that water (and dye) reaches the borehole from the injection point within 48 hours. The peak concentration of the dye was found in the sample taken three days after injection (Appendix 3). Groundwater flow rates are greater than 450 m/d for first appearance, and greater than 300 m/d for peak dye concentration.

A small quarry (KF04) located approximately 215 m north-northwest of the bridge at Waterunder Bridge; shows well developed epikarst, with frequent, large solutional openings in the rock. The locations of karst features identified during the hydrogeological mapping surveys are shown in Figure 8 and details of each location are given in Table A1.1.

Borehole logs from the area also show well developed karstification. Two trial boreholes drilled in Mell townland through the Tullyallen and Yellowbatter limestone formations, one penetrating to 72 m and the other to 54.7 m, showed cavities accounting for approximately 10% of the total borehole length (NERDO, 1981). Both the geological log and the caliper log of the 1979 drilling work at borehole PWSBH01 at Drybridge show substantial karstification, including fissure zones at 15 m, 25 m and at 40 mbgl (NERDO, 1981). The three fissures intersected were filled with unconsolidated material. Borehole records from the site investigation for the M1 Northern Motorway recorded cavities/fissures with vertical depths of up to 3 m (BMA, 1996).

7.3 SOILS AND SUBSOILS

Soils

The soils around the source and across the majority of the study area are classified as deep, poorly drained mineral soils (AminPD) derived from mainly non-calcareous parent materials. On the Hill of Rath, and on the till close to the sand and gravel deposits to the west of the source, the soils are mapped as deep, well drained mineral soils (AminDW) derived from mainly non-calcareous parent materials. The soils overlying the glaciofluvial sands and gravels are mapped as shallow, well drained mineral soils (AminSW) derived from mainly non-calcareous parent materials (Teagasc, 2004b).

Subsoils

According to GSI and EPA web mapping, a number of different subsoil units underlie the areas around the borehole PWSBH01. Drilling and permeability mapping carried out by the GSI for this project provide additional information on the subsoils. The subsoil map of the area is shown in Figure 4.

The subsoils around the source comprise glaciofluvial sands and gravels (GLPSsS), till derived from Lower Palaeozoic shale and sandstones (TLPSsS) and Irish Sea Till (IrSTLPSsS). The glaciofluvial sands and gravels form a 0.5 to 2 km wide gravel terrace on the north side of the Boyne River, and underlie the area to the south of the source. The gravel is typically comprised of sandstone and shale. Lower Palaeozoic shale and sandstone tills occupy the area to the north and northwest of the source and are described as till with a generally clay matrix. The Irish Sea Till is similar to the Lower Palaeozoic shale and sandstone till, but is typically more clay dominated, and it occupies the area immediately around the source and to the northeast.

Alluvial deposits occur along the River Boyne, on the margins of the Drybridge Stream downstream of the source, and in smaller localised areas to the north. Evidence from the dry channel of the Drybridge Stream downstream of the source suggests that the alluvial deposits are thin and rest on underlying sand and gravel. An isolated pocket of lake sediments occurs to the northeast of the source, just northeast of Mell Quarry.

Areas of outcropping rock are found to the north of the source on Red Mountain and at incised stream valleys, such as in the Drybridge Stream in the vicinity of Waterunder Bridge. A large area of rock outcrop has been created at Mell Quarry. Islands of rock outcrop occur within the sand and gravel deposits where towers of resistant limestone rise up through the unconsolidated material to form outcrops. Two such towers occur at Obelisk Bridge and Grove Island 1.5 km and 1 km west of the source respectively.

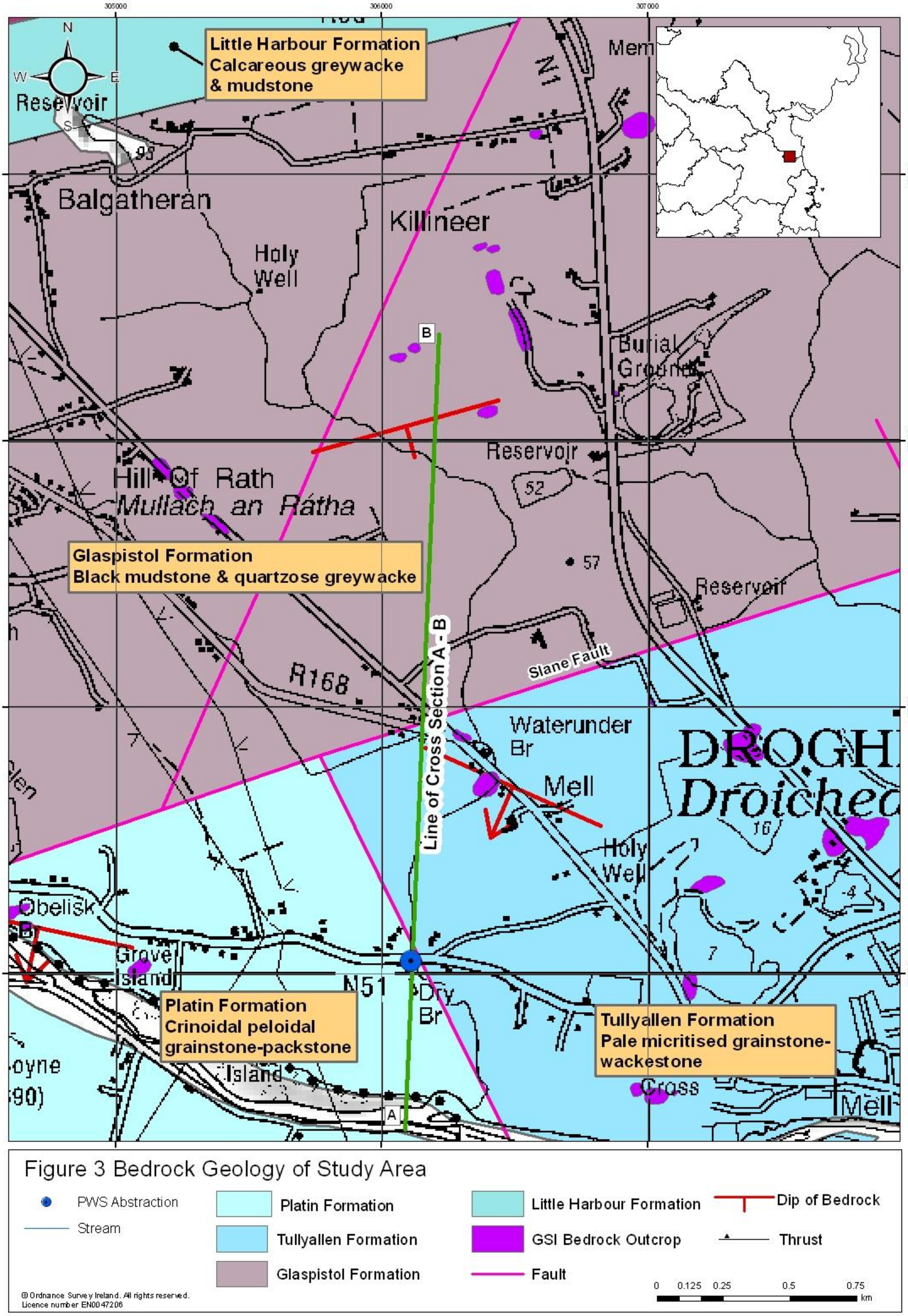

Figure 3 Bedrock Geology of Study Area

Subsoil Permeability

Under the GSI investigations, the permeability of the till units in the study area has been classed as '***Low Permeability'***. The glaciofluvial sand and gravel subsoils are classified as ***'High Permeability'***. Subsoil samples from auger holes drilled by the GSI in the vicinity of the source were logged in accordance with BS5930. The data from the auger hole drilling are summarised in Table 7-2.

Plant indicators of poor drainage are infrequent in the area as much of the agricultural land is intensively managed. In less managed areas north of the source, rushes are present sometimes, while deep machinery tracks in some fields indicate heavy soils. Field drains are also observed in places and natural drainage density is high. These indicators support the low permeability classification of the tills to the north of the source.

Table 7-2 Subsoil data from Auger Drilling samples taken in vicinity of Drybridge Public Supply

Location	Easting	Northing	DTB (m)	BS5930 Result	Subsoil Permeability	Subsoil Unit
DRY01	306624	276375	>9.5	SILT/CLAY with rounded gravels	Low	IrSTLPSsS
DRY02	306507	277331	>11.5	CLAY & SILT/CLAY with fine sands & SILT	Low	TLPSsS
DRY03	306294	276027	6	CLAY with occasional gravels	Low	IrSTLPSsS
DRY05	305951	276132	10	gravelly CLAY	Low	TLPSsS
DRY06	305986	275960	3.5	GRAVEL	High	GLPSsS
DRY07	305517	276310	>12	CLAY	Low	TLPSsS

7.4 DEPTH TO BEDROCK

Depth to bedrock (DTB) has been interpreted across the study area based on bedrock outcrops mapped by the GSI, outcrops mapped during site visits, areas mapped as extreme groundwater vulnerability under the GSI Groundwater Protection Scheme (GWPS), DTB data from the GSI Well Database, and logged evidence from drilling of GSI auger holes in the vicinity of the source.

The borehole log for PWSBH01 indicates a depth to bedrock of 7.8 m. The incised Drybridge Stream valley between the outcrop at Waterunder Bridge and the source has a depth to bedrock of 3 to 5 m. Other areas, away from the river channels are considered to have thicker till deposits, generally greater than 10 m. The glaciofluvial sand and gravel deposits are generally 5 to 10 m thick, but may extend to depths of up to 40 m or more beneath the Boyne River (Robert Meehan, pers comm., 2010). Data from GSI auger holes are shown in Table 7-2, above. Data from other sources is shown in Tables A1.1a to A 1.1d in Appendix 1. Depth to bedrock data points are shown on Figure 4.

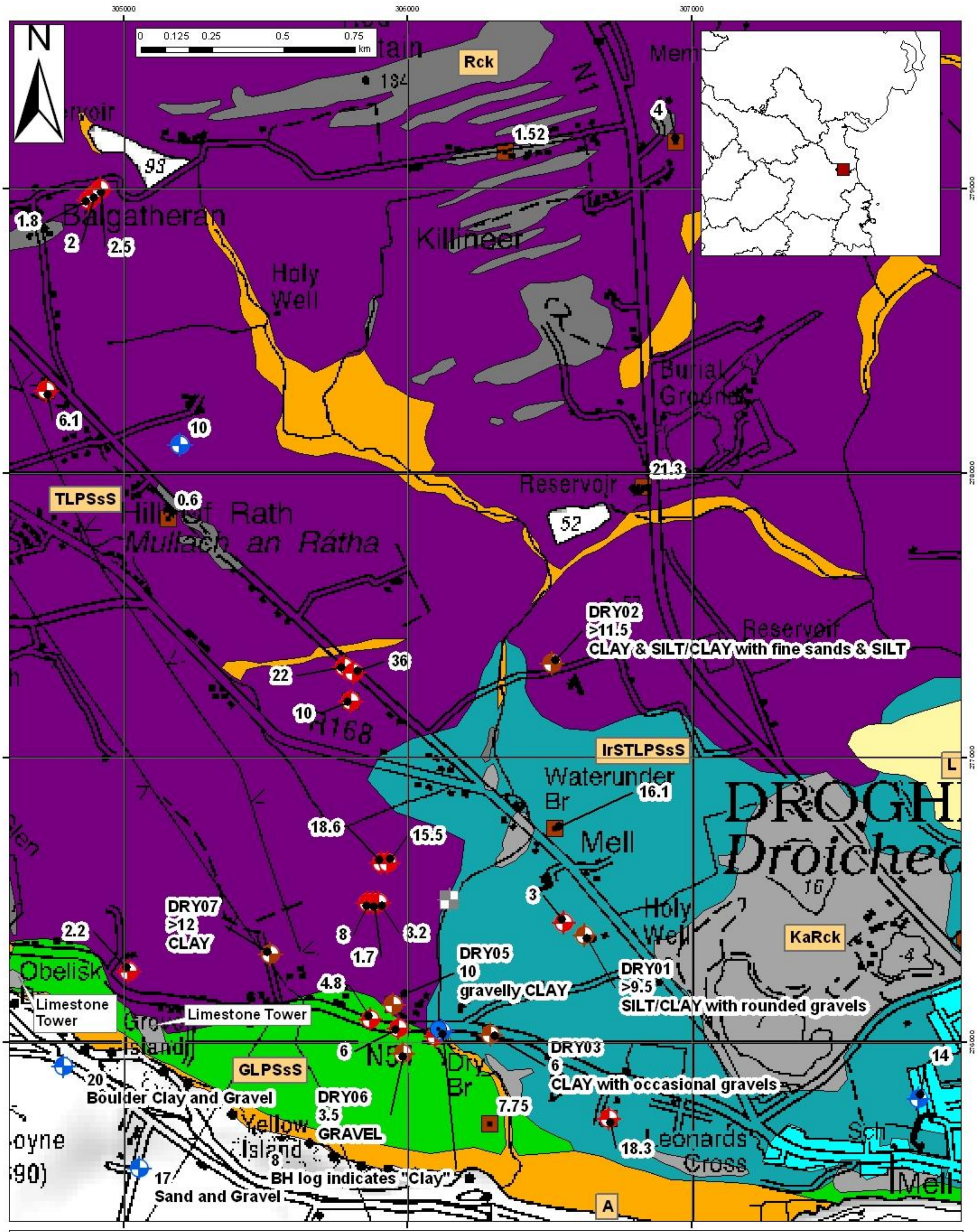

Figure 4 Subsoil Geology of Study Area

- PWS Abstraction
- Stream
- Till - Lower Paleozoic Sandstones & Shales (TLPSsS)
- Irish Sea Till - Lower Paleozoic Sandstones & Shales (IrSTLPSsS)
- Glaciofluvial Sands and Gravels (GLPSsS)
- Alluvium (A)
- Bedrock Outcrop (Rck)
- Karst Bedrock Outcrop (KaRck)
- Made Ground (Made)
- Lacustrine Sediments (L)
- DRY07 >12 CLAY: Location Name, Depth to Bedrock (m), Subsoil K Assessment
- GSI Auger Hole
- Other GSI DTB Point Data
- Private Borehole
- GSi Well Database Borehole

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8 GROUNDWATER VULNERABILITY

Groundwater vulnerability is determined by the nature and thickness of the material overlying the uppermost groundwater 'target'. In this area this means that vulnerability relates to the permeability and thickness of the subsoil. 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).

The vulnerability map shows areas of extreme vulnerability on Red Mountain, on the Hill of Rath and at Mell Quarry. Extreme vulnerability is also mapped at rock outcrops along the Drybridge Stream and where underground 'towers' of limestone bedrock occur and form outcrop. The Drybridge Stream upgradient of the sinking reach is also mapped as extreme vulnerability in a buffer 30 m wide on either side of the losing reaches of the stream, and 10 m wide upstream of losing reaches.

Away from the areas of outcrop, where subsoil thickness is less than 5 m, vulnerability is high. High vulnerability also occurs in the glaciofluvial sand and gravel areas due to the high permeability of these deposits. As the till subsoil thickens to 5 to 10 m moving away from the river valleys, the vulnerability rating changes to moderate, as it is around the source borehole. Across the remainder of the study area, the till thickness exceeds 10 m and the vulnerability is therefore low. The groundwater vulnerability map is shown in Figure 5.

9 HYDROGEOLOGY

This section describes the current understanding of the hydrogeology in the vicinity of the source. Hydrogeological and hydrochemical information was obtained from the following sources:

- ⇨ GSI and EPA Websites and Databases (April/May 2010)
- ⇨ Louth County Council Staff and Local Authority Drinking Water returns
- ⇨ Groundwater Resources in the Northeast Regional Development Organisation (NERDO, 1981)
- ⇨ Mid-Louth Regional Water Supply Strategy (Atkins, 2002)
- ⇨ Designation of Nitrate Vulnerable Zones for Louth County Council (WYG, 2004)
- ⇨ Hydrogeological mapping by Caoimhe Hickey (May 2007 & 2008) and by Peter Conroy and Robert Meehan (April 2010)
- ⇨ Karst dye tracing by Caoimhe Hickey (June 2013)
- ⇨ Drilling and permeability mapping carried out by GSI in May 2007
- ⇨ 16 year well hydrograph for Dry Bridge 1/01/79 to 2/01/96 (GSI and Louth Co. Co.)
- ⇨ Met Eireann rainfall and evapotranspiration data

9.1 GROUNDWATER BODY AND STATUS

Borehole PWSBH01 is located in the Drogheda groundwater body (GWB) (IE_EA_G_025), which has been classified as being of Good Status. The Silurian Metasediments and Volcanics to the north of the source form part of the Wilkinstown GWB (IE_EA_G_010), which also has Good Status. The groundwater body descriptions are available from the GSI website: www.gsi.ie and the 'status' is obtained from the Water Framework Directive website: www.wfdireland.ie/maps.html.

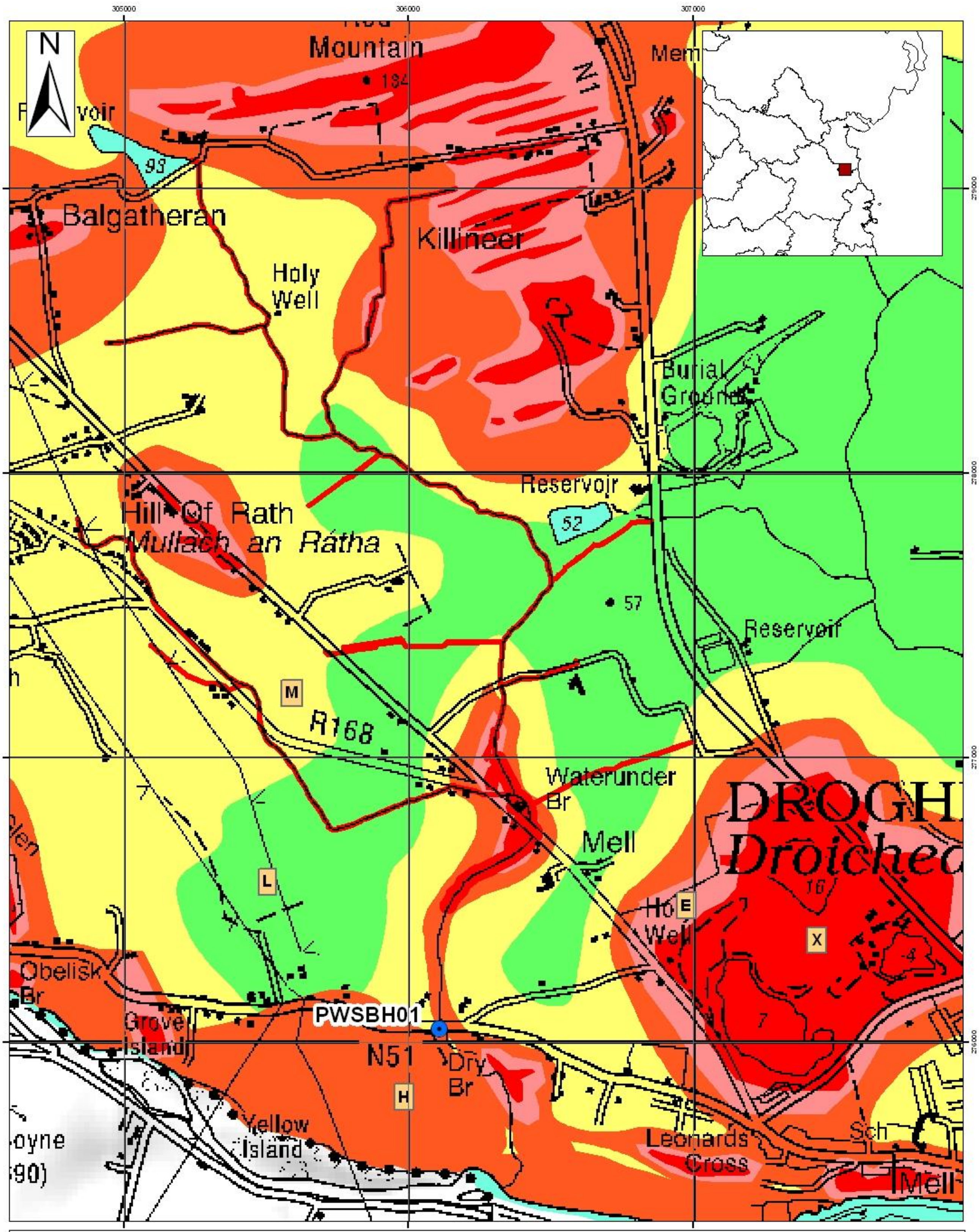

Figure 5 Groundwater Vulnerability of the Study Area

PWS Abstraction
Stream
Extreme (Rock Close to Surface) (X)
Extreme (E)
High (H)
Moderate (M)
Low (L)

0 0.125 0.25 0.5 0.75 km

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9.2 GROUNDWATER LEVELS, FLOW DIRECTIONS AND GRADIENTS

Full details of the water level data collected and collated for the report are provided in Table A1.1 and Figure A1.1 in Appendix 1.

A water level recorder was installed in borehole PWSBH01 between 25/10/1979 and 20/09/1995. The full well hydrograph is shown in Figure A1.2 in Appendix 1. The hydrograph represents rest groundwater level at the borehole. The water level in the borehole ranges from <5 mAOD to >12 mAOD (<4 m to >11 mbgl) with lowest water levels occurring in dry summer months. There is also a general rising trend in maximum water levels in the hydrograph. Figure 6 shows the hydrograph for the final three years of monitoring. From this it can be seen that that the water level is very responsive to rainfall, as often individual rainfall events can cause the water level to rise up 3 m or more within one to two days. For example, the water level on the 5/10/93 is at 8.2 mAOD and on the 7/10/93 it has risen to 11.16 mAOD. This is typical of point recharge in karst, such as at the swallow hole in the base of the river, and the losing stream to the north of the borehole.

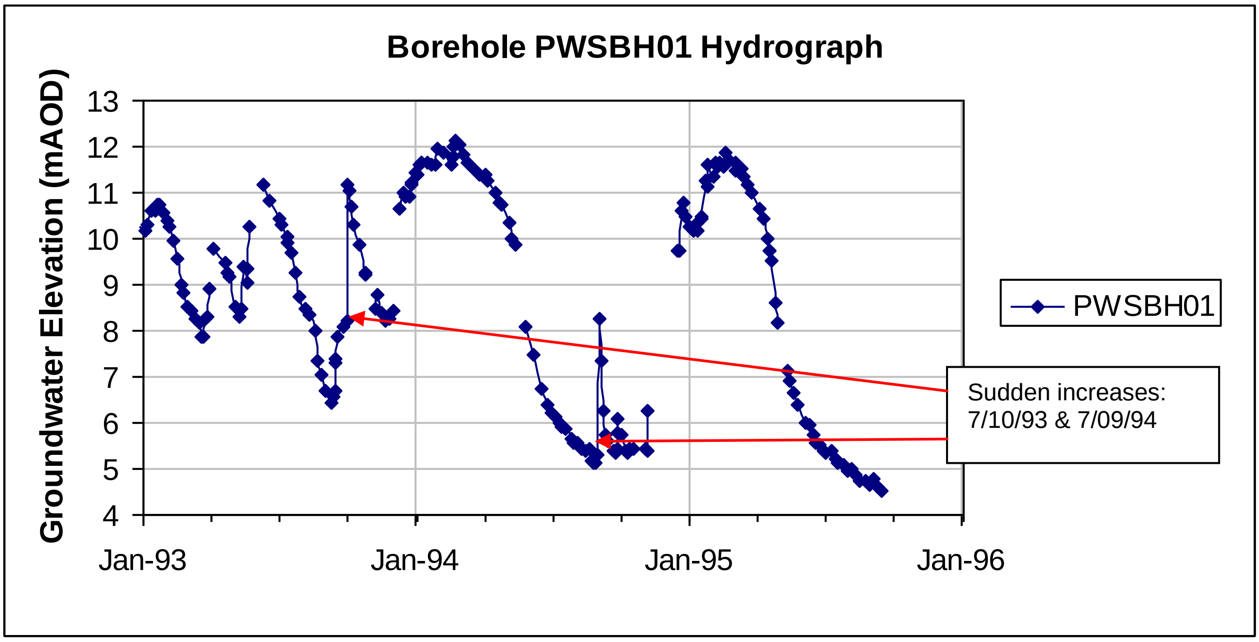

Figure 6 Borehole PWSBH01 Hydrograph

The water level in the borehole drops rapidly in response to pumping. A 72 hour pumping test in February 1980 at 924.5 m^3/day generated just over 12 m of drawdown, 89% of which occurred in the first 120 minutes of pumping, suggesting low storage in the karst in the vicinity of the borehole.

The NERDO (1981) report records that water levels in the borehole are influenced by tides, and that a twice daily rise and fall in water levels occurs which corresponds to the tidal movements in the Boyne estuary. This is considered to be the result of tidal oscillation of the water table south of the borehole, where groundwater discharges to the River Boyne. It does not indicate that the borehole interacts directly with the saline estuary. The hydrograph data comprise daily average data which mask the tidal signature. Downgradient of PWSBH01, the Boyne is at the upper extremity of the saline estuary. As such, there may be a natural salt wedge at depth below fresh groundwater in the aquifers adjacent to the river.

The ground/river level at the edge of the Boyne River is estimated at 1.0 mAOD based on the EPA 20 m grid spacing Digital Terrain Model for Co. Louth. The maximum proven karst aquifer thickness in the area is 72 m (approximately -66 mAOD at PWSBH01; Section 8.5). Based on the Ghyben-Herzberg Relationship, for the toe of the salt wedge to reach the base of the aquifer, the PWSBH01 pumping water level would need to drop to 2.7 mAOD. The measured pumping water level (PWL) for the current abstraction rate (4.7 mAOD; 394 m^3/day) is well above this threshold. Figure 9 shows the estimated approximate position of a saltwater-freshwater interface at current pumping rates. Saline intrusion into the borehole is unlikely even at higher pumping rates, as the bottom of the pumping well is about 30 m higher up than the base of the aquifer, and groundwater storage in the sand and gravel deposits act as a buffer against saline intrusion. Any planned increase in pumping rates should verify the risk, however.

An interpretative water level contour map from the NERDO (1981) report is shown in Appendix 1. The 20 m and 10 mAOD contours run approximately east-southeast to west-northwest in the vicinity of the PWSBH01. This suggests that groundwater flow is generally south towards the Boyne River. Borehole PWSBH01 is located on a fault running NNW to SSE. Drilling evidence from borehole PWSBH01 indicates that the fault zone is karstified. The fault zone is likely to act as a zone of preferential flow through the limestone, pulling in groundwater flow from the east and west and draining it southwards to the gravel deposits adjacent to Boyne River.

Water level data and water balance calculations suggest that the rising trend in the hydrograph for borehole PWSBH01 is related to the recovery of water levels in Mell Quarry following closure of the quarry in 1979 and cessation of dewatering. The quarry forms a large reservoir of water and acts as a relatively fixed head, with a controlling influence on the water table in the surrounding limestone. As the open water quarry will receive close to 100% of potential recharge it should act as a slight groundwater mound discharging radially to the surrounding aquifer. The groundwater flow between the quarry and the borehole is, however, considered to be negligible (see Section 8.5).

Based on the mapped water level contours (NERDO, 1981), the regional groundwater gradient in the vicinity of the source is approximately 0.01. Based on the hydrograph minimum (summer) and maximum (winter) rest water levels in borehole PWSBH01 of 4.53 and 12.11 mAOD respectively, and the estimated elevation of 1 mAOD for the Boyne River 500 m to the south, the hydraulic gradient between the borehole and the river ranges from approximately 0.007 to 0.022. The gradient in the active fissures intersected by the well may differ greatly from this depending on weather, flow in the Drybridge Stream, and tidal conditions.

In the Silurian bedrock to the north of the source, groundwater flow paths are likely to be short and groundwater typically will discharge to nearby surface water features (GSI, 2004b). The 25-inch historical map of the area to the north of the source indicates the presence of a spring at GW03, 250 m north of the fault, which shows groundwater discharging to surface water in that area rather than flowing south across the Slane fault into the limestone areas. There may be limited flow across the fault from the Silurian bedrock immediately adjacent to the fault.

Groundwater-surface water interaction in the karst limestone is high, with Drybridge stream sinking, re-emerging, then partially sinking again to the north of the borehole.

9.3 HYDROCHEMISTRY AND WATER QUALITY

Twenty-two groundwater samples were collected and analysed from borehole PWSBH01 between 1st June 1993 and 17th December 2009. The majority of the samples were collected and analysed by the EPA as part of their national groundwater monitoring programme. Five of the samples were collected and analysed for a limited suite of parameters by the EPA during 2009 on behalf of Louth County Council. The resulting data are presented in Table A1.2 in Appendix 1. Field water quality data (pH, conductivity and temperature) were collected from borehole PWSBH01 during the site visit of 30/04/2010. The field data are presented in Table A1.3 in Appendix 1.

The samples of groundwater are collected from the sampling tap in the middle underground chamber at the source compound (see Section 2). The tap supplies partially treated backflow from the clearwater tank when the borehole pump is switched off, and untreated borehole water when the pump is on. No record has been kept regarding pumping times and sampling events. As such some of the samples collected to date are likely to have comprised partially treated water.

Overall the source has a high level of mineralization as indicated by the average electrical conductivity (627 µS/cm), alkalinity (236 mg/l as $CaCO_3$) and hardness (258 mg/l as $CaCO_3$). The hydrochemistry is dominated by the calcium and bicarbonate, which is to be expected in a karstified limestone groundwater flow system. The pH of the groundwater is slightly alkaline with a field measured average of 7.2. Based on the electrical conductivity and chloride data, there is no evidence of saline intrusion impacts on the source water quality.

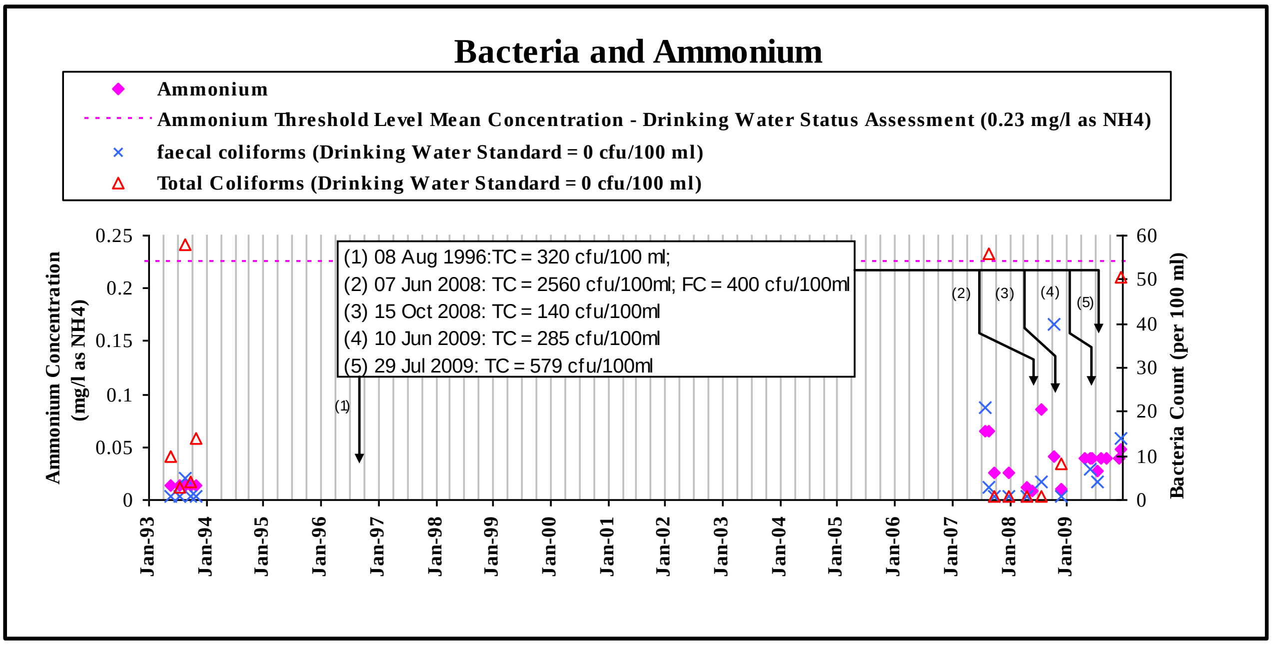

Figure 7a Graph of Bacteria and Ammonia Concentrations at Borehole PWSBH01

Figure 7a shows the concentrations of faecal and total coliforms and ammonia at the source. Faecal coliforms concentrations were above the drinking water limit of zero counts per 100 ml on all sampling occasions where coliform analysis took place. Typically the numbers encountered are less than 7 cfu/100 ml; however gross pollution incidences with counts up to 400 cfu/100 ml (07/06/2008) have occurred occasionally. Total coliforms exceeded the same compliance limit on all occasions. The highest occurrence of 2,560 cfu/100 ml was coincident with the maximum faecal coliform occurrence. Given the consistency of occurrences, it is possible that samples with low coliform counts may indicate samples affected by chlorination treatment. No exceedences of the ammonium drinking water standard or threshold level have occurred.

Figure 7b shows the measured concentrations of nitrate and chloride. The average nitrate concentration over the monitoring period was 19.1 mg/l as NO_3, which is below the EPA threshold of 37.5 mg/l as NO_3. There is a slight decreasing trend in nitrate over time. Average chloride concentrations measured 31.9 mg/l which exceeds the EPA threshold of 24 mg/l. All chloride measurements since 2007, except 07/06/2008 have exceeded the chloride threshold and the data show a general rising trend in chloride since the record began in 1993. The average chloride concentration in the second half of 1993 was 22 mg/l, rising to 28 mg/l, 31 mg/l and 40.2 mg/l in 2007, 2008 and 2009 respectively. This does not correlate with the decreasing trend in nitrate.

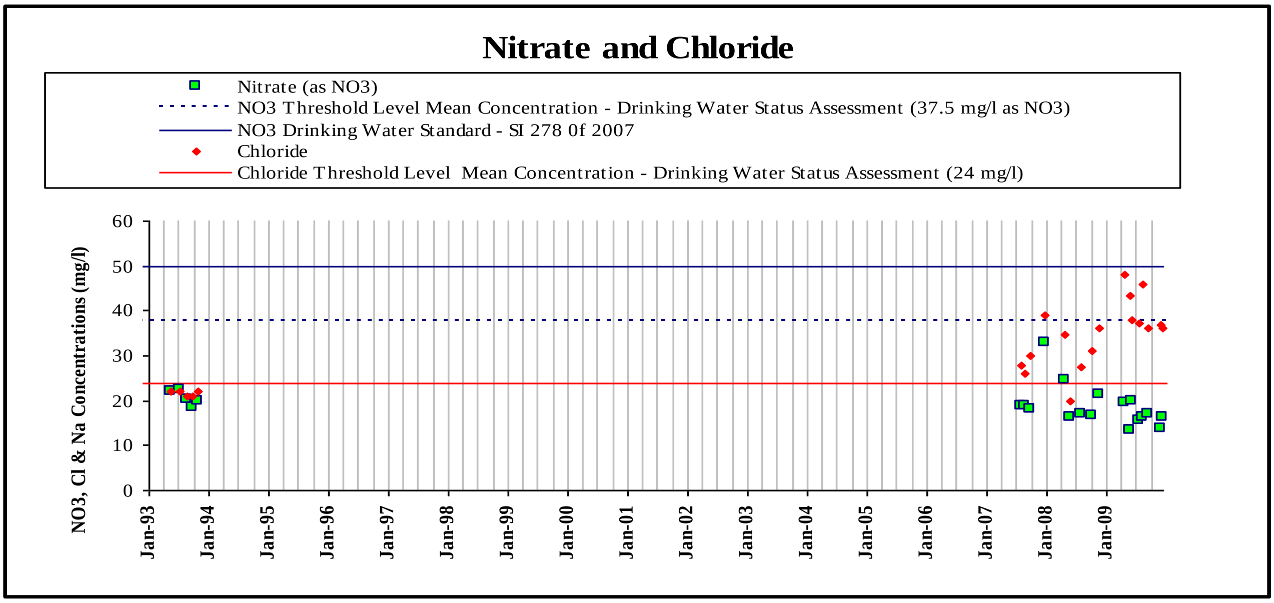

Figure 7b Graph of Nitrate and Chloride Concentrations at Borehole PWSBH01

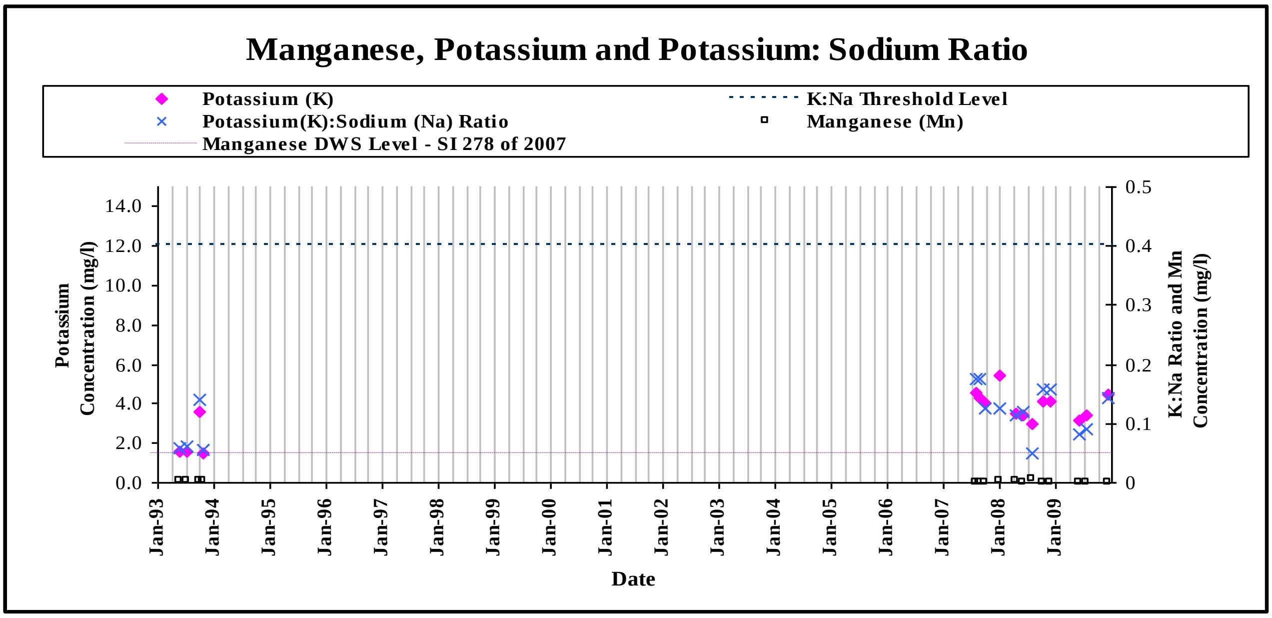

Figure 7c Graph of Manganese, Potassium and Potassium:Sodium Ratio at Borehole PWSBH01

The correlation between chloride and sodium is poor, such that natural inputs of chloride from rainfall and sea-spray alone do not account for the rising trend in the chloride data. This suggests that additional chloride inputs are occurring from contaminant sources in the catchment, possibly potassium chloride fertiliser. The magnitude of chloride and bacteria exceedences has only a moderate correlation. This may be due to multiple chloride sources (e.g. sea spray and agriculture) and the masking of bacteria in the partially treated groundwater samples.

Figure 7c shows the EPA measured concentrations of manganese and potassium and the Potassium:Sodium ratio at the source. None of these parameters exceeded their thresholds.

Figure 7d shows the EPA measured concentrations of orthophosphate at the source. The average orthophosphate concentration for the monitoring period was 0.037 mg/l as PO_4, which exceeds the EPA threshold of 0.035 mg/l as PO_4. Exceedences of the phosphate threshold do not correlate with peak coliform exceedences and show a weak correlation with peak chloride exceedences.

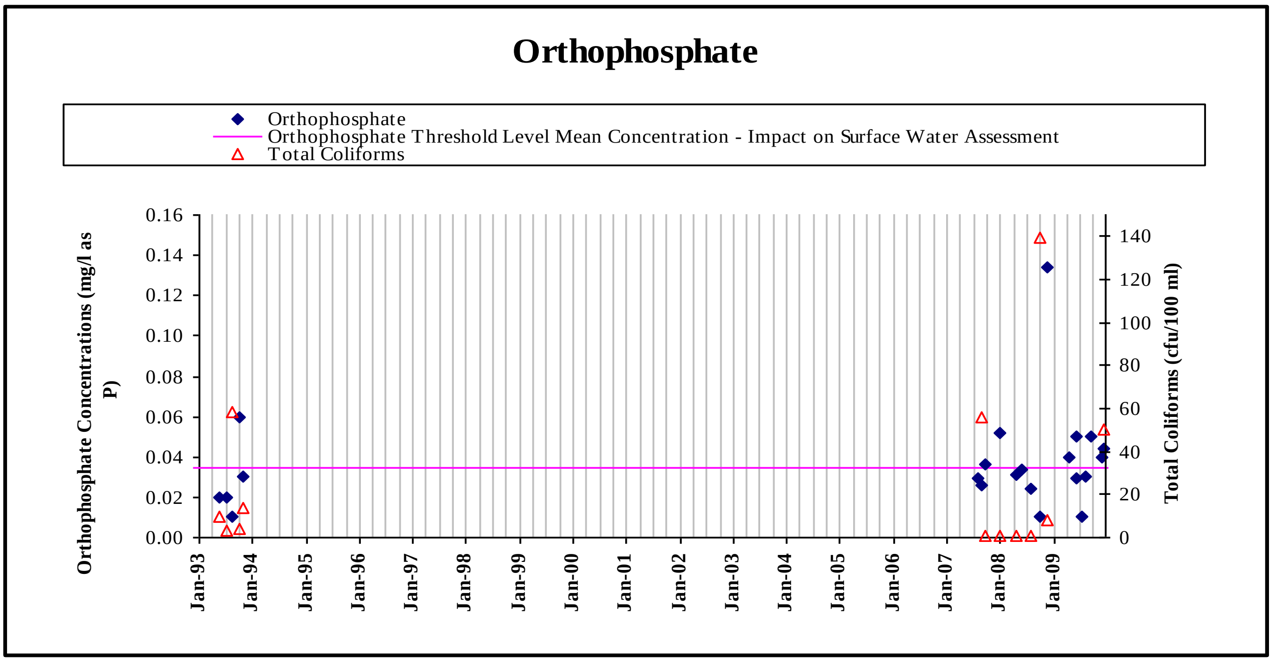

Figure 7d Graph of Orthophosphate at Borehole PWSBH01

The remaining parameters measured do not exceed their respective drinking water standards and have average concentrations less than their respective EPA thresholds.

In summary, elevated chloride, phosphate and bacteria suggest contamination from an organic waste source, although the elevated chloride concentrations are partially due to the natural coastal influence on the source.

9.4 AQUIFER CHARACTERISTICS

The GSI bedrock aquifer map of the area indicates that the Dinantian Pure Bedded Limestones are classified as a *Regionally Important Aquifer – Karstified (diffuse) (Rk_d).* The Silurian Metasediments and Volcanics rock unit is classified as a *Poor Aquifer* which is *generally unproductive except for local zones (Pl).* The bedrock aquifer map of the area is shown in Figure 8.

Groundwater flow in the Rk_d aquifer is diffuse via fractures, however karstified and dolomitised conduits also occur. The conduits and fissures are typically expected to be orientated north-northwest to south-southeast, in line with the jointing and fault zones in the bedrock which facilitate the karst development. Aquifer transmissivity is expected to be highest in this direction.

The large pumping water level drawdown and natural fluctuations in groundwater level at borehole PWSBH01 suggest that the transmissivity between the borehole and quarry is low. Otherwise the quarry-water storage buffer would supply large borehole yields at PWSBH01 for minimal drawdown and dampen natural water level fluctuation at the borehole. This suggests that east-west transmissivity within the karst system is low.

The Drybridge Stream sinks into and resurges from the karstified cavities and fissures upstream of borehole PWSBH01, in the vicinity of Water Underbridge. The exact locations of the sinking and resurgence varied slightly between site visits in 2008, 2010 and 2013 showing that the karst system is dynamic and that different karst pathways are followed depending on the magnitude of flow through the system. It is probable that surface water and groundwater mix along the underground reach of the stream. As such, although the stream resurges upgradient of borehole PWSBH01, it is likely that a component of surface water reaches the borehole (as suggested by the rapid hydrograph spikes; Section 8.3)

Shallow karst conduits encountered in boreholes PWSBH01 and an adjacent abandoned trial well (OW1) were infilled with unconsolidated material. Pumping from deeper fissures in PWSBH01 yielded turbid water, which indicated further sediment infill at depth. The unconsolidated material decreases the transmissivity of the karst pathways, particularly in the shallow bedrock.

Two 72 hour pumping tests were carried out on borehole PWSBH01 in August 1979 and February 1980 (NERDO, 1981). The test data are analysed and discussed in Appendix 2. A further 14 day pumping test was carried out on the rehabilitated borehole at some point in 2001/2002 (Atkins, 2002). The results of the analyses suggest that that the karst aquifer transmissivity is between 44 and 160 m^2/day. Interpretation of the pumping test data suggests that the borehole is likely to draw water from point recharge when these features are active; from the saturated gravel deposits down gradient of the borehole; and from the diffuse karst fissure network.

The thickness of the bedrock aquifer intersected by borehole PWSBH01 is 36 m, however karst features down to 72 m below ground level has been proven in a trial hole at Mell townland (NERDO, 1981). The secondary porosity of the aquifer in the vicinity of Drybridge and Mell Quarry is estimated at between 5 and 10% (NERDO, 1981). Infilling of karst fissures by unconsolidated material will lead to lower values for the effective porosity. An average porosity of 1% was assumed for the regional scale Rk_d aquifer (equivalent to the Drogheda GWB) in the NERDO (1981) report.

The Groundwater Body report for the Wilkinstown GWB suggests aquifer transmissivity in the Silurian Metasediments is likely to be low, perhaps less than 6 m^2/d (GSI, 2004b). Data from Killineer PWS borehole suggests the transmissivity to be approximately 5.4 m^2/d (Conroy *et al*, 2010). Most of the groundwater flow in the Pl aquifer is estimated to be in the top 10 m of the bedrock (GSI, 2004b).

Based on the estimated Rk_d bedrock aquifer transmissivity and the aquifer hydraulic gradients, the average groundwater flow velocity can be estimated using the equation:

$$v = \frac{T \cdot i}{b \cdot n_e}$$

where: v = average groundwater velocity (m/day); T = aquifer transmissivity (m^2/day); n_e = effective porosity (dimensionless); i = hydraulic gradient; and, b = aquifer thickness.

The estimated groundwater velocity range in the bedrock aquifer, based on the available data is shown in Table 8-2. The groundwater velocity values represent an average for the aquifer away from the conduits. Velocities in individual fissures or conduits will greatly exceed the calculated values, as shown by the dye trace results, which are also summarised in the Table.

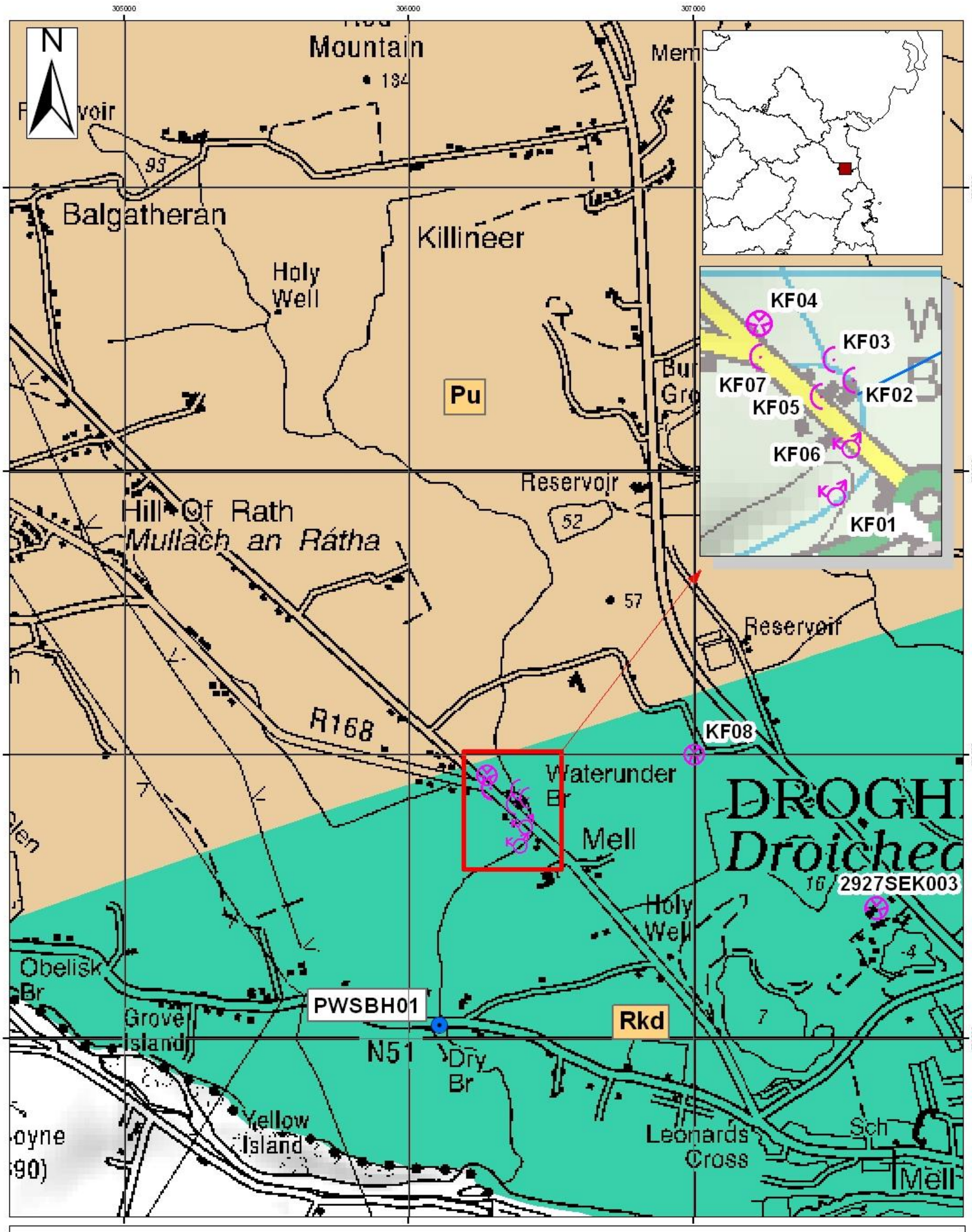

Figure 8 Bedrock Aquifer Map of Study Area

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Table 8-2 Estimated Groundwater Velocity Range for the bedrock aquifer at Drybridge Source

Parameter	Units	Minimum	Maximum	Average	Data Source
T	m^2/d	44.1	160	99	Appendix 2, NERDO (1981)
i	[-]	0.007	0.022	0.015	Section 8.3, NERDO (1981)
b	m	36	72	54	NERDO (1981)
n_e	[-]	0.01	0.1	0.055	NERDO (1981)
v (average)	m/d	0.04	9.78	0.50	
v (conduit) *	m/d	125	540	270	Dye trace (2013)

* fastest time of dye arrival estimated as 1.5 days, and last detection estimated as 6.5 days. Straight line travel distance approximately 810 m. Peak dye recovery 3 days used for 'average' velocity value.

9.5 CONCEPTUAL MODEL

A schematic cross section illustrating the conceptual model is shown in Figure 9.

Borehole PWSBH01 abstracts groundwater from a karstified limestone aquifer dominated by diffuse groundwater flow (Rk_d) but with conduits in the vicinity of the borehole.

Subsoils in the area are generally low permeability tills, with sands and gravels occurring to the south of the borehole, and exposed rock areas in the north of the catchment. In the vicinity of PWSBH01 the aquifer is recharged by diffuse infiltration. Additional recharge of the karst aquifer is also provided by point recharge from the sinking reach of the Drybridge Stream upgradient of the borehole (as suggested by hydrograph and pumping test data and proven by the dye trace), and minor inflow to the aquifer from the Silurian PI aquifer adjacent to the northern side of the Slane Fault.

Groundwater flow in the karstified limestone is generally south towards the River Boyne via distributed fractures; however where large conduits occur (such as at PWSBH01) flow is likely to be focused in these preferential pathways. The network of fractures and large conduits accommodating preferential flows is likely to develop along existing bedrock joints and fault zones and so will inherit the same north-northwest to south-southeast orientation. This orientation forces the majority of groundwater flow to conform to the generally southern direction.

On the local scale minor east and west oriented fractures and conduits will allow flow to focus into the main preferential pathways; however transmissivity is considered to be low in the east-west direction on a regional scale. As such, groundwater flow from Mell Quarry to PWSBH01 is likely to be negligible. Groundwater flow from the fractured shale and sandstone to the north into the karst limestone aquifer will be limited. Stream runoff from this aquifer does, however, sink in the karst aquifer to the south.

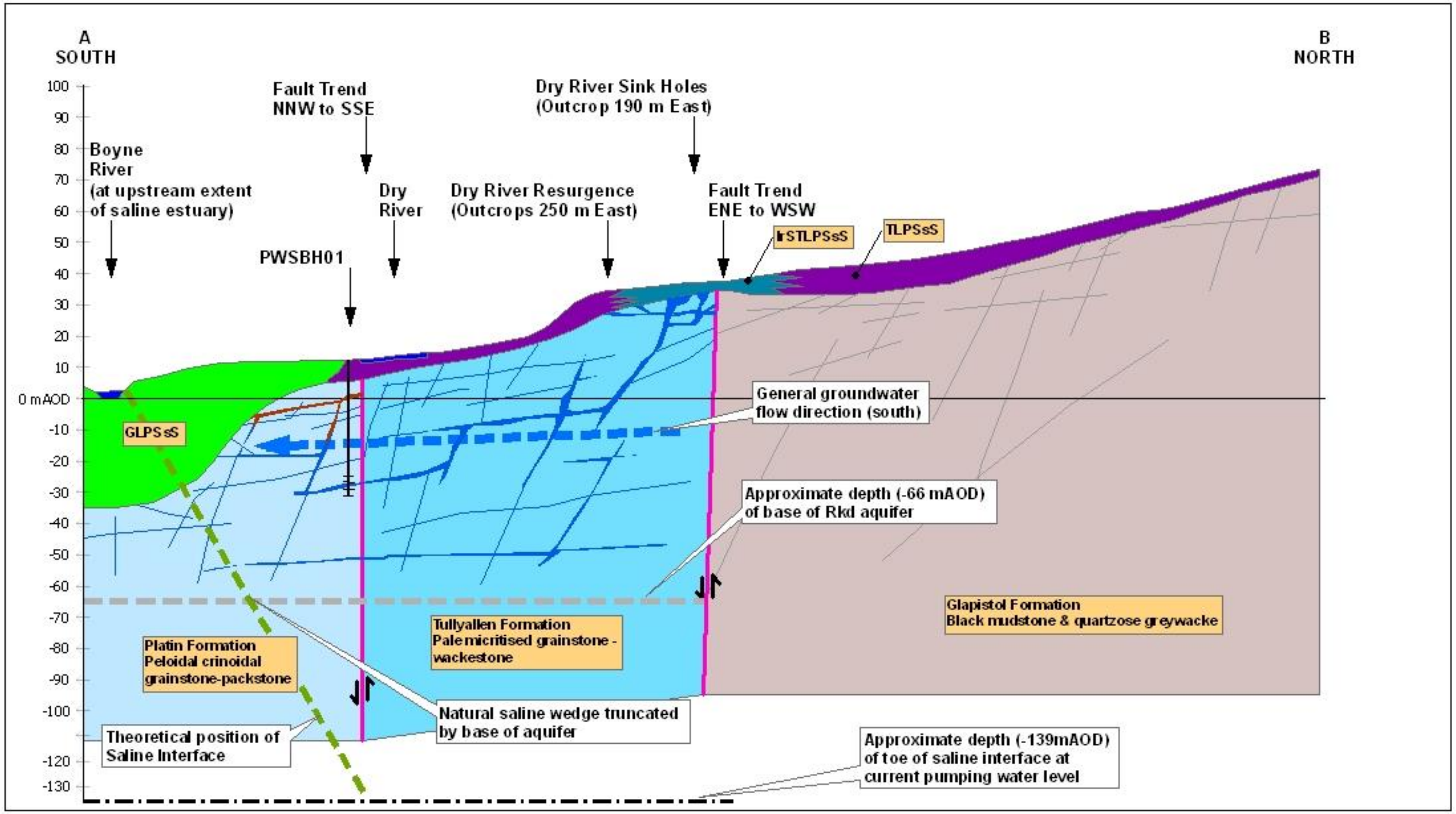
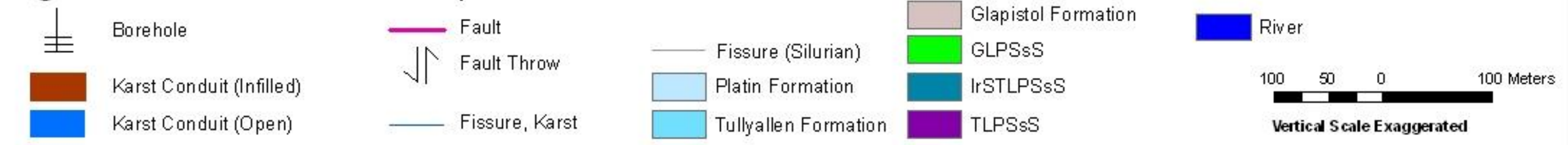


Figure 9 Schematic Conceptual Model



Abstraction from PWSBH01 creates drawdown and induces groundwater inflow. The bulk of the inflow will come from the north via preferential flow along the conduit intersected by the borehole, as well as groundwater flowing along fractures. If the borehole demand exceeds the conduit supply capacity, additional drawdown will be induced in order to attract more inflow from the lower transmissivity east and west directions. As drawdown increases, the borehole will draw increasing volumes of groundwater from the downgradient, southern side. This will give access to groundwater in the sand and gravel deposits, with water flowing north to the borehole along the intersected conduit. Water level variations in the sand and gravel terrace are buffered. This will control the position of the saline wedge such that the risk of saline intrusion at PWSBH01 is considered to be low. Drawdown in the aquifer induced by the abstraction will increase the probability of leakage to the aquifer from the sunken reach of the Drybridge River.

The natural discharge zone for the limestone aquifer is the sand and gravel terrace adjacent to the Boyne River, which in turn discharges to the river. The Boyne reach downgradient of PWSBH01 is at the upper extremity of the saline estuary, such that there may be a natural salt wedge at depth in the aquifers adjacent to the river. The untreated water quality data for PWSBH01 show evidence of contamination of the groundwater by organic matter sources.

10 ZONE OF CONTRIBUTION

This section describes the delineation of the areas around the source that are believed to contribute groundwater to it (based on the conceptual model), and that therefore require protection.

Two source areas are generally delineated:

- Inner Protection Area (SI), designed to give protection from microbial pollution.
- Outer Protection Area (SO), encompassing the zone of contribution to the source.

The delineated source protection areas are shown in Figure 10.

10.1 BOUNDARIES OF THE ZOC

Outer protection area

The Outer Protection Area (SO) is bounded by the catchment area to the source, i.e. **the zone of contribution (ZOC)**, which is defined as the area required to support an abstraction from long-term recharge. The size and shape of the ZOC is controlled primarily by (a) the discharge, (b) the groundwater flow direction and gradient, (c) the subsoil and rock permeability and (d) the recharge in the area.

The shape and boundaries of the ZOC were determined using hydrogeological mapping, water balance estimations, and the conceptual understanding of groundwater flow. The boundaries are described below along with associated uncertainties and limitations.

The water balance calculates the areal footprint required to supply a recharge volume equal to the public water supply abstraction. The average annual abstraction for the source is 275 m^3/day; the observed, actual pumping rate at the source was 394 m^3/day on 30/04/2010; and pumping tests from the commissioning period in 2001-2003 indicate that the source is capable of supplying up to at least 530 m^3/day. In order to provide a safety factor in the ZOC delineation and because the source is capable of increased abstraction rates, the water balance has been carried out for an abstraction rate of 412 m^3/day, i.e. 150% of the average annual abstraction.

Based on an annual average recharge of 93 mm (see Section 102, below), this abstraction would require a recharge footprint of 1.62 km^2. This is for diffuse recharge that has percolated through the subsoils, and does not take into account the (unknown) volume of streamwater that sinks into the aquifer. The ZOC based on the water balance and constrained by the source conceptual model has been delineated as follows.

The northwestern boundary is the upgradient boundary of the ZOC and is parallel to the Slane Fault. Groundwater flow across the fault into the Rk_d aquifer is expected to be minimal and derived from the Pl aquifer immediately adjacent to the fault. As such, the fault-boundary of the Rk_d aquifer is the practical limit of the ZOC. A 100 m buffer zone has been applied on the north side of the fault to account for any potential through-flow from the Pl aquifer adjacent to the fault, and for direct runoff from the Pl aquifer onto the Rk_d aquifer. Because the sinking reach of the Drybridge Stream is likely to recharge the limestone aquifer, the stream channels plus a buffer zone of 10 m either side are also added to the zone of contribution.

The southwestern and northeastern boundaries are taken as flow lines from the extremities of the up-gradient boundary. The positions of the boundaries to the east and west of borehole PWSBH01 are set at the maximum likely lateral limits of the source conceptual model in order to accommodate the water balance requirements. This also constrains the length of the upgradient boundary. As such, the northeastern boundary approximately bisects the area between the fault adjacent to PWSBH01and Mell Quarry, based on minimal flow between the source and the quarry. The southwestern boundary is delineated approximately along a topographic divide between the fault and the Boyne River / King William's Glen, with recharge to the west of the boundary expected to discharge to the Boyne and to the glen. The northwest to southeast fault adjacent to PWSBH01 forms a rough axis around which the ZOC is aligned; however the ZOC is skewed to the upgradient, northeastern side of the fault because the regional hydraulic gradient is roughly north to south.

The southern boundary is the downgradient boundary of the ZOC and is extended up to 250 m south of PWSBH01 in order to capture a sufficient area of the saturated gravel terrace to fulfil the water balance requirements.

These boundaries delineate a ZOC area of 1.58 km^2 and capture a diffuse recharge footprint of 415 m^3/day based on an annual recharge for the area of 96 mm. Of the total ZOC area delineated, 0.17 km^2 are underlain by saturated gravel deposits which account for 111 m^3/day of the total recharge volume captured.

This is considered to be a conservative approach to the delineation of the ZOC for the source. The delineated area represents the likely maximum, steady state extent of the source ZOC for an abstraction of 412 m^3/day. There are several reasons to suggest the actual abstraction would be unlikely to reach this maximum extent:

- The ZOC delineation does not take account of the additional recharge from stream sinks.
- The gravel deposits can release stored groundwater if abstraction temporarily exceeds flow from the limestone bedrock aquifer.

Inner protection area

The Inner Source Protection Area is the area defined by the horizontal 100 day time of travel from any point below the watertable to the source (DoELG, EPA, GSI, 1999). It also includes any surface water courses contributing to the source via point recharge. The 100-day horizontal time of travel to the source is calculated from the velocity of groundwater flow in the bedrock. The velocities are normally calculated based on the average aquifer hydraulic properties of the ZOC. In this instance however, the very rapid groundwater velocities in individual karst conduits through the aquifer render such calculations almost irrelevant with respect to protection of the source from pollution by micro-organisms. Results from tracing programmes in similar rock types indicate velocities of many metres / day. In this catchment, as the surface water courses potentially directly recharge the aquifer *via* a sinking stream, it is also necessary to incorporate the time of the travel of the surface water on the Pl rocks. On this basis, it is considered appropriate to designate all of the ZOC as part of the inner protection area to the source (SI).

The Inner and Outer Source Protection Areas (SI and SO) at the Drybridge Source are the same.

10.2 RECHARGE & WATER BALANCE

The term 'recharge' refers to the amount of water replenishing the groundwater flow system. The recharge rate is generally estimated on an annual basis, and assumed to consist of input (*i.e*. annual rainfall) less water loss prior to entry into the groundwater system (*i.e*. annual evapotranspiration and runoff). The estimation of a realistic recharge rate is important in source protection delineation, as it will dictate the size of the ZOC to the source (and therefore the Outer Source Protection Area). The recharge is estimated as follows.

Potential recharge is equivalent to 268 mm/yr i.e. (Annual Effective Rainfall, see Section 8.1).

Actual recharge has been estimated to be 96 mm/yr, which is 36% of potential recharge; this value is based on averaging of the recharge for the different settings outlined in in Appendix 2.

Runoff losses: 172 mm (64% of potential recharge).

These calculations are summarised in Table 8-3.

Table 8-3 Recharge Calculation Summary

Parameter	**Coefficient**	**Rate**
Average rainfall (R)		800 mm/yr
Estimated P.E.		560 mm/yr
Estimated A.E. (95% of P.E.)		532 mm/yr
effective rainfall		268 mm/yr
Potential recharge		268 mm/yr
Averaged runoff losses	(64%)	172mm/yr
Bulk recharge coefficient	0.36	
Recharge		96 mm/yr

Diffuse recharge to the Pl aquifer has not been taken into account. As discussed in Section 8.3 recharge to this aquifer is likely to discharge to surface water rather than flow from the Pl aquifer to the Rk_d aquifer. The surface runoff from the Pl aquifer onto the Rkd aquifer will augment the recharge via the sinking reach of the Drybridge Stream upstream of the source. This additional component of Rk_d aquifer recharge has not been assessed quantitatively.

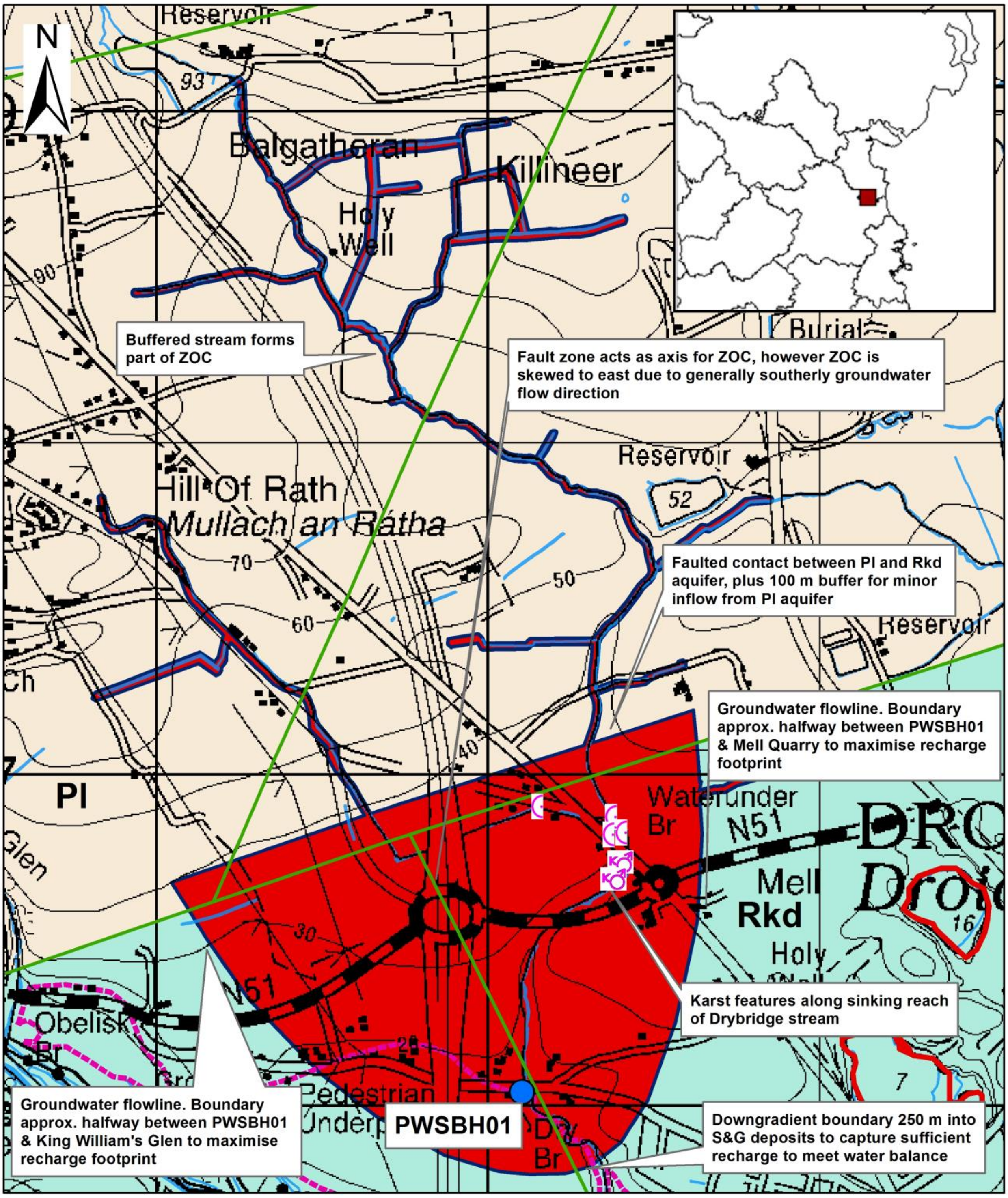


Figure 10 Source Protection Areas

- PWS Abstraction
- Drybridge PWS Zone of Contribution (ZOC)
- Drybridge PWS Inner Source Protection Area (SI)
- Stream
- Bedrock faults
- Regionally Important Karstified aquifer (Rkd)
- Poor Aquifer productive only in local zones (Pl)
- Boundary of sand & gravel deposits
- Mell Quarry pit boundaries
- swallow hole
- spring

0 0.125 0.25 0.5 0.75 km

11 GROUNDWATER SOURCE PROTECTION ZONES

Groundwater protection zones are shown in Figure 11 and are based on an overlay of the source protection areas on the groundwater vulnerability. Therefore the groundwater protection zones are SI/X, SI/E, SI/H, SI/M and SI/L.

12 POTENTIAL POLLUTION SOURCES

The main potential sources of contamination within the ZOC are:

- Given the substantial agricultural land use in the area, extreme groundwater vulnerability and potential point recharge along the Drybridge Stream upgradient of the source, contamination from these sources carries a high probability. Grazing cattle are likely to have access to streams in the upper part of the catchment, and it is likely that landspreading of organic matter from agricultural sources (*e.g.* cattle slurry) takes place within the delineated ZOC. Runoff from farmyards to surface water courses may also be contaminated by organic matter. The main potential contaminants from this source are ammonia, nitrates, phosphates, chloride, potassium, BOD, COD, TOC, pesticides, faecal bacteria, viruses and cryptosporidium.
- Surface water quality in the Drybridge Stream will likely have a direct impact on the quality of the groundwater with the potential direct recharge via the sinking reach of the stream. Any surface water contamination should therefore also be considered a threat to groundwater.
- Direct microbial contamination of the source from ponded water within the well head chamber. The ponded water may derive from drainage along service ducts. This water may be contaminated by animals and birds. The main potential contaminants from these sources are faecal bacteria, viruses and cryptosporidium.
- Part of the area is serviced by mains sewerage and leakage could contaminate groundwater. There may also be active onsite wastewater treatment systems within the ZOC. Potential contaminants from these sources include ammonia, nitrates, phosphates, chloride, potassium, BOD, COD, TOC, faecal bacteria, viruses and cryptosporidium.
- Roadways are present within the ZOC. The main potential contaminants from this source are hydrocarbons and metals.
- Private home heating fuel tanks are likely to be located within the catchment area. The main potential contaminants from this source are hydrocarbons.

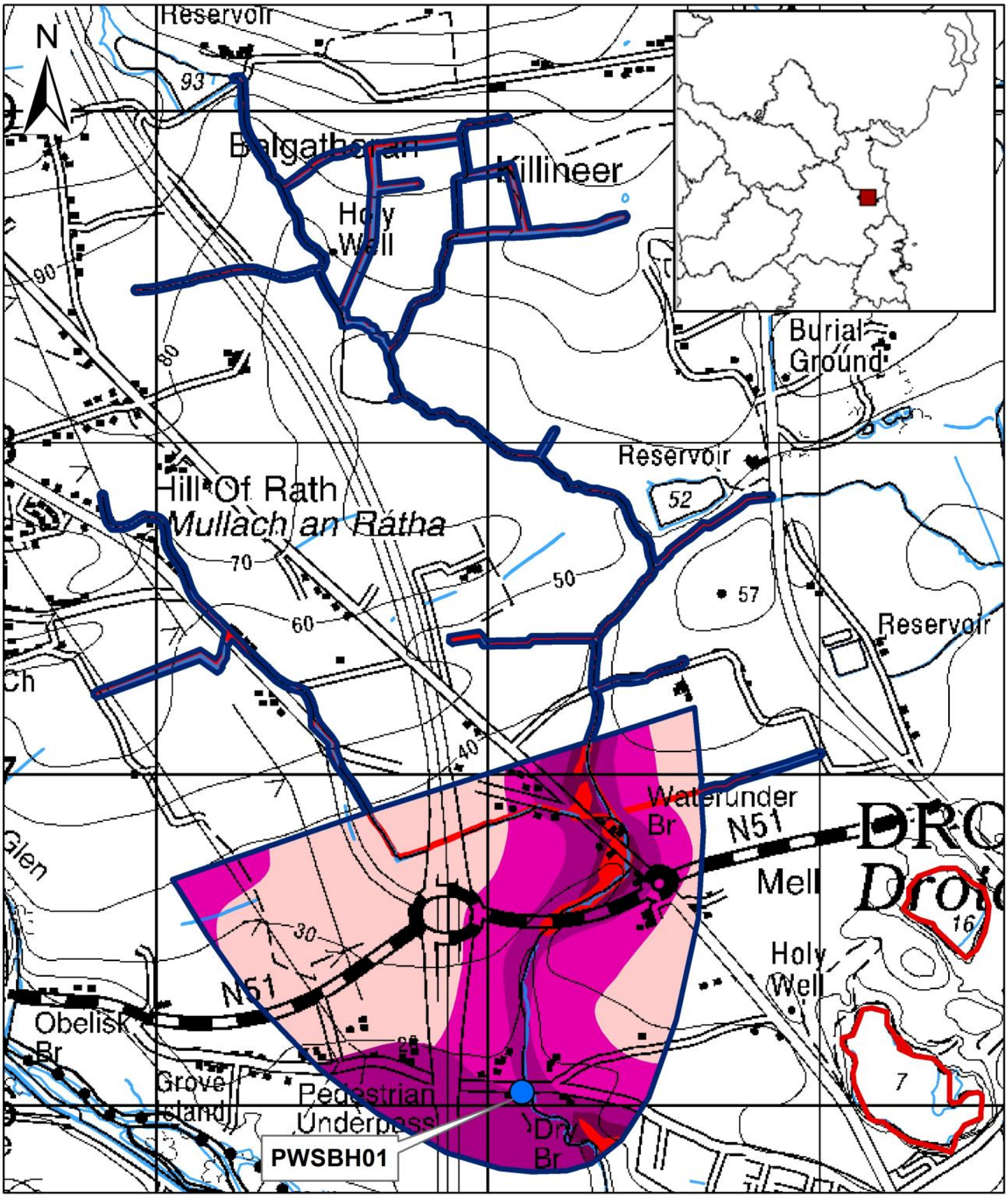


Figure 11 Source Protection Zones

13 CONCLUSIONS

A conservative ZOC for the source has been delineated for an abstraction of 412 m^3/day (150% of the current abstraction rate of 275m^3/day), assuming that all of the abstraction comes from diffuse recharge to the limestone bedrock aquifer. Point recharge within the ZOC has not been included in the calculation of the ZOC size. All of the ZOC has been designated as SI due to the high groundwater velocities that occur in karst environments. The source protection zones delineated in this report are SI/X, SI/E, SI/H, SI/M and SI/L.

The untreated groundwater is currently impacted by microbial contamination, chloride and phosphate. Treatment is in place at the source to manage the microbial contamination issues. The main sources of the contamination are likely to be farmyard runoff and agricultural waste.

The Source Protection Zones are based on the current understanding of the groundwater conditions and the available data. Additional data obtained in the future may require amendments to the protection zone boundaries.

14 RECOMMENDATIONS

- Improvement works at the source might usefully include upgrade of the wellhead protection at the source. A drain should be installed in the base of the borehole well head chamber to ensure that no ponding of water can occur within the chamber.
- It is recommended that either a new sampling tap should be installed that can sample untreated water when the pump is off, or, every effort should be made to sample the source when the pump is on. At the very least a note should be made when the sample is taken as to whether or not the pump is pumping.
- Further investigations could be made into the relationship between the water quality in the Drybridge Stream and the water quality at the source. This may be helpful for developing risk management strategies for the source should a contamination event occur in the stream. Regular measurements of the flow in the stream, both where it leaves the poor aquifer and passes by the source, may help to constrain further volume of stream water that sinks into the aquifer, and the extent of the ZOC.
- In general pumping water levels at PWSBH01 should be kept above 1.7 mAOD to minimize saline intrusion risks.

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APPENDIX 1

DATA

- Table A1.1a – Point Data from hydrogeological Mapping
- Table A1.1b – GSI Auger Hole Data
- Table A1.1C – GSI Depth to Bedrock Data
- Table A1.1d – GSI Well Database Data
- Table A1.2 – EPA Water Quality Data For Drybridge PWS Source
- Table A1.3 – Field Water Quality Data For Drybridge PWS Source
- Figure A1.1 – Original & Rehabilitated Borehole PWSBH01 Schematic
- Figure A1.2 – Borehole PWSBH01 Hydrograph
- NERDO (1981) – Borehole PWSBH01 Borehole Log
- NERDO (1981) – Groundwater Contour Map
- Pumping test analysis summary
- Table A1.3 – Pumping Test Data (NERDO, 1981)

APPENDIX 2

- Table A2.1 – Recharge coefficient table (general)
- Table A2.2 – recharge coefficients for Drybridge cachment

The term ‘recharge’ refers to the amount of water replenishing the groundwater flow system. The recharge rate is generally estimated on an annual basis, and is assumed to consist of the rainfall input (i.e. annual rainfall) minus water loss 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 delineation, as this dictates the size of the zone of contribution to the source (i.e. the outer Source Protection Area).

The main parameters involved in the estimation of recharge are: annual rainfall; annual evapotranspiration; and a recharge coefficient (**Table A2.1**). The recharge coefficient is estimated using Hunter Williams et al (2013), which is based on Guidance Document GW5 (Groundwater Working Group 2005).

Table A2.1 Recharge coefficients for different hydrogeological settings

Groundwater vulnerability category	Hydrogeological setting		Recharge coefficient (RC)		
			Min (%)	*Inner Range*	*Max (%)*
Extreme	1.i	Areas where rock is at ground surface	30	80-90	100
(X or E)	1.ii	Sand/gravel overlain by ‘well drained’ soil	50	80-90	100
	1.iii	Sand/gravel overlain by ‘poorly drained’ (gley) soil	15	35-50	70
	1.iv	Till overlain by ‘well drained’ soil	45	50-70	80
	1.v	Till overlain by ‘poorly drained’ (gley) soil	5	15-30	50
	1.vi	Sand/ gravel aquifer where the water table is ≤ 3 m below surface	50	80-90	100
	1.vii	Peat	1	15-30	50
High	2.i	Sand/gravel aquifer, overlain by ‘well drained’ soil	50	80-90	100
(H)	2.ii	High permeability subsoil (sand/gravel) overlain by ‘well drained’ soil	50	80-90	100
	2.iii	High permeability subsoil (sand/gravel) overlain by ‘poorly drained’ soil	15	35-50	70
	2.iv	Sand/gravel aquifer, overlain by ‘poorly drained’ soil	15	35-50	70
	2.v	Moderate permeability subsoil overlain by ‘well drained’ soil	35	50-70	80
	2.vi	Moderate permeability subsoil overlain by ‘poorly drained’ (gley) soil	10	15-30	50
	2.vii	Low permeability subsoil	1	20-30	40
	2.viii	Peat	1	5-15	20
Moderate	3.i	Moderate permeability subsoil and overlain by ‘well drained’ soil	35	50-70	80
(M)	3.ii	Moderate permeability subsoil and overlain by ‘poorly drained’ (gley) soil	10	15-30	50
	3.iii	Low permeability subsoil	1	10-20	30
	3.iv	Peat	1	3-5	10
Low	4.i	Low permeability subsoil	1	5-10	20
(L)	4.ii	Basin peat	1	3-5	10

The recharge coefficients in this table are summarised in a paper by Hunter Williams *et al.* (2013) in the Quarterly Journal of Engineering Geology and Hydrogeology. Aquifer recharge acceptance capacity is generally limited in Ll aquifers (200 mm/yr) and Pl and Pul aquifers (100 mm/yr). Made ground has recharge coefficient of 20%.

Table A2.1 Recharge coefficients for the study area

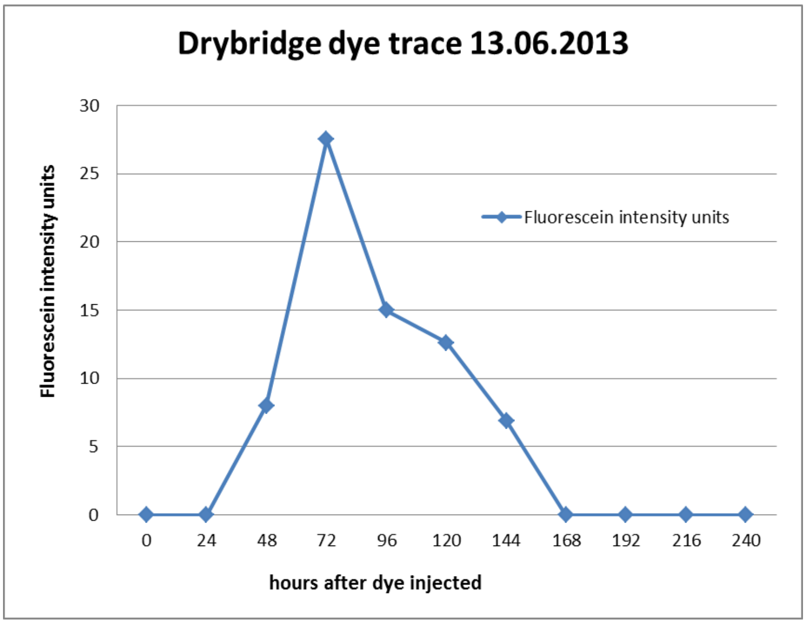
Vulnera-bility	Location in Study Area	Additional Factors	% Area	Recharge Coefficient Guidance		Chosen Recharge Coefficient	Calculated Recharge Component
				Inner Range	Outer Range		(mm/yr)
Low	Till subsoils, bands to the east and west of the source, and large area to northeast	Moderate slope, high drainage density. Low permeability subsoils. Poorly drained soils.	38.5	5 – 15%	2 - 20%	0.15	40
Moderate	Till subsoils, thin bands to the east and west of the source, and large area to northwest	Moderate slope, high drainage density. Low permeability subsoils. Mainly poorly drained soils.	25.4	10 – 20%	5 - 30%	0.2	54
	Alluvial subsoils downgradient of source	Eroded through to underlying sands and gravels by stream. Stream sinks into sands and gravels. Recharge equivalent to adjacent sand and gravel deposits	0.05	80 - 90%	60 - 100%	0.9	241
High	Till subsoils in stream gulley	Steep sided stream gully overlain by low permeability subsoils.	7.8	23 – 30%	10 – 40%	0.23	62
	Gravel & alluvial deposits adjacent to the Boyne River	Low to moderately sloping, hummocky. Well drained soils	10.3	80 – 90%	60 - 100%	0.9	241
Extreme (E)	Sands and gravels and alluvium downgradient of source	Low to moderately sloping, hummocky. Thin deposits around towers of limestone bedrock. Well drained soils.	0.3	80 – 90%	60 - 100%	0.9	241
	Immature' Till subsoils in stream gulley	Steep sided stream gully with poorly drained soils.	1.5	25 – 40%	15 - 50%	0.35	94
Extreme (X)	Along the incised stream valley	Steep sided stream gully.	16.1	80 – 90%	60 – 100%	0.8	214

APPENDIX 3

- Details of dye trace 13th June 2013
- Table A3 – Recharge coefficient table
- Chart A3 – graph of fluorescein intensity

Injection 13.06.13 400g of fluorescein injected into swallow hole in bed of stream (E306356 N276824). Dye measured in water from borehole (E306128 N276043), approximately 810 m to the south

Date	Hours after injection	Fluorescein intensity units
13.06.13	0	0
14.06.13	24	0
15.06.13	48	8
16.06.13	72	27.5
17.06.13	96	15
18.06.13	120	12.6
19.06.13	144	6.9
20.06.13	168	0
21.06.13	192	0
22.06.13	216	0
23.06.13	240	0
24.06.13	264	
25.06.13	288	
26.06.13	312	
27.06.13	336	
	360	
	384	
	408	
	432	
	456	



Swallow hole - near small quarry
Grid Ref: 306356 276824
Conductivity: 374 uS/cm (19/05/08)
Temperature: 11.2^{o}C
Presumably sinks in other places in the bed (flow seems smaller than upstream) but this is example of one. In this relatively dry weather all flow is sinking.

Stream Resurgence
Grid Ref: 306398 276754
Conductivity: 403 uS/cm (19/05/08)
Temperature: 10.8^{o}C
No obvious rises - just seeps that gather in the dry river channel through gravels

APPENDIX 4

- Saline intrusion potential calculations

The proven depth of the karst conduit development in the limestone is to -66 mAOD. The bottom of the borehole is -32 mAOD approximately.

Based on the Ghyben-Herzberg Relationship[4], for the toe of the salt wedge to stabilize at -66 mAOD (i.e. directly below PWSBH01), the PWSBH01 pumping water level would need to drop to 2.7 mAOD.

- The measured pumping water level (PWL) for the current abstraction rate (4.7 mAOD; 394 m^3/day) is well above this threshold. This suggests that the toe of the wedge would equilibrate at -139 mAOD and will therefore be truncated by the base of the aquifer at some distance downgradient of PWSBH01 (Figure 9).

- The PWL from the PWSBH01 commissioning pumping test (530 m^3/day) is estimated at 4.0 mAOD, which is also well above the threshold.

- The maximum drawdown recorded in the borehole was 12.0 m (0.65 mAOD; 924 m^3/day) during the 3 day pumping test in 1980 (NERDO, 1981). This PWL is below the threshold and implies a potential saline intrusion risk.

Nonetheless, the downgradient sand and gravel deposits would also need to be dewatered to less than the threshold level before an intrusion could occur, such that groundwater storage in the deposits act as a significant buffer against saline intrusion. This buffer is particularly relevant where current pumping water levels might drop briefly below the threshold during a seasonal low.

[4] Z ~ -40h, where z = depth of saline interface below estuarine saline water level (ESWL); and h = groundwater head above ESWL.