Monaghan Public Water Supply

Groundwater Source Protection Zones

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1: Introduction

The objectives of the report are as follows:

- To delineate source protection zones for the ten public supply wells.
- To outline the principal hydrogeological characteristics of the Monaghan area.
- To assist Monaghan County Council in protecting the water supply from contamination.

2: Location, Site Description and Well Head Protection

Ten boreholes are used for the Monaghan Public Water Supply. All of the boreholes are located around Monaghan town, with eight wells positioned in an east-west line that is roughly one kilometre north of Monaghan town. The remaining two wells are located closer to Monaghan town, near St. Davnett's Asylum (Roosky). Currently, three wells are in production: the two wells at Roosky, and a well at Lambs Lough (PW1). These Roosky wells combined supply around 1100 m^3/d; the well at Lambs Lough recently began pumping at between 1100 – 1350 m^3/d, supplying a volume of approximately 450 m^3/d. The remaining wells will not be brought into production until 2002. Table 1 provides a summary of the wells, including the name, drilled date and their general location.

Table 1: Summary of the locations of the wells serving Monaghan town.

Borehole	Date Drilled	General Location
Roosky 1 – St. Davnett's	April 1978	In lay-by along entrance to mental hospital
Roosky 2 – St. Davnett's	September 1995	In field along entrance to mental hospital
PW1 – Lamb's Lough	July 1997	Adjacent to Lambs Lough pump house
PW2 – The Wood	September 1998	In field at top of hill, across from St. McArtens seminary
PW3 – Cappog Bridge	October 1997	In Drumreaske Estate
PW4 – Ballyalbany	January 1998	Across road from Lambs Lough
PW5 – Raffeenan Bridge	October 1997	In lay-by next to stone house
PW6 – Emyvale Road	December 1997	In lay-by along Emyvale Road, approx. 2 km north of Monaghan
PW7 – Silver Stream	November 1997	In lay-by between the Armagh Road and the Glaslough Road
PW8 – Crosses	September 1998	At the site of the new water treatment plant

With the exception of PW8, at least one observation borehole is located near every well. Production wells 1, 3 and 5 have multiple observation wells, as they were used during the 4-week pumping test. The observation boreholes are generally between 5-10 m from the production wells; although some are located farther away.

3: Summary of Well Details

Table 2, below, provides a summary of well detail information.

Table 2: Summary of well detail infomation

	Well Name									
Well Details	**Roosky A**	**Roosky B**	**PW1**	**PW2[1]**	**PW3**	**PW4**	**PW5**	**PW6**	**PW7**	**PW8[2]**
GSI Well Number (all on 2633SW)	W081	W287	W255	W278	W249	W254	W256	W260	W262	W279
Grid Ref (1:50,000)	26778E, 33447N	26781E, 33441N	26690E, 33591N	26790E, 33592N	26383E, 33560N	26708E, 33550N	26508E, 33615N	29793E, 33671N	27061E, 33593N	26595E, 335725N
Location	Roosky	Roosky	Lambs Lough	The Wood	Cappog	Ballyalbany	Drumbenagh	Kilnadreen	Lisnanole	Crosses
Well type	Bored	Bored	Bored	Bored	Bored	Bored	Bored	Bored	Bored	Bored
Owner	Monaghan Co. Co.	Monaghan Co. Co.	Monaghan Co. Co.	Monaghan Co. Co.	Monaghan Co. Co.	Monaghan Co. Co.	Monaghan Co. Co.	Monaghan Co. Co.	Monaghan Co. Co.	Monaghan Co. Co.
Elevation (ground level) (m)	63	NA	59.5	89	59.4	61.9	59.1	57.9	51.6	
Depth of borehole (m)	47	NA	91	134.1	103	91.4	84	91.4	91	91.4
Diameter of borehole (mm)	NA	NA	300	300	300	300	300	300	300	300
Depth to rock (m)	18	NA	5	39.6	6	4.9	8	4.3	4.5	19.8
Bedrock Unit	BA	BA	BS	BS	BN	BS	DA/BN	DA	BA	BS
Static water level (m)	53.1?	NA	57	NA	56	53-57	57	56.2	47.3	N/A
Pumping water level (m)	52.6?	NA	NA	NA	NA	NA	NA	NA	NA	NA
Abstraction Rate[3] (m^3/d)	1100		1250	*1250*	*1250*	*1250*	*1250*	*500*	*1250*	*1250*
Pumping test summary – 72hr pumping test on associated trial wells[4]:										
Avg. Abstraction (m^3/d)	689/648		1240	1971	1700	2122	1889	906		N/A
Maximum Drawdown (m)	8		24.5	16.5	30.5	13.5	21	33	11.5	N/A
Transmissivity (m^2/d)	100		40 or 200	65-90 (145 from obs well)	125-210	100	200-290	50	not determined	N/A

Notes:

1. Trial well 2 is located approximately 1 km from PW2. Although they are located in the same bedrock unit, information from the pumping test at TW2 may not reflect conditions at PW2.
2. Trial well 8 is not located near PW8, which is at Crosses. No pumping test information is available for either the trial or production well.
3. The abstraction rate for the two wells at Roosky is a combined amount. Wells 2-8 will not be in production until 2002; the amounts shown are the expected abstraction rates.
4. Pumping test information taken from KTC, 1997a.
5. NA = not available.

Available pumping test and abstraction data include:

- ♦ A 72-hour and a 20-day pumping test at the trial well for Roosky A, carried out in February and October 1977, respectively.
- ♦ Limited, combined abstraction data from the two production wells at Roosky.
- ♦ 72-hour pumping tests carried out at the original trial wells TW1 – TW7. These tests were carried out independently of one another; observation borehole data is available only for TW2 (KTC, 1997a).
- ♦ 4-week pumping tests carried out by K.T. Cullen and Company (KTC) at Production Wells 1, 3 and 5 in November 1997 (KTC, 1997b). All three wells were pumped simultaneously and water levels were monitored in these and the associated observation wells. Water levels in the original trial wells TW2, TW4, TW6, TW7, and TW8 were monitored, as were in 17 domestic wells around the area.

4: Methodology

4.7 Desk Study

Details about the boreholes such as elevation, abstraction figures, along with geological and hydrogeological information were obtained from GSI records, County Council personnel and hydrogeologic reports by KTC and P.J. Tobin Engineering.

4.8 Site visits and fieldwork

This included carrying out depth to rock drilling, subsoil sampling and vulnerability mapping. Field walkovers were also carried out to investigate the subsoil geology, the hydrogeology and vulnerability to contamination.

4.9 Assessment

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

5: Topography, Surface Hydrology and Land Use

The locations of the Monaghan boreholes are shown on Map 1. The two Roosky boreholes are located at the northeast edge of Monaghan town, along the entrance to the St. Davnett's Mental Hospital. These are located on a hill that slopes down to the River Blackwater.

The remaining seven boreholes are located in an east-west trending line about one kilometre north of Monaghan. Three of these wells, PW3, PW5 and PW8 are located at the base of hills, along the Blackwater River. Wells PW1 and PW4 are located near Lambs Lough and a small stream that feeds into the Blackwater River. PW2 is located at the top of a hill, across from St. McArten's Seminary; PW6 is along the Emyvale Road, located adjacent to a small tributary to the Blackwater River. PW7 is the eastern most borehole, located at Silver Stream, near the former Ulster Canal.

The overall topography in the area is hilly due to the large number of drumlins in the region. The Blackwater River is the primary surface water feature in the area.

Agriculture and business associated with Monaghan Town are the main activities in the area. The fields around the boreholes are primarily used for grazing. Organic waste is landspread in fields near the wells, and septic tank systems are located at houses near the wells.

6: Geology

6.7 Introduction

This section briefly describes the relevant characteristics of the geological materials that underlie the Monaghan 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 (Geraghty et al, 1997)
- Hydrogeological reports and borehole logs from KTC (1997a, b) and P.J. Tobin (P.J. Tobin and KTC, 1998)
- The NERDO Report (An Foras Forbartha (AFF) and GSI, 1981)

Subsoils information was gathered from Quaternary geology maps from the 1950's, and from permeability mapping by GSI field personnel in 2000.

6.8 Bedrock Geology

The Monaghan production wells are located in four different bedrock units: the Ballyshannon Limestone, Dartry Limestone, Ballysteen Limestone and the Bundoran Shale. The limestones are expected to be clean, well bedded rock units of similar geology. The Bundoran Shale, which is comprised of shales with sandstone interbeds, is located to the north of the limestones. While predominantly shaly, the lower portion of this unit is thought to contain interbeds of dolomite that will influence the permeability. Bands of dolomitised limestone are recorded in the borehole logs for PW 3 (Cappog), which is located in the Bundoran Shale.

The rocks that the boreholes are drilled into are commonly known as the 'Lower Limestones'. In Monaghan, the Lower Limestones are found in a northeast-southwest band from Monaghan to Killeshandra in County Cavan, and are faulted against Lower Palaeozoic bedrock. They are comprised of various rock units, described below in Table 3.

Table 3: Bedrock Geology of the Monaghan area.

Age			Geological Name	Geological Description	Thickness (m)
CARBONIFEROUS	*Lower Limestones*		**Dartry Limestone (DA)**	Dark grey, cherty, clean limestone.	N/A
			Bundoran Shale (BN)	Dark shale, minor fine grained limestones and sandstones	N/A
			Ballyshannon Limestones (BS)	Limestones and silty shales at base of unit with pale grainstones at top of unit	560
			Ballysteen Limestones (BA)	Clean sandy or silty limestones at base of unit grading into a muddy fine grained limestone	N/A
			Ulster Canal Limestones (UC)	Silty and sandy limestones, some fine grained limestones	60
		Basal Clastics	**Cooldaragh Limestones (CH)**	Pale brown-grey siltstones and mudstones; algal, evaporitic and fine grained limestones; muddy siltstones	125
			Fearnaght Sandstones (FT)	Pale conglomerate and red sandstone	~20
ORDOVICIAN (LOWER PALAEOZOIC)			**Coronea Sandstones (CA)**	Muddy sandstone, red shale, minor volcanic	1,600 - 2,300

Along this band, the contact between the Lower Limestones and the Lower Palaeozoic rocks is offset by a series of northwest-southeast trending faults. Some of these faults occur within the area of the boreholes, usually offsetting the Ballyshannon and Ballysteen limestones. East-west trending faults also occur, which tend to repeat the sequence of rocks. Near PW3, the Bundoran Shale is faulted against itself. In the area of the boreholes, the Dartry Limestone is bounded completely by these faults. Production well 5 (Drumbenagh) is mapped as being located along the fault between the Dartry Limestone and Bundoran Shale. The borehole logs for this well record "cavernous and collapsing limestone" and "soft fissured limestone", which are likely to represent the fault or associated fissures.

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 (Geraghty et al., 1997).

6.9 Subsoil Geology

The subsoils in Monaghan were mapped in the 1950's by Mike O'Meara of the GSI. Drilling and permeability mapping carried out by the GSI provided additional information on the subsoils. The subsoils comprise a mixture of coarse and fine-grained materials, namely alluvium, peat, tills, and gravel. The characteristics of each category are described briefly in the following sections.

6.9.1 Alluvium

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 Blackwater River and its tributaries. No sections or boreholes from the area are located in alluvium. Based on the gradient and energy regime of the Blackwater River, the deposits are expected to be primarily sands and silts with minor clay bands.

6.9.2 Peat

Deposition of peat occurred in post-glacial times with the onset of warmer and wetter climatic conditions. Peat is an unconsolidated brown to black organic material comprising a mixture of decomposed and undecomposed plant matter which has accumulated in a water logged environment. It has an extremely high water content averaging over 90% by volume. In the source area, peat is found in the lowlying areas north of PW8, and along the stream adjacent to PW6.

6.9.3 Till (Boulder Clay)

'Till' is an unsorted mixture of coarse and fine materials lain down by ice and are the dominant subsoil type in the locality. Most of the drumlins (elongated hills) around the boreholes are composed of till. The tills around these public supply wells have a variable texture, and range from dark grey sandy CLAY with 20% clay to clayey SAND with only 12% clay. With the exception of PW7, all of the production wells are located in till.

6.9.4 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.

Within the source area, a large, continuous gravel deposit is mapped around PW7. 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.

6.9.5 Depth to Bedrock

Nine boreholes were drilled adjacent to the production wells to ascertain the depth, thickness and permeability of the subsoils. Using this information and knowledge of sites that have rock cropping out, the depth to rock is estimated across the area. The depth to bedrock is generally greater than 3 m, with most of the drumlins being greater than 10 m.

7: Hydrogeology

7.7 Introduction

This section presents our current understanding of groundwater flow around the Monaghan 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:

- A 72-hour and a 20-day pumping tests carried out on the trial well associated with the Roosky borehole from February and October 1997, respectively.
- 72-hour pumping tests carried out on all the new trial wells by K.T. Cullen & Co. from December 1996 to February 1997 (KTC, 1997a)
- Four-week, simultaneous pumping tests at PW 1, 3 and 5 performed by KTC from October-November, 1997 (KTC, 1997b)
- A report on the expected impact of the new production wells, which includes numerical modelling of predicted drawdowns, by P.J. Tobin and K.T. Cullen & Co. (P.J. Tobin and KTC, 1998)
- Local, hydrogeological mapping carried out by the GSI.
- Drilling and permeability mapping carried out by GSI to ascertain depth to bedrock and subsoil permeability.
- GSI files and archival Monaghan County Council data.
- Water quality test results from samples collected during the various pumping tests at the new wells (P.J. Tobin and KTC, 1998)
- Water quality test results from the Roosky wells, collected by the EPA Regional Inspectorate in Monaghan.
- Numerical modelling by the GSI to estimate the ZOC and 100-day time of travel.

7.8 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.

In areas where point recharge from sinking streams and other karst features do not play a role, 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.

7.8.1 Average Annual Rainfall

Average annual rainfall is calculated to be 958 mm yr^{-1}. Rainfall data are from Met Eireann average annual rainfall values for 1961-1990 at the Monaghan-Knockroe station (Fitzgerald and Forrestal, 1996).

7.8.2 Annual Evapotranspiration

Potential evaporation (P.E.) is estimated to be 438mm yr^{-1}. P.E. data are from a synoptic weather station located in Clones, and are averaged over the years 1961-1990. Actual evapotranspiration (A.E.) is then estimated as 95% of P.E., or 416 mm yr^{-1}.

7.8.3 Potential Recharge

Potential recharge is calculated at 542 mm yr^{-1}. This is calculated by subtracting the estimated evapotranspiration from the average annual rainfall. It represents an estimation of the excess soil moisture available for either vertical downward flow to groundwater, or lateral flow through soil and overland flow to surface water.

7.8.4 Estimated Actual Recharge

Estimated Actual Recharge represents the amount of water that will infiltrate to groundwater. This is an estimation of recharge which allows for surface water outflow, particularly during periods of heavy rainfall. It roughly estimates the amount of groundwater available to each well.

Within the zone of contribution (ZOC) of the wells, there are many small and discontinuous sand/gravel deposits, many of which are too small to be shown at the 1:50,000 scale, and in some cases are too small to be mapped at larger scales. Because of this, the subsoils in the area appear to be mixed, with descriptions of 'CLAY' adjacent to those of 'SAND' or 'SILT'. Where possible, areas with consistent low permeability indicators were delineated and are expected to allow less recharge through to groundwater. With the exception of these areas, the tills and alluvial deposits in this area are considered to be moderately permeable. Gravels in the area are clean and have a high permeability. Peat deposits in this area are generally thin, so the underlying subsoil is assumed to dominate the vertical permeability. The NERDO report provides an infiltration rate of approximately 30% for tills in the Blackwater catchment around Monaghan town (AFF and GSI, 1981). Given this information, the following range of infiltration rates were used both in the conceptual and numerical model:

Subsoil Type	Infiltration rate
Rock outcrop	60 – 90%
Gravel	60 – 80%
Moderate permeability subsoils	20 – 60%
Low permeability subsoils	2 – 20%

7.9 Groundwater Levels, Flow Directions and Gradients

As part of the investigations by KTC and P.J. Tobin, water levels in the vicinity of the production wells were monitored before, during and after the 4-week pumping test. Water levels were monitored in:

- all of the trial wells
- all production wells and associated observation boreholes, except for PW2 and PW8, which were not drilled at the time
- 17 domestic bored wells

The water table is generally assumed to be a subdued reflection of topography. The topography in the Monaghan area is hilly because of the number of drumlins in the area, with a gentle gradient to the east. The Blackwater River runs adjacent to many of the production wells west of Monaghan town. A contour map of the water level data from just prior to the 4-week pumping test shows that in the west, and north of the river, groundwater flows toward the Blackwater River. Given this, it is safe to assume that groundwater contributes to flow in the Blackwater river; however, the amount of groundwater contributing to the river flow is difficult to determine since it depends upon the permeability of the river bottom. In the east, near PW7, the groundwater probably does not discharge into the river, but is more likely flowing east towards the Blackwater/Cor River system, near the Armagh border.

The groundwater gradient in the western part of the public supply area is approximately 0.005; in the east, near PW7, the gradient is around 0.002.

7.10 Aquifer Characteristics and Category

The supply wells lie in a series of bedrock units that are hydrogeologically similar and hydraulically connected. They have been grouped together to form the Monaghan – Clones Aquifer, which is classified as a **regionally important, fissured aquifer (Rf)**. More information regarding the specific well information used to arrive at this classification is presented in the County Monaghan Groundwater Protection Scheme Main Report (Swartz and Daly, 2001).

The Monaghan-Clones area aquifer is bounded to the south by a fault that juxtaposes the Fearnaght Sandstone against Lower Palaeozoic rocks; to the north, primarily the Benbulben shales bound it. However, the mapped geological boundary is not used as the aquifer boundary in this case. The bedrock compilation sheets indicate that the lower portion of the Benbulben Shale contains dolomitised limestone interbeds. As shown by one of the public supply wells (PW3), these interbeds are capable of supplying large amounts of water. Similarly, faulting and/or associated fractures between the Dartry limestones and Benbulben shales is probably responsible for high yields for the well at Drumbenagh (PW5). Based on these well data and outcrop information from the 1:10,560 bedrock sheets, a portion of the Benbulben Shale is included in the Monaghan-Clones area aquifer.

Groundwater flow will occur largely along fractures and faults. Numerous north-south faults have been mapped cross-cutting this aquifer, offsetting it against itself. Additionally, east-west trending faults are mapped around the Dartry Limestone. These faults are likely to increase the permeability of the aquifer, and additional fracturing may be associated with these faults. Where clean limestones are present, dissolution may occur along faults, fractures and bedding planes, widening them and enhancing the permeability.

Overall, the permeability will be influenced by the fracturing and faulting within and between the various rock units. However, the permeability will also be effected by low permeability fine grained and shaly beds within some of the limestone rock units. In general, the effect of the low permeability beds, which trend east-west, may be reduced, or even negated completely, by the fracturing and faulting which is largely north-northeast to south-southwest. The permeability in the Bundoran Shale will be dictated by the presence and continuity of the clean limestones and dolomite interbeds.

With the exception of two wells, the Monaghan boreholes are located in the Ballysteen, Ballyshannon and Dartry Limestones, as shown in Table 4 below. The well at Cappog (PW3) is located in the Bundoran Shale. Although these shales were not expected to be highly productive, the borehole logs for the trial and production wells show zones of dolomitised limestone that correspond to water inflows. Detailed information on the bedrock in the area suggests that the base of the Bundoran shale contains interbeds of Ballyshannon-type limestone; these interbeds are probably responsible for the high transmissivity found in this well. The well at Drumbenagh (PW5) is located near a fault boundary between the Dartry Limestone and Bundoran Shale. The borehole log for this well indicates 'cavernous and collapsing limestone', which may reflect the presence of fracturing associated with the fault.

Analysis of aquifer characteristics around the supply wells are based on test pumping of the trial wells undertaken by K.T. Cullen and Company from December 1996 to February 1997. Additionally, four-week constant discharge tests were run in November 1997, simultaneously testing the production wells at Drumbenagh (PW5), Cappog (PW3) and Lambs Lough (PW1). Information gained from the pumping tests, such as average discharge, drawdown, specific capacity and transmissivities are summarised in Table 4.

Overall, the transmissivities and permeabilities calculated from the 72-hour pumping tests range from 50-250 m^2/d and 1-6 m/d, respectively. The specific capacities range from 30 – 160 m^3/d/m, and productivity values for these wells are in classes I and II, indicating that these wells are located in an productive, permeable aquifer. Productivity classes range from I (highest) to V (lowest), and provide a more consistent and objective measure of an aquifer's ability to yield water (Wright, 2000).

Analysis of the 72-hour pumping tests indicates that recharge boundary conditions were likely to have been met in the Roosky, Lambs Lough (TW1), Cappog (TW3), Rafeen Bridge (TW5) and Silver Stream (TW7) boreholes. On the pumping test graphs, a flattening of the drawdown curve can represent a recharge boundary and indicates stabilization of the drawdown. However, these were only short pumping tests from which the long term effects of pumping can not be fully predicted. It is recommended that water level monitoring should be carried out once the wells are in production.

Table 4: Summary of Aquifer Characteristics. These values are calculated from 72-hour pumping test data from the trial wells.

Well	Average Discharge (m^3/d)	Drawdown (m)	Specific Capacity ($m^3/d/m$)	Productivity Class	Transmissivity (m^2/d)
Ballysteen Limestone					
TW7	1740*	5.5*	316	I	160*
Roosky A†	660	8	82.5	II	100
Ballyshannon Limestone					
TW1	1240	24.5	51	II	~100
TW2	1971	17	116	I	150
TW4	2122	13.5	157	I	100
Dartry Limestone					
TW5	1889	21	90	I	250
TW6	906	33	27.5	II	50
Bundoran Shale					
TW3	1700	31	55	II	175

Notes: Pumping test data were analysed using the Jacob straight-line method.
* Data for this well are taken directly from the KTC report on the pumping tests (KTC, 1997a) due to varying discharge rates during the test.
† Data for the Roosky well are from pumping tests carried out at the original borehole

7.11 Hydrochemistry and Water Quality

Water quality samples from the Roosky wells are collected routinely by the EPA Regional Inspectorate in Monaghan. Samples are collected from a tap after the water from both wells are mixed, but before chlorination. Since the wells are only approximately 100 m apart, and are in the same rock unit, the water quality results are still representative of the aquifer. These data are tabulated in Table 5, and are summarised below.

Water quality samples from the recently drilled trial and abstraction wells were collected by KTC during the 4-week pumping test in 1998 (P.J. Tobin and KTC, 1998). Each well was sampled four times during the pumping test, although not every parameter was analysed for each time. The well at Lambs Lough, which is currently in production, was also sampled twice by the GSI in February and August 2001. These data are presented in Table 6, and are summarised below.

- Total hardness in the Roosky wells ranges from 436-588 mg/l $CaCO_3$. This is higher than the other wells, where the range of hardness is between 261-373 mg/l $CaCO_3$. These data suggest that the groundwater has a hydrochemical signature of a calcium bicarbonate type water. These values are typical of groundwater from a limestone source.

- Electrical conductivity values are indicative of limestone bedrock. Conductivity values are higher in the Roosky wells, where the range is from 965-1145 μS/cm. In the other wells, the conductivity values are consistent with each other, ranging from 505-691 μS/cm.
- With the exception of one sample from the Roosky wells, sulphate (SO_4) concentrations are below the EU MAC in the wells. Overall, sulphate concentrations are significantly higher in the Roosky wells, ranging from 12-270 mg/l, as opposed to 6-128 mg/l found in the new trial and production wells. Sulphate concentrations are also higher (but not above the EU MAC) at the Silver Stream wells (TW7, PW7; 87 and 128 mg/l) and TW2 (80 mg/l). In the remaining new wells, the highest concentration found is 44.6 mg/L at Lambs Lough (PW1). The Roosky and Silver Stream wells are located in the Ballysteen Limestone; TW2 is located in the Ballyshannon Limestone. Elevated concentrations of sulphates are associated with evaporite lenses in the Lower Limestones, and samples collected by the GSI and EPA show that elevated sulphate levels occur in other wells located in the Ballysteen limestone. Evaporite deposits are not mapped as occurring in the Ballysteen, but are found in the Cooldaragh limestone, which lies to the south of these wells. The occurrence of high sulphates is probably due to the presence of unmapped evaporite deposits in the Ballysteen limestones.
- Chloride concentrations are also higher in the Roosky wells (38-70 mg/L) than in the new trial and production wells (13-18 mg/L). Chloride is a constituent of organic wastes and a concentration higher than 30 mg/l usually indicates significant contamination has occurred. However, given the hardness, EC and sulphate results, the chloride at the Roosky well is most likely due to naturally occurring evaporite deposits in the rock. The chloride levels in the new wells are suggestive of background conditions but should continue to be monitored once pumping begins.
- The levels of ammonium (NH_4) are below the EU MAC in all but one well, TW2. However, new wells often have high ammonium levels that typically drop during pumping. High ammonium levels can also indicate reducing conditions caused by organic waste pollution. One sample (23 Sept 97) from the Roosky wells had an ammonium concentration above the GSI Guideline, potentially indicating a nearby contamination event around the time the sample was collected.
- One sample (22 Jan 98) from the Roosky wells has a concentration of potassium (K) above the GSI Guideline, potentially indicating contamination by organic waste around the time the sample was collected.
- Concentrations of iron (Fe) are occasionally above the EU MAC value in the Roosky wells. No obvious seasonal trend can be observed from the available data. Iron concentrations are above the EU MAC value in four of the seven new boreholes. While the elevated levels are most likely derived from the bedrock and indicate reducing conditions, they may also indicate contamination by organic waste.
- Manganese (Mn) concentrations were also consistently above the EU MAC value in the Roosky wells and in six of the seven new wells. While the elevated levels are most likely derived from the bedrock and indicate reducing conditions, they may also indicate contamination by organic waste.
- Elevated Magnesium (Mg) levels are found in the Roosky wells. Magnesium is generally derived from magnesium-rich rock types, such as dolomite, or from evaporite lenses within the rock.
- The sample collected from the trial well at Lambs Lough (TW1) has a turbidity count above the EU MAC, which is not surprising since the well is new and had not previously been pumped.
- The suspended solids are elevated in three samples from the Roosky wells, which probably indicates sediment influx into the well.
- Occasional counts of total coliforms were detected in the Roosky wells, the worst being a count of 52/100 ml in August 96. A count of 31/100 ml faecal coliforms were also detected in this sample, indicating contamination by organic waste. Subsequent counts of total coliforms were never higher than 3/100 ml, and only one sample had associated faecal coliforms (1/100 ml, September 1999). Total coliforms can result from organic materials in the soil, and alone do not indicate contamination by human activities. No counts of total, faecal or *Escherichia* coliforms were identified in the new trial or production wells.

Overall, the samples from the new trial and production wells do not indicate significant contamination or pollution of these wells. Concentrations of iron and manganese are elevated in some of the wells; this is most likely due to bedrock conditions.

In the Roosky wells, conductivity and hardness values are higher than in the new wells, and may indicate the presence of evaporite lenses within the rocks around the wells. The presence of evaporites may also explain the consistently 'high' (above GSI Guidelines) chloride levels and the elevated sulphate concentrations. Bedrock mapping has not confirmed the presence of evaporite lenses in the Ballysteen limestones; evaporites are expected in the Cooldaragh Limestone, which lies to the south. However, other water quality data from wells in the Ballysteen Limestone indicate elevated sulphate concentrations, further suggesting the presence of evaporite lenses.

The presence of an occasional elevated ammonium concentration and of faecal coliforms at the Roosky wells suggests that contamination events have occurred within the zone of contribution. This is somewhat surprising in that the vulnerability of the area in the immediate vicinity of the well is mapped as 'low'. Contaminants may be arising from shallow surface water and groundwater that is entering the well around the outside of the casing. As these wells are located close to Monaghan town, there are many potential hazards in the vicinity.

7.12 Conceptual Model

- The combined planned abstraction for the public supply is 4545 m^3/d. The rates for supply wells, as presented in P.J. Tobin and KTC (1998), are listed below in Table 7, and include an increase of 25%. As a factor of safety in delineating zones of contribution, the planned abstraction rate is increased to allow for possible future increases in abstraction and for expansion of the ZOC in dry periods (DoELG/EPA/GSI, 1999).

Table 7 Planned Abstractions for the Monaghan Public Supply Wells.

Well Name	Abstraction + 25% increase (m^3/d)
Roosky A&B	1100
PW1 (Lamb's Lough)	433
PW2 (The Wood)	677
PW3 (Cappog)	677
PW4 (Ballyalbany)	677
PW5 (Rafeenan Bridge)	677
PW6 (Kilnadreen)	200
PW7 (Silver Stream)	677
PW8 (Crosses)	677
Total	*5733*

- The groundwater regime in the area is complex due to the structural history of the rocks and the available hydrogeological information does not allow a definitive understanding of the hydrogeology.
- The boreholes lie in east-west trending band of limestones, which is bounded to the south by relatively impermeable bedrock. Two of the boreholes lie within or near a shale formation, the base of which contains high permeability beds of dolomitised limestones. We refer the portion of the shales containing these higher permeability beds as the 'transitional zone'. Low permeability shales are north of this zone. Transmissivities for the different rock types are within the following possible ranges:

'Limestone'	150 – 325 m^2/d
'Transitional Bundoran Shale'	50 – 100 m^2/d
'Bundoran Shale'	10 – 50 m^2/d

Table 5: Summary of Hydrochemistry Data from the Roosky production wells

Parameter	**Units**	**MAC Value (*GSI Threshold*[1])**	**Roosky**								
			06 Aug 96	29 Jan 97	23 Sept 97	22 Jan 98	11 Aug 98	22 Sept 99	21 Feb 00	11 Oct 00	11 Jan 01
Colour	Hazen	20	-	-	-	-	-	-	-	-	-
Turbidity	N.T.U	10	-	-	-	-	-	-	-	-	-
pH		6-9	7.22	7.2	7.16	7.18	7.08	7.1	7.1	7.2	7.1
Conductivity	µS/cm	1500	965	977	1020	1012	1056	1073	1049	1120	1145
Hardness	$CaCO_3$ mg/L		436	588	540	516	308	562	550	560	505
Alkalinity	$CaCO_3$ mg/L		308	352	320	292	200	320	380	300	323
Sulphate	SO_4 mg/L	250	140	12	225	93	-	**270**	-	202	217
Chloride	Cl mg/L	250 (*30*)	41*	38*	48*	47*	57*	55*	56*	69*	70*
Nitrate	NO_3 mg/L	50 (*25*)	0.18	-	0.53	0.13	0.13	0.09	-	-	-
Nitrite	NO_2 mg/L	0.1	0.001	0.001	0.001	0.001	0.005	<0.002	-	<0.002	<0.002
Ammonium Total	NH_4 mg/L	0.3 (*0.15*)	0.14	0.01	0.17*	0.03	0.04	0.04	0.04	0.08	0.08
Copper	Cu mg/L	0.5	<0.001	<0.001	<0.001	-	-	0.006	0.004	0.008	0.004
Iron	Fe mg/L	0.2	**0.44**	**0.25**	<0.005	**0.34**	**0.29**	<0.1	0.072	0.197	0.191
Magnesium	Mg mg/L	50	39.3	46.4	33.6	**52.3**	37.5	**53.9**	40.0	29.2	-
Manganese	Mn mg/L	0.05	**0.28**	**0.3**	**0.261**	**0.3**	0.039	**0.24**	**0.27**	**0.27**	**0.29**
Aluminium	Al mg/L	0.2	-	-	-	-	-	-	<0.02	<0.05	<0.05
Phosphorous	P205 mg/L	5	-	-	-	-	-	-	-	-	-
Fluoride	F mg/L	1.0	0.17		0.168	0.22	0.165	<0.3	-	<0.3	<0.3
Sodium	Na mg/L	150	17.14	18.53	19.08	50.72	20.8	34.22	21.12	26.18	42.52
Potassium	K mg/L	12 (*4*)	1.42	2	1.42	4.47*	1.5	1.73	1.66	1.97	<1
K:Na Ratio	K:Na	(*0.3*)	0.08	0.11	0.07	0.09	0.07	0.05	0.08	0.08	<0.02
Suspended Solids	mg/L	No Visible	0	1	5	0	2	-	-	-	-
Lead	Pb mg/L	0.05	<0.0008	<0.0008	-	-	-	<0.005	<0.0005	0.0029	<0.001
Zinc	Zn mg/L	1.0	-	-	-	-	-	-	-	-	-
Odour	Dilution No.	2/12 DegC	-	-	-	-	-	-	-	-	-
Total Coliforms	no./100 mL	0	**52**	0	0	0	**1**	**1**	0	0	**3**
Faecal Coliforms	no./100 mL	0	**31**	0	0	0	0	**1**	0	0	0
E. Coliforms	no./100 mL	0	-	-	-	-	-	-	-	-	-

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 with an asterisk.

Table 6 Summary of Hydrochemistry Data from the new trial and production wells around Monaghan

Parameter	**Units**	**MAC Value (*GSI Threshold*[1])**	**TW1**	**PW1**			**TW2**	**TW3**	**PW3**	**TW4**	**PW4**
			Jan 97	18 Nov 97	14 Feb 01	13 Aug 01	Jan 97	Jan 97	11 Nov 97	Jan 97	11 Nov 97
Colour	Hazen	20	7	<5	-	-	2	6	<5	9	<5
Turbidity	N.T.U	10	**14.1**	2.7	-	-	2.3	8.6	5	**12.3**	**40**
pH		6-9	8.37	7.6	**5.72**	5.99	7.97	7.4	7.4	7.3	7.2
Conductivity	µS/cm	1500	591	570	684	629	691	505	525	530	605
Hardness	$CaCO_3$ mg/L		312	328	313.8	291.9	367	287	290	285	336
Alkalinity	$CaCO_3$ mg/L		332	306	314	296	324	-	280	-	320
Sulphate	SO_4 mg/L	250	18	24	44.6	22.5	80	11	14	6	21
Chloride	Cl mg/L	250 (*30*)	14.7	18	14.4	15.2	26.5	13.3	16	13.9	17
Nitrate	NO_3 mg/L	50 (*25*)	0.74	<0.5	1.84	2.01	<0.22	0.8	<0.5	0.09	0.5
Nitrite	NO_2 mg/L	0.1	<0.007	<0.01	<0.1	<0.1	<0.007	0.076	<0.01	0.023	<0.01
Ammonium Total	NH_4 mg/L	0.3 (*0.15*)	0.129	-	0.071	<0.02	**0.36**	0.013	-	0.013	-
Copper	Cu mg/L	0.5	<0.001	<0.01	<0.005	<0.005	<0.001	<0.001	<0.01	<0.001	<0.01
Iron	Fe mg/L	0.2	**1.08**	**0.95**	**0.532**	**0.313**	0.196	**0.509**	**0.79**	**1.34**	**1.8**
Magnesium	Mg mg/L	50	23	25	22.3	21.7	22	18	22	18	12
Manganese	Mn mg/L	0.05	**0.06**	**0.06**	**0.064**	**0.056**	**0.25**	**0.097**	0.04	**0.153**	**0.14**
Aluminium	Al mg/L	0.2	0.007	<0.05	<0.02	<0.02	0.004	0.13	<0.05	0.008	0.43
Phosphorous	P205 mg/L	5	-	-	<0.25	<0.25	-	-	-	-	-
Fluoride	F mg/L	1.0	0.33	0.42	0.37	0.4	0.25	0.42	0.52	0.42	-
Sodium	Na mg/L	150	11	12	15.46	12.53	22	14	17	13	9.5
Potassium	K mg/L	12 (*4*)	1.3	0.3	1.6	1.6	1.9	1.3	1.3	1.6	1.2
K:Na Ratio	K:Na	(*0.3*)	0.118	0.108	0.1	0.13	0.09	0.09	0.076	0.12	0.13
Suspended Solids	mg/L	No Visible	-	-	-	-	-	-	-	-	-
Lead	Pb mg/L	0.05	<0.2	-	<0.02	<0.02	<0.02	<0.02	-	<0.02	-
Zinc	Zn mg/L	1.0	-	-	<0.001	0.011	0.190	0.0081	-	0.0034	-
Odour	Dilution No.	2/12 DegC	-	-	-	-	-	-	-	-	-
Total Coliforms	no./100 mL	0	Nil	Nil	Nil	Nil	Nil	Nil	-	Nil	Nil
Faecal Coliforms	no./100 mL	0	Nil	Nil	Nil	Nil	Nil	Nil	-	Nil	Nil
E. Coliforms	no./100 mL	0	Nil	Nil	-	-	Nil	Nil	-	Nil	Nil

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 with an asterisk.

Table 6, *continued* Summary of Hydrochemistry Data from the new trial and production wells around Monaghan

Parameter	Units	MAC Value (*GSI Threshold*[1])	TW5 Jan 97	PW5 11 Nov 97	TW6 Jan 97	PW6 19 Dec 97	TW7 Jan 97	PW7 11 Dec 97
Colour	Hazen	20	<2	<5	4	<5	7	<5
Turbidity	N.T.U	10	0.4	9.2	1.4	0.3	2.4	0.95
pH		6-9	7.2	7.4	8.37	7.5	8.08	7.4
Conductivity	µS/cm	1500	649	550	561	555	668	680
Hardness	$CaCO_3$ mg/L		324	303	274	261	347	373
Alkalinity	$CaCO_3$ mg/L		262	298	295	282	271	250
Sulphate	SO_4 mg/L	250	23	19	24	40	87	128
Chloride	Cl mg/L	250 (*30*)	15	15	14.9	13	16.7	18
Nitrate	NO_3 mg/L	50 (*25*)	<0.22	<0.5	0.7	<0.05	8.46	4.8
Nitrite	NO_2 mg/L	0.1	0.007	<0.01	0.007	<0.01	0.02	0.2
Ammonium Total	NH_4 mg/L	0.3 (*0.15*)	0.013	-	0.116	-	0.103	-
Copper	Cu mg/L	0.5	<0.1	<0.01	0.006	<0.01	<0.1	<0.01
Iron	Fe mg/L	0.2	**0.61**	**0.75**	0.034	0.04	0.188	0.13
Magnesium	Mg mg/L	50	25	22	20	33	25	27
Manganese	Mn mg/L	0.05	**0.282**	**0.19**	0.01	0.014	**0.068**	**0.07**
Aluminium	Al mg/L	0.2	0.036	<0.05	<0.004	<0.05	<0.05	<0.004
Phosphorous	P205 mg/L	5	-	-	-	-	-	-
Fluoride	F mg/L	1.0	0.5	0.47	0.57	0.8	0.21	0.21
Sodium	Na mg/L	150	16	15	20	28	14	14
Potassium	K mg/L	12 (*4*)	1.7	1.5	1.6	1.6	1.7	2
K:Na Ratio	K:Na	(*0.3*)	0.11	0.1	0.08	0.057	0.143	0.121
Suspended Solids	mg/L	No Visible	-	-	-	-	-	-
Lead	Pb mg/L	0.05	<0.002	-	<0.002	-	<0.002	-
Zinc	Zn mg/L	1.0	0.006	-	0.021	-	0.017	-
Odour	Dilution No.	2/12 DegC	-	-	-	-	-	-
Total Coliforms	no./100 mL	0	Nil	Nil	Nil	Nil	Nil	Nil
Faecal Coliforms	no./100 mL	0	Nil	Nil	Nil	Nil	Nil	Nil
E. Coliforms	no./100 mL	0	Nil	Nil	Nil	Nil	Nil	Nil

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 with an asterisk.

- Groundwater flow is primarily controlled by faults and fractures in the bedrock. The overall direction of groundwater flow is towards the Blackwater River. In the east, near PW7, groundwater probably does not discharge to the Blackwater River, but flows east towards the Cor River.
- Where groundwater discharge occurs through the base of the Blackwater River, it is hindered due to the moderate and low permeability subsoils. Because of this, groundwater can flow under the river when heads are low.

7.13 Numerical Model

In order to help define the extent of the Zone of Contribution (ZOC) and 100-day time of travel for the ten wells, numerical modelling using MODFLOW was carried out at the GSI. The numerical model is based on the conceptual model outlined above. A summary of the model, including the boundary and conditions, is presented below:

Configuration

- The model is split into three layers: an upper one representing the subsoil deposits, a thin layer representing a weathered rock layer and a lower layer representing the bedrock aquifer.
- The modelled boundaries are based on the conceptual model:
  - The southern boundary is defined by the relatively impermeable Lower Palaeozoic rocks and is considered a ‘no flow’ boundary.
  - The western boundary is defined by a groundwater divide, as shown in the NERDO report (AFF and GSI, 1981).
  - The north-western boundary is defined by two subcatchments of the Blackwater River, and are considered ‘no flow’ boundaries. The north-eastern boundary, also considered ‘no flow’ is the catchment divide for the Blackwater River. These boundaries were also modelled as fixed head boundaries, which gave a similar result. Where this boundary lies south of the Dartry Limestone, the geological contact is used as the no flow boundary.
  - The eastern boundary is partially defined by the no flow boundary associated with the Lower Palaeozoic rocks. It is also defined by the Cor River, which is assumed to have a constant head.
- The Blackwater River, which runs through the middle of the catchment, is included in the model as the main groundwater discharge zone. The river boundary is located in Layer 1, with a conductance derived from a permeability of 8.6 x 10^{-2} m/d; an assumed river width of 5 m; an additional 5 m either side of the Blackwater to allow for floodplain recharge to the river; with the dimensions of the river cells being determined by the grid spacing; and a variable depth to bedrock taken from depth to rock mapping. Conductance controls the ease with which groundwater can enter the river and estimated values rise to 86 m^2/d, with small cells will have smaller values, e.g. where there is high grid refinement near the pumping wells. Assigning the river to Layer 1 allows groundwater flow to pass under the river if heads are low.
- Groundwater is expected to flow towards the Blackwater River. However, in the east, near PW7, it is expected to flow east towards the Cor River.
- The subsoil (upper) layer is divided into different recharge and hydraulic conductivity zones, based on the permeability mapping carried out by the GSI. These values are summarised in Table 8.

Table 8 Summary of the Layer 1 parameters used in the numerical model

Area	Hydraulic Conductivity (m/s)		Recharge (mm/yr)
	Horizontal	Vertical	
Low Permeability Subsoils	5 x 10^{-8}	1 x 10^{-8}	27
Moderate Permeability Subsoils	5 x 10^{-7}	2.5 x 10^{-7}	163
Gravels	1 x 10^{-4}	1 x 10^{-4}	325
Rock outcrop	-	-	325

- The weathered bedrock layer (Layer 2) is given a thickness of three meters and an overall hydraulic conductivity of 1.0 x 10^{-4}m/s. This conductivity is taken as uniform over the modelled area.
- The aquifer (Layer 3) is divided into three different aquifer units, as outlined below. The transmissivities used for each unit are shown in Table 9.
  - 'Limestones', which represent the Ballysteen, Ballyshannon and Dartry limestones. With the exception of two wells (PW3 and PW5), the production wells lie in this aquifer unit.
  - 'Transitional shale', which represents the lower Bundoran Shale including the high permeability dolomite interbeds recorded in the borehole log for PW3. Wells PW3 and PW5 lie in this unit.
  - 'Bundoran Shale', which represents the shale-dominated portion of the Bundoran Shale. While this transmissivity and the transmissivity of the 'Transitional shale' are higher than would be expected, these higher values are used in the model as a mean of compensating for increased runoff in these areas relative to the 'Limestones' area.

Table 9 Summary of the Layer 2 parameters used in the numerical model

Area	Transmissivity (m^2/d)
Limestones	320
Transitional shale	150
Bundoran shale	35

Calibration

Pre-pumping water levels measured as part of the KTC/P.J. Tobin survey of domestic wells were used to calibrate the model. This consisted of running the model with only the Roosky wells pumping in order to simulate conditions prior to when the four week pumping test began. The values of transmissivity and recharge were varied within the acceptable ranges, outlined in Section 7.6.1, to meet the following conditions:

- Less than 10 m absolute error in the predicted heads and the pumping and observations wells
- Minimal recharge from the Blackwater River
- The predicted gradients in different areas of the model matched those measured from the hand-drawn water table map

Validation

Once the model was calibrated, it was validated against drawdowns measured during the 4-week pumping test at PW1, PW3 and PW5. Overall, the predicted drawdowns were similar to the measured drawdown at wells PW3 and PW5. For PW1, the predicted drawdown was off by about 5 m, which may be partly due to well losses and/or a localised low permeability zone around the well. A sensitivity analysis was also undertaken.

Prediction

Finally, conditions were modelled where all production wells were pumping at the increased planned abstraction rates outlined in Table 7. The results of this were valuable in helping to delineate the zone of contribution and the 100-day time of travel, as described in the following section.

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 pattern, as described in Section 7.6, and are presented on Map 3.

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.

8.7 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 an abstraction from long-term recharge. The ZOC is controlled primarily by a) the total discharge, b) the groundwater flow direction and gradient, c) the rock permeability and d) the recharge in the area. In general when delineating a ZOC, the maximum abstraction rate is increased to allow for possible future increases in abstraction and for expansion of the ZOC in dry periods (DELG et al., 1999). The planned combined abstraction rate for the Monaghan boreholes is 4545 m^3/d; the total planned abstraction with a 25% increase is 5733 m^3/d.

The ZOC for the Monaghan sources are delineated as follows:
1) An estimate of the area size is obtained by using the average recharge and the abstraction rates.
2) The shape of the area is then derived by both numerical modelling (using MODFLOW) and hydrogeological mapping techniques.

Estimated recharge values and discharge estimates are used to carry out a water balance. A water balance estimates the areal extent of the catchment providing the water to the source. The area constrained by hydrogeological mapping, and the area represented in the numerical model, is 84 km^2. The total ZOC area for all the public supply wells is 33 km^2. Numerical modelling indicates that wells PW1, 2, 3, 4, 5, 6, and 8 share a common ZOC with an area of approximately 28 km^2. The Roosky wells and PW7 have separate ZOCs with minimal overlapping at the upgradient end of PW7's ZOC. The areas for these ZOCs are 4.0 and 0.8 km^2, respectively.

Overall, the shape and boundaries of the ZOCs were determined using numerical modelling. These boundaries were amended to take account of uncertainties and elements of our conceptual understanding that could not be readily included in the numerical model. The ZOCs are shown in Maps1-3 and the boundaries are described below:

Roosky Wells

The northern and eastern boundaries are obtained from the numerical model. The southern boundary is based on the geological contact with the Lower Palaeozoic rocks. An additional 30 m buffer south of the contact is included to account for any groundwater that may come from the Lower Palaeozoic rocks, and as a precautionary measure.

Well PW7

The ZOC produced by the numerical model was taken as the starting point. To account for uncertainties with the groundwater flow direction, the modelled direction was varied by ±10° and new boundaries were drawn.

Wells PW1-PW6, PW8

These wells have one combined ZOC. The southern and western boundaries are taken from the numerical model. As the western boundary was both difficult to conceptualise and model, there is some uncertainty with this boundary. The eastern boundary is influenced by the numerical model, but is based on a topographic boundary, east of the boundary given by the numerical model. Therefore it is more conservative than the numerical model, but is fits our conceptualisation of groundwater flow in this area. The northern boundary is a topographic divide in the Bundoran Shale. While it is defensible to include the area of lower permeability (the upper part of the unit) in the ZOC, it is probable that much of the effective rainfall (and potential contaminants) will flow away as surface water rather than groundwater. There is significant uncertainty with this boundary in the Ballinode area, where there is no clear hydrogeological basis for delineating the boundary.

The total area of this ZOC (28 km^2) is over 3 times larger than is required according to the water balance calculations, and is therefore conservative. However, it is not feasible to refine this area further with the available hydrogeological information. In particular there are uncertainties with the northern boundary of the ZOC and recharge/runoff conditions. It is probable that in Winter the ZOC is considerably less than 28 km^2.

8.8 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. Estimations of the extent of this area cannot be made by hydrogeological mapping and conceptualisation methods alone. By using the aquifer parameters for permeability and hydraulic gradient, 100-day ToT estimations are made.

Analysis of the pumping tests results in average permeabilities of 3 m d^{-1} for the limestones and 0.6 m d^{-1} for the 'transitional zone'. The porosity of the fissured rocks is assumed to be 0.02, and the gradient ranges from 0.002 – 0.005. The 100 day times of travel were calculated within the numerical model, and take into account expected pumping levels (and associated higher gradients near the pumping wells). The modelled results were checked by comparison with the uniform flow equation and the WHPA numerical model.The SI zones are presented on Map 3.

9: Vulnerability

The distribution of interpreted groundwater vulnerability in the ZOC is presented on Map 2. The subsoils in the ZOCs range from low to high permeability, and are generally 3 m to >10 m thick, as described in Section 6.3.4. Vulnerability categories in the ZOCs are predominantly Moderate and Low, with smaller areas of High and Extreme.

9.7 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 3. All eight groundwater protection zones are present around the Monaghan public supply wells as shown below in Table 10.

Table 10: Matrix of Source Protection Zones for the Monaghan 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

9.8 Potential Pollution Sources

The lands around the wells are largely grassland-dominated and are primarily used for grazing. Agricultural activities and the few domiciles in the ZOC are the principal hazards to the new supply wells. Near the Roosky wells, businesses and activities associated with Monaghan town are also potential sources of pollution. Overall, the main potential sources of pollution within the ZOCs are landspreading of organic fertilisers, 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 Monaghan are excellent yielding wells, which are located in a regionally important fissured limestone aquifer (**Rf**).

Vulnerability in the ZOC is primarily Moderate and Low, with small areas of High and Extreme.

The runoff from the roads, houses, farms and landspreading are possible sources of pollution to the water quality in the ten 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 hydrogeological complexity of the area, there may be uncertainty regarding some of the boundaries.

Overall, our recommendations are as follows:
1. Regular 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 on a regular basis at both boreholes.
3. Particular care should be taken when assessing the location of any activities or developments that might cause contamination at the borehole.
4. The potential hazards in the ZOC should be located, and a risk assessment of each hazard is recommended.

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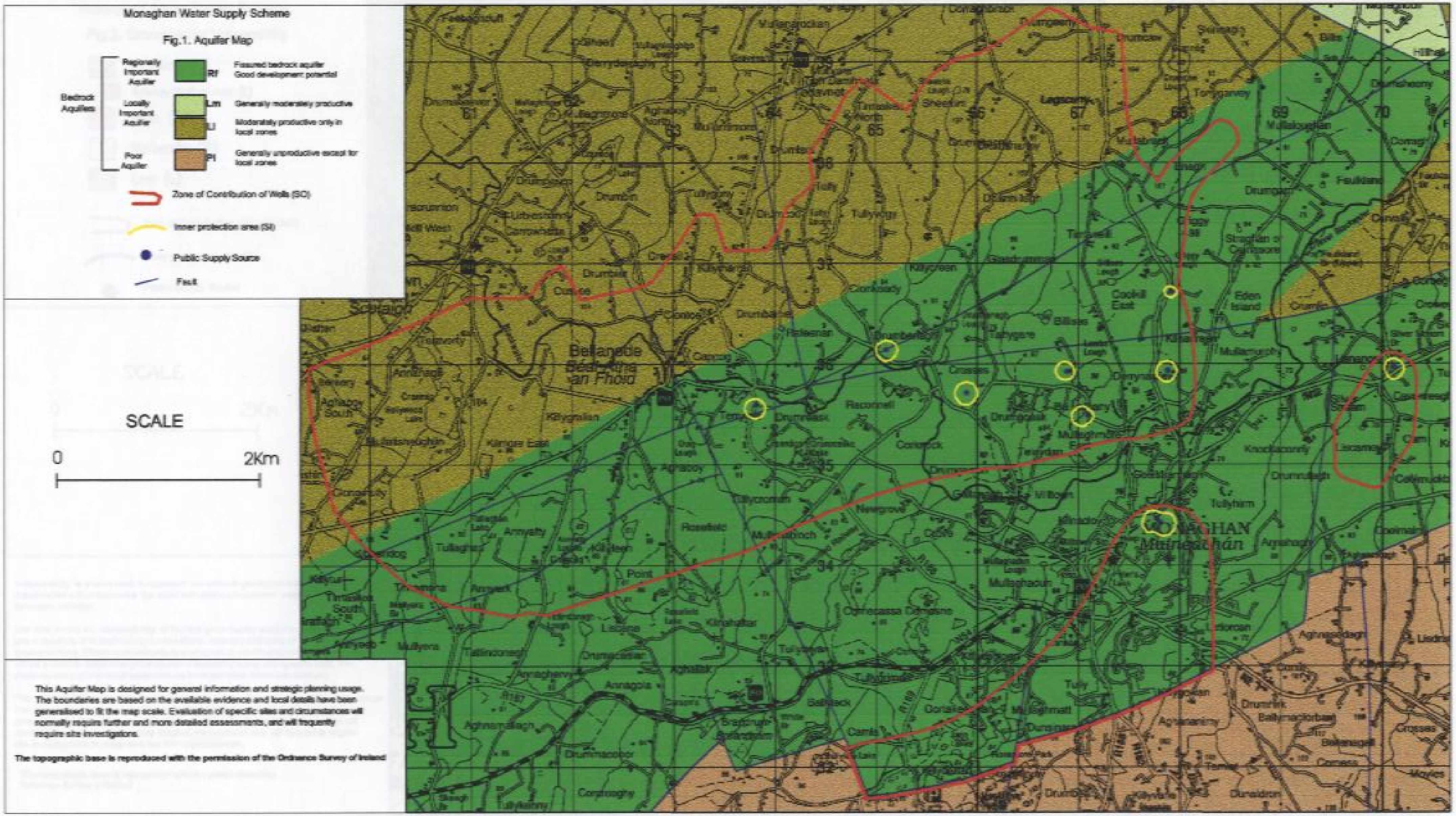
Monaghan Water Supply Scheme
Fig.1. Aquifer Map
Bedrock Aquifers
Regionally Important Aquifer
Rf Fissured bedrock aquifer Good development potential
Locally Important Aquifer
Lm Generally moderately productive
Ll Moderately productive only in local zones
Poor Aquifer
Pl Generally unproductive except for local zones
Zone of Contribution of Wells (SO)
Inner protection area (SI)
Public Supply Source
Fault
SCALE
0
2Km
This Aquifer Map is designed for general information and strategic planning usage. The boundaries are based on the available evidence and local details have been generalised to fit the map scale. Evaluation of specific sites and circumstances will normally require further and more detailed assessments, and will frequently require site investigations.
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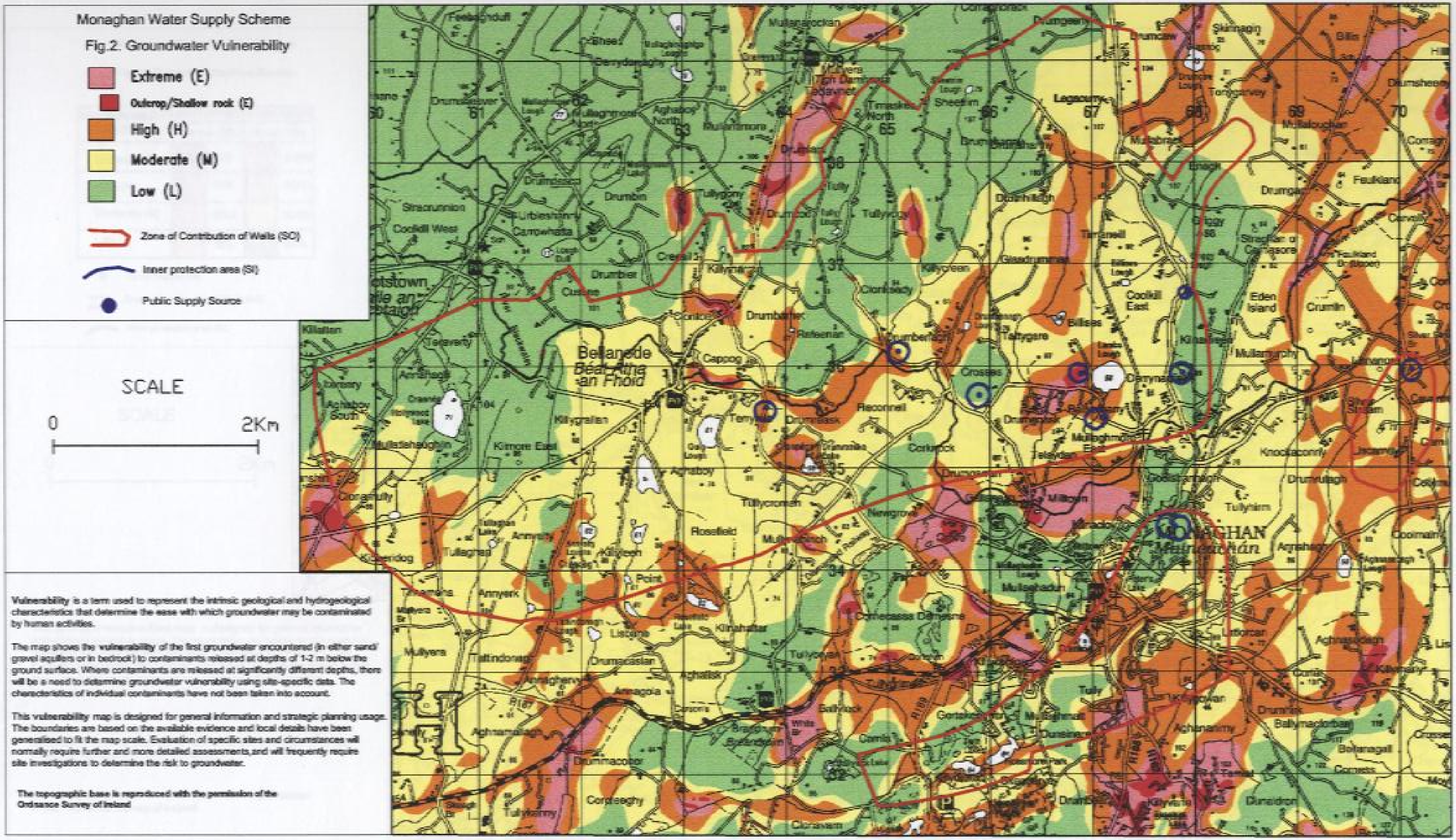
Bellanode
Béal Átha an Fhóid
MONAGHAN
Muineachán



Vulnerability is a term used to represent the intrinsic geological and hydrogeological characteristics that determine the ease with which groundwater may be contaminated by human activities.

The map shows the **vulnerability** of the first groundwater encountered (in either sand/gravel aquifers or in bedrock) to contaminants released at depths of 1-2 m below the ground surface. Where contaminants are released at significantly different depths, there will be a need to determine groundwater vulnerability using site-specific data. The characteristics of individual contaminants have not been taken into account.

This **vulnerability** map is designed for general information and strategic planning usage. The boundaries are based on the available evidence and local details have been generalised to fit the map scale. Evaluation of specific sites and circumstances will normally require further and more detailed assessments,and will frequently require site investigations to determine the risk to groundwater.

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Monaghan Water Supply Scheme

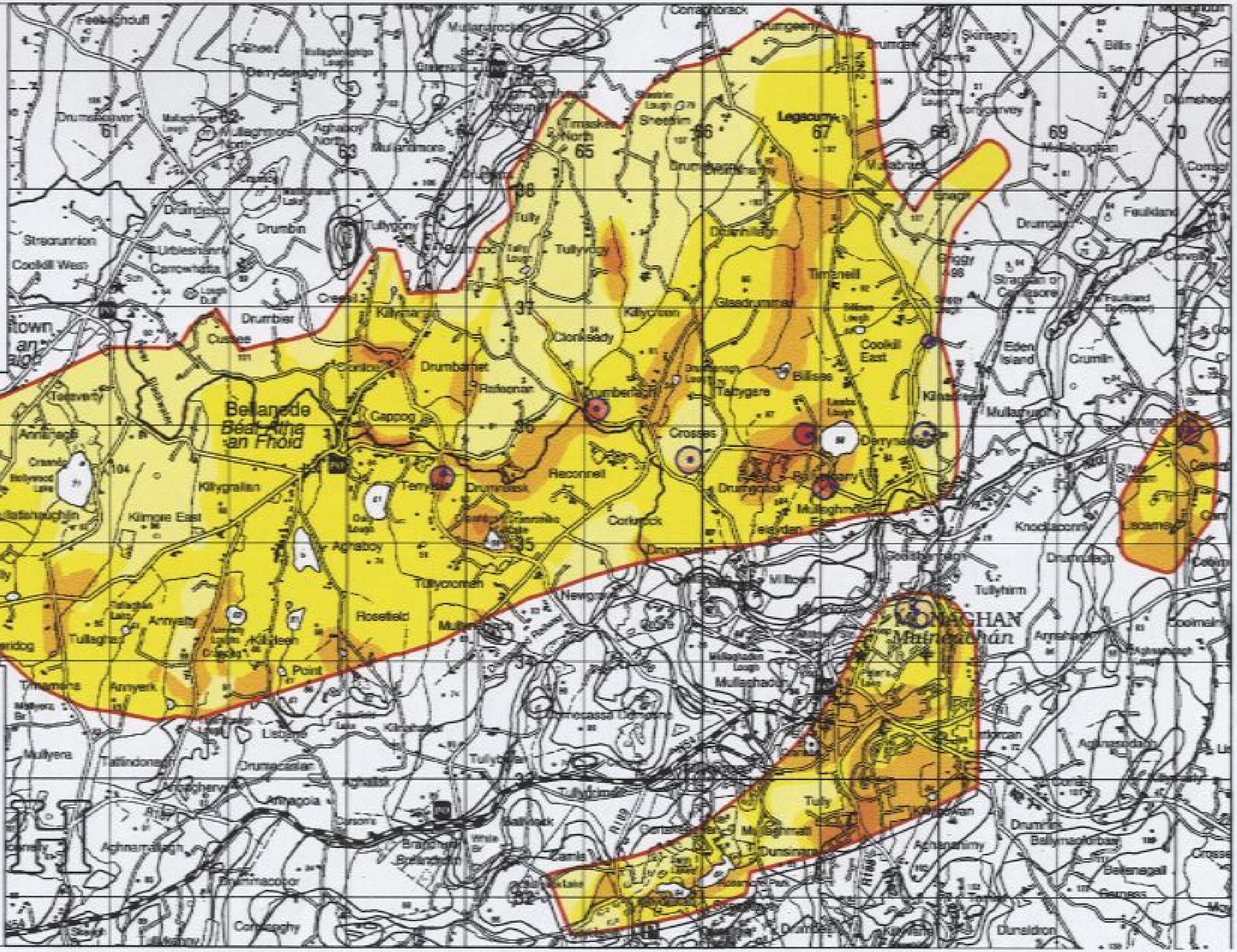
Fig. 3. Source Protection Zones

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

- Public Supply Well
- Zone of Contribution of Wells (SO)
- Inner protection area (SI)

SCALE

0 — 2Km



This **Source Protection Zone map** is designed for general information and strategic planning usage. The boundaries are based on the available evidence and local details have been generalised to fit the map scale. Evaluation of specific sites and circumstances will normally require further and more detailed assessments and will frequently require site investigations to determine the risk to groundwater.

The map is intended for use in conjunction with groundwater protection responses for potentially polluting activities, which lists the degree of acceptability of these activities in each zone and describes the control measures necessary to prevent pollution.

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