INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS (IRISH BRANCH)

2010 ANNUAL FIELD TRIP

'IF YOU WANT TO GO EAST DON'T GO WEST'

WELCOME ALL TO THIS YEARS IAH FIELDTRIP

This year be finding out about those shallow sand and gravel aquifers with their lovely 'uncomplicated' intergranular flow, although I am sure we will hear that they have their own quirks. Following that we will find out about the legacy of our past in terms of mining and how such sites can have a long-term influence on the environment. A brief visit will be made to a quarry in Ordovician volcanics where we can get back into the issues of fracture flow and quarry water management.

Following our overnight in Waterford, on Sunday we will be visiting some great coastal sites to consider groundwater vulnerability issues and also return to the legacy of the past and how that can be a positive thing to help engage both locals and tourists in appreciating the fantastic story of the history of the earth told in the rocks.

<u>Acknowledgements</u>

Thanks to all our field guides and their efforts in contributing to this document and taking the time to show us the sites. Thanks also to Coran and Robbie for help with organisation and site selection, Orla for helping out with finance and thanks to McLorinan Consulting for their support in producing this document.

Cover Image – Avoca Mine: Courtesy GSI.

Image: Wexford Ordovician Volcanics Quarry: Courtesy G Baker, WYG

Arklow PWS – Woodenbridge Well Field

G Baker - WYG

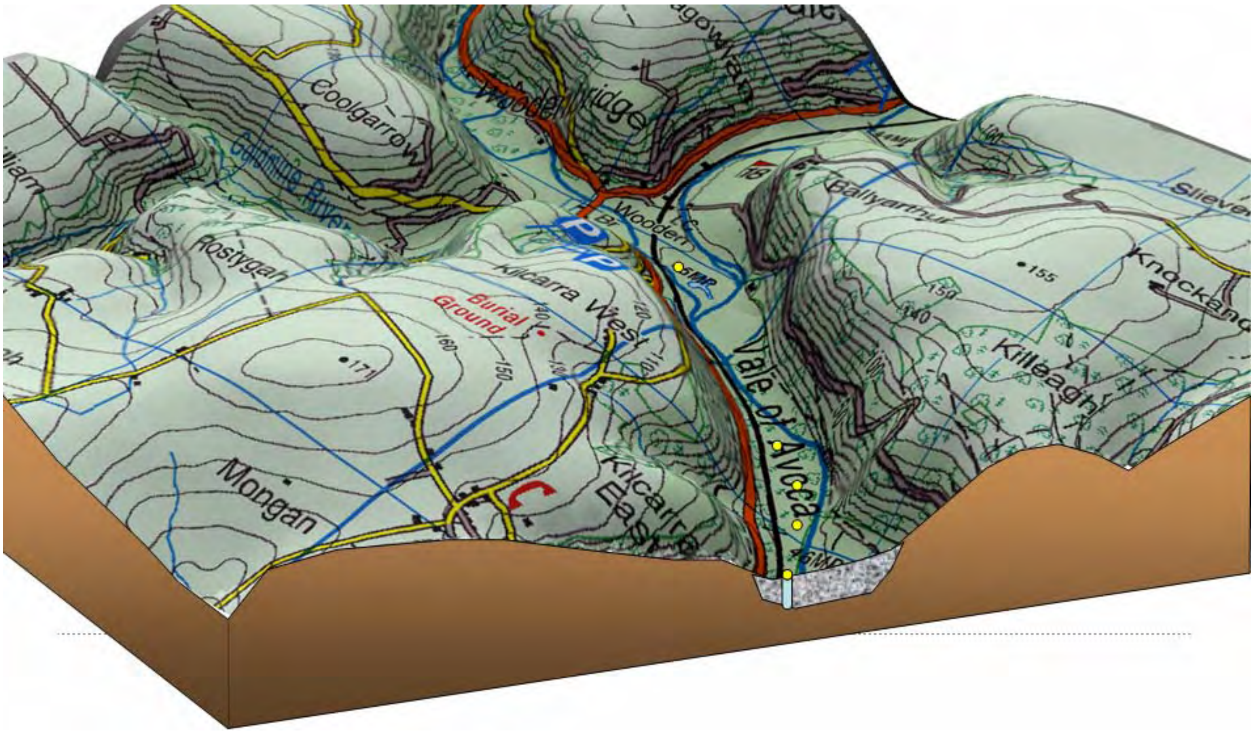
Background

WYG (formerly KT Cullen and Company) has been involved in the Arklow Water Supply Scheme as consultant hydrogeologists since 1993. As part of the water supply developed for the Arklow Water Supply Scheme, trial wells were drilled at the Woodenbridge Well Field between 2004 and 2005. Initial pumping tests, including 72 hour tests, were undertaken on the trial wells at this time. Production wells were drilled at Woodenbridge in 2008. Individual 72hr step tests was completed on all wells between 2008 and 2009. A simultaneous 10 day yield test was completed on wells PW13 – PW16 between 2008 and 2009.

Following an assessment of the pumping test results it was considered highly likely that there may be a significant contribution from the River Avoca to the wells. A report on the potential impact on the surface water bodies adjacent to the wells was completed by WYG in 2005 (WYG 2005). This report concluded that the abstractions would have no impact on the Rivers Avoca or Aughrim as the abstractions represent only a small percentage of the dry weather flows in both rivers.

The River Avoca receives acid mine discharge from the historic mines at Avoca, which is upstream of the Woodenbridge Well Field. As a consequence of the mine water discharges, the Environmental Protection Agency has categorised the Avoca River as having very poor water quality. There is therefore a risk that these elevated metal concentrations in the River could result in poor water quality at the wells.

An initial hydrogeological model was completed by WYG to determine the travel time from the river to the wells during pumping. The results of the model indicated that the proportion of river water contribution to the wells would increase over time with pumping until the system stabilised. The modelling suggested the time taken to arrive at this stabilisation could be between 45 days and 100 days. The model also indicates that once stabilisation occurred, the river water contribution to the wells would comprise 75% of the total water abstracted.



This closely matches the recharge estimates for the aquifer. The figure above clearly shows how the wells are located within a small limited topographic catchment. So while the aquifer material the wells are penetration is highly permeable the aquifer is of limited extent. As a result this the cone of depression extends towards the river and causes the river water to flow towards the wells. The total meteoric recharge available from the up-gradient area to the wells indicates there is only 25% of the required yield available from this source of recharge.

The supply can therefore be considered a Riverbank Filtration scheme. Such schemes are widely and deliberately exploited throughout Europe and the US. A selection of such supplies is shown in the Table below.

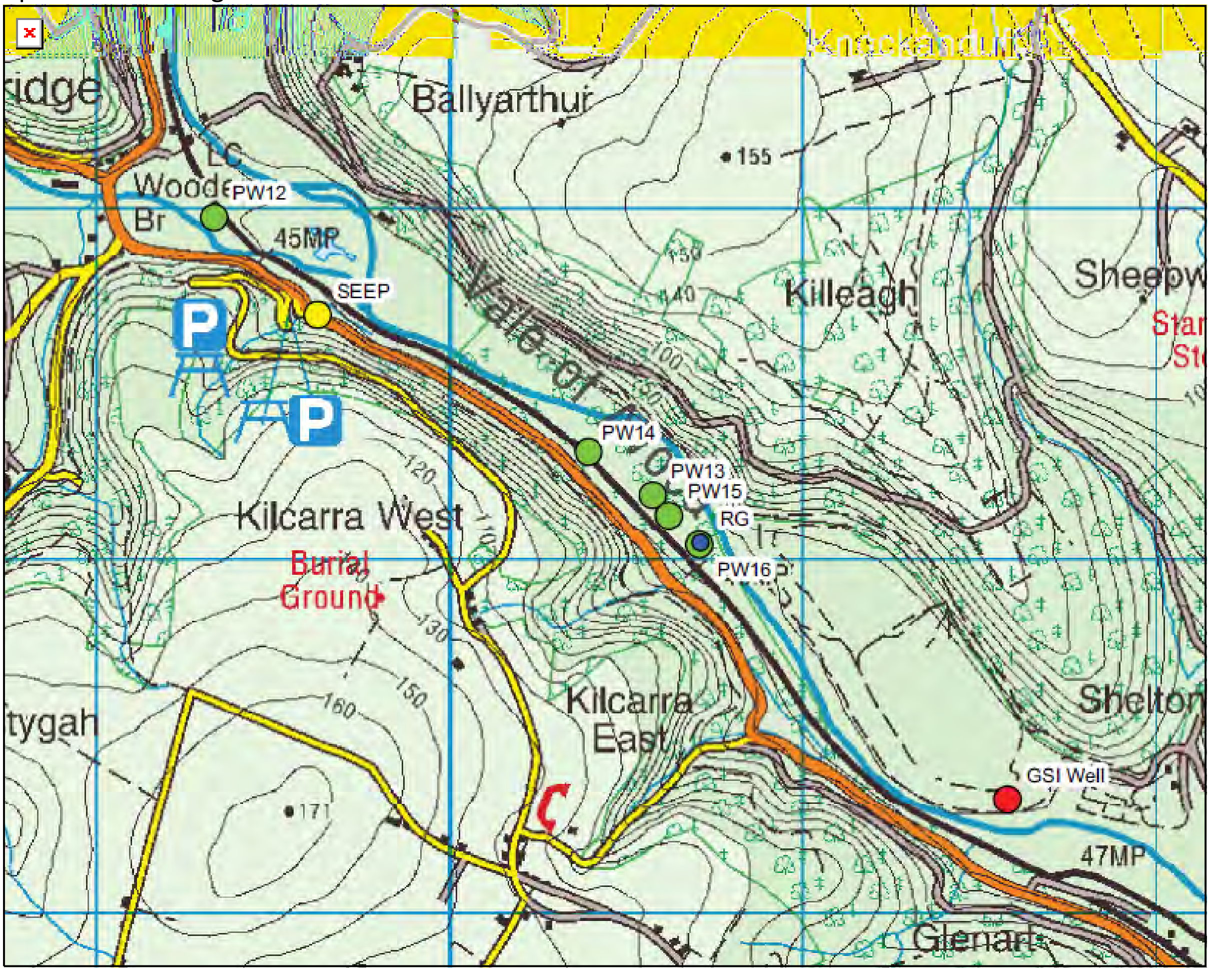
Table 1 - Riverbank Filtration Systems in Europe & USA

Location	River	Yield (m^3/d)
Netherlands, 26 Well Fields	Numerous including: Rhine & Meuse & abstraction from polders	29,200,000 7% of national Supply
Dusseldorf, Germany	Rhine	100,000 (Grind Well Field) 22,000 (Flehe Well Field) 19,000 (Staad Well Field)
Torgau, Germany	Elbe	150,076
Mockritz, Germany	Elbe	108,864
Cincinnati, Ohio, USA	Great Miami	150,000
Columbus, Ohio , USA	Scioto/ Bigwalnut	150,000
Lincon, Nebraska, USA	Platte	130,000
Kansas City, Kansas, USA	Missouri	150,000
Boardman, Oregon, USA	Columbia	90,000
Louisville, Kentucky, USA	Ohio	75,000

Based on these assessments it was concluded that the 10 day test completed on the wells was insufficient to allow the systems to stabilise. Water quality results from the 10 day test would not reflect water quality with the full contribution of the river under operational circumstances of the Well Field. It was therefore decided to conduct an extended pumping test of 90 days on the wells to allow the system to stabilise and flow paths from the river to the wells to become established.

90 Day Pumping Test Plan

The extended pumping test on the production wells was scheduled for 90 days. It was planned to pump PW13, PW14, PW15 and PW16 at the maximum pumping rate for the entirety of that duration. The locations of the wells are shown on the Figure below. At the time of commencing the extended pumping test PW12 was under construction and it was not possible to include the well at the start of the test as works were under way at the site. PW12 was sampled whenever it was operational during the test.



The start date of the test was Wednesday 19th of August 2009. All water levels were measured before pumping started. The first water sample water was collected shortly after the pumps were operational.

Sampling was completed weekly for the duration the test. Samples were also collected from a spring/seep which emanates from the road cutting adjacent the site. This was used to perform mass balance analyses between the hydrochemistry of the bedrock aquifer, the river and the gravels. The pumps were shut off on Tuesday the 17th of November 2009. A water sample was collected just before the pumps were shut off. Water level and conductivity measurements on site were continued for a further week after the cessation of pumping to monitor the recovery of the wells.

Monitoring Well Installation

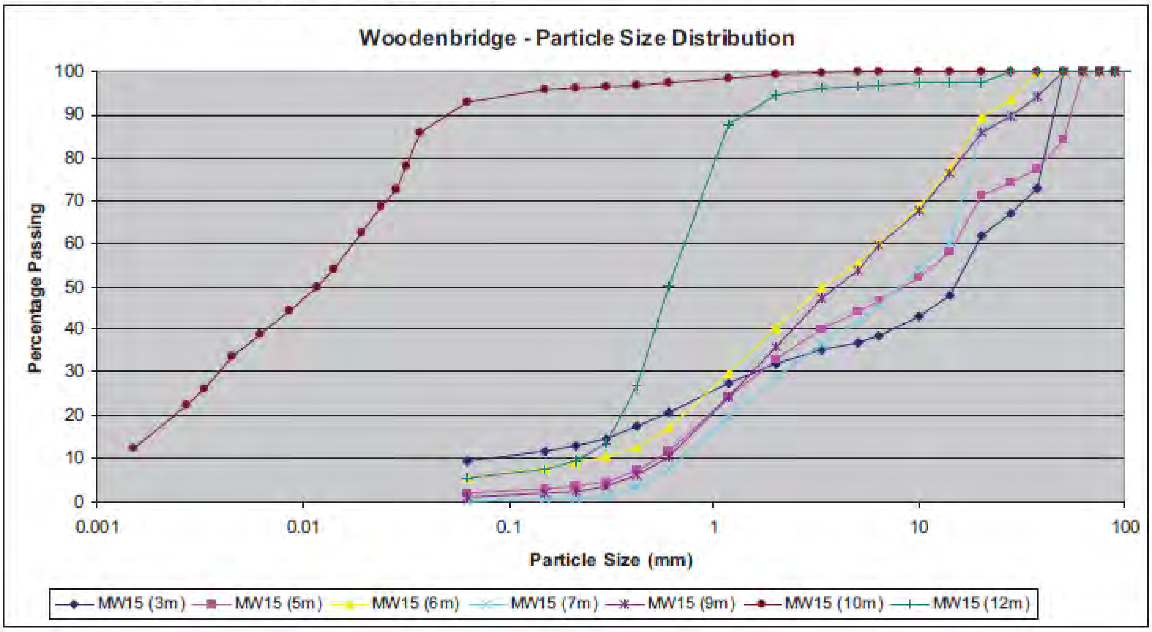
It was decided to install monitoring wells between the production wells and the River Avoca. The purpose of installing the monitoring wells was to monitor the water level between the production wells and the River Avoca. The monitoring wells would give a fuller appreciation of the surface water - groundwater interactions at the site.

The monitoring wells were drilled using the Shell & Auger technique. The drilling allowed for retrieval of representative samples from the wells. Sediment samples were collected at 1m intervals during the drilling. These sediments were examined by a WYG hydrogeologist. A selection of subsoils from PW15 were analysed using the Particle Size Distribution (PSD) methodology to further characterise the nature of the subsoil. The results of the PSD are presented below and summarised in the Table below

The results of the drilling and the particle size distribution show that the general trend is for an upper layer of c. 2m of poorly sorted gravely boulder clay/organic soil. This is underlain by well sorted sands and gravels with occasional thin layers of very fine sediments. The PSD results are summarised below and show the Sand and Gravel materials are quite consistent with around twice as much gravel than sand and minor amount of fines. The occasional layers of densely compacted well fines are predominantly silts but with a high proportion of clays (17%). There are also layers consisting almost entirely of cobbles and boulders however it was not possible to include these in the PSD analysis due to the sediment size.

Sample Depth (m)	Gravels (%)	Sand (%)	Fines (%)	Moisture Content (%)
3.0	68	23	9	7.7
5.0	67	31	2	6.4
6.0	60	35	5	8.1
7.0	71	29	0	4.9
9.0	64	35	1	7.1
10.0	1	6	Silt – 76% Clay 17%	26
12.0	5	89	6	18

Chart 15 - MW15 Particle Size Distribution



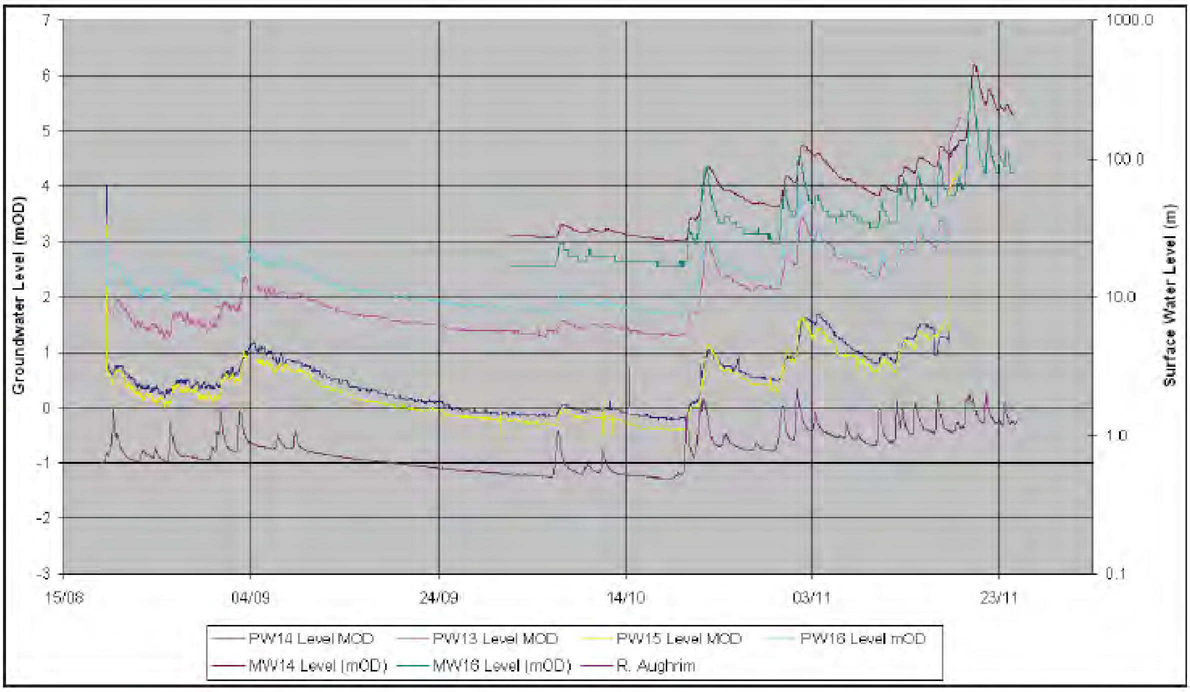
Pumping Test Results

The test was completed largely as planned. The pumping rates employed and details of wells and pumps are outlined below. The water levels measured through the wells during the test are presented on the chart below.

The water levels are seen to drop rapidly in the first hour of the test and then respond to the river water levels. A long recession can be seen during the middle of the test with coincides with a dry period. Individual rainfall events can be seen in the hydrograph of the wells and the production wells. There is a noticeable time lag and difference in the flashiness of the various hydrographs based on the proximity to the river.

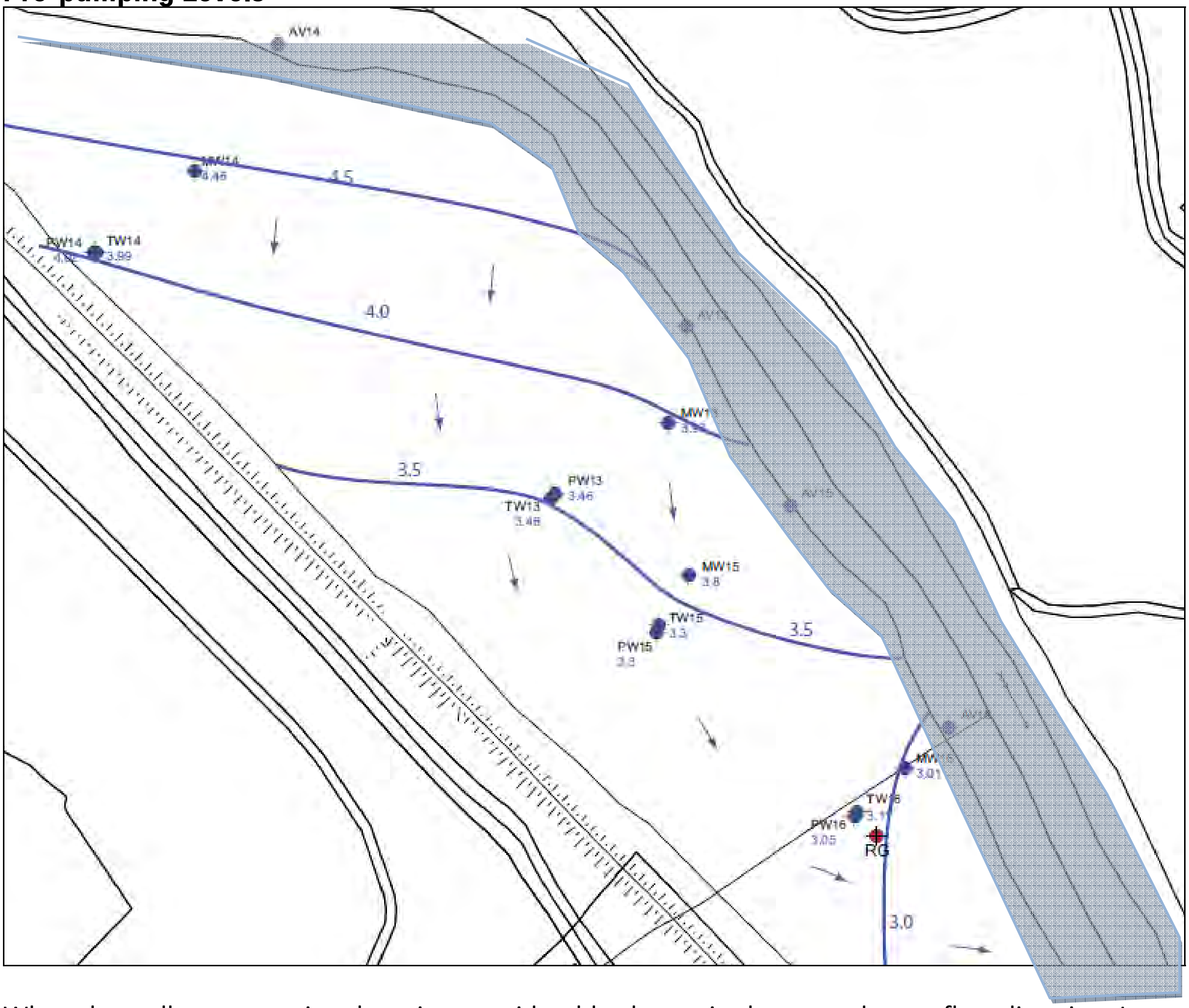
Table 2 - Production Well Details

Location	Well Depth (m)	Finished Internal Diameter (mm)	Static Water level (mbtoc) (19/08/2009)	Base of Pump (mbgl)	Screened Section (mbgl)	Pumping Rate (m3/d)
PW12	12.5	250	2.0	12.0	5 - 12	1,728
PW13	20	280	4.45	19.4	10 - 19	1,920
PW14	19.3	280	3.1	18.64	10 - 19	1,920
PW15	20.6	250	3.42	19.24	10 - 19	1,920
PW16	20	168	3.1	19.53	10 - 19	480



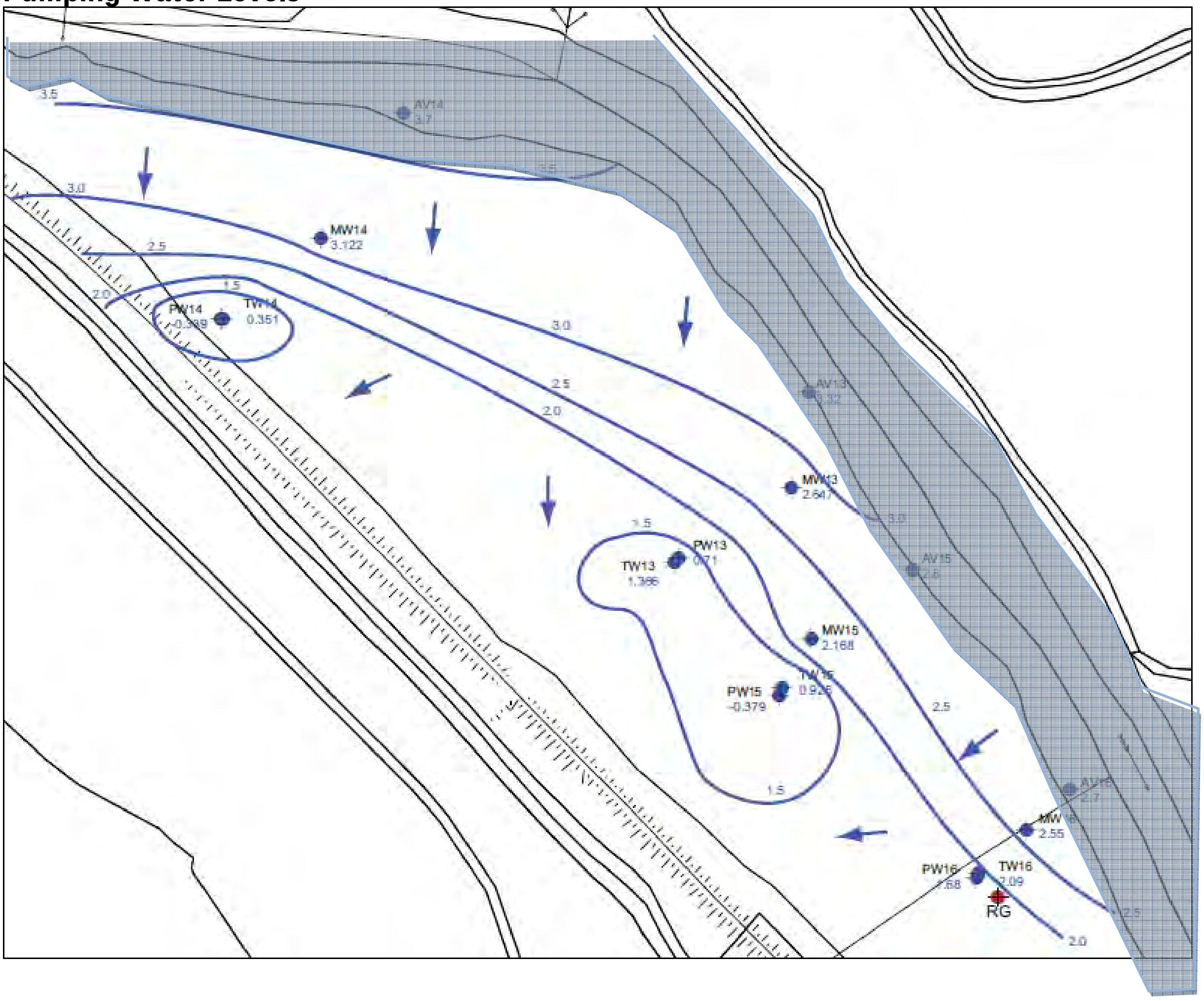
Water levels measured at the wells are presented in the figure below. The wells have been surveyed in to ordnance datum and the pumping and pre-pumping groundwater contours are shown on the figures below. These show that prior to pumping there is flow into the gravel from the river on up-gradient of the well field. Water then discharges from the aquifer back into the river down gradient of the well field. This is a clear indication of the groundwater-surface water interactions occurring under the undisturbed conditions.

Pre-pumping Levels



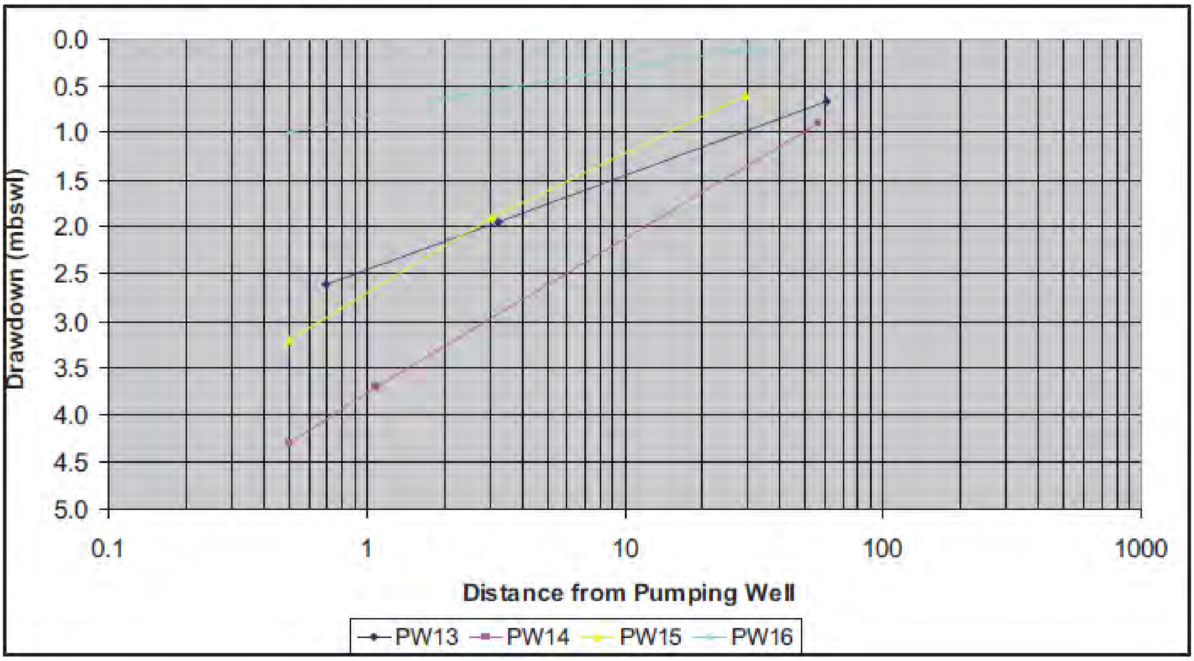
When the wells are pumping there is a considerable change in the groundwater flow direction. It can be seen that a cone of depression extends from the wells towards the river. As a result river water is drawn into the aquifer towards the wells. There is direction contribution of river water to the wells.

Pumping Water Levels

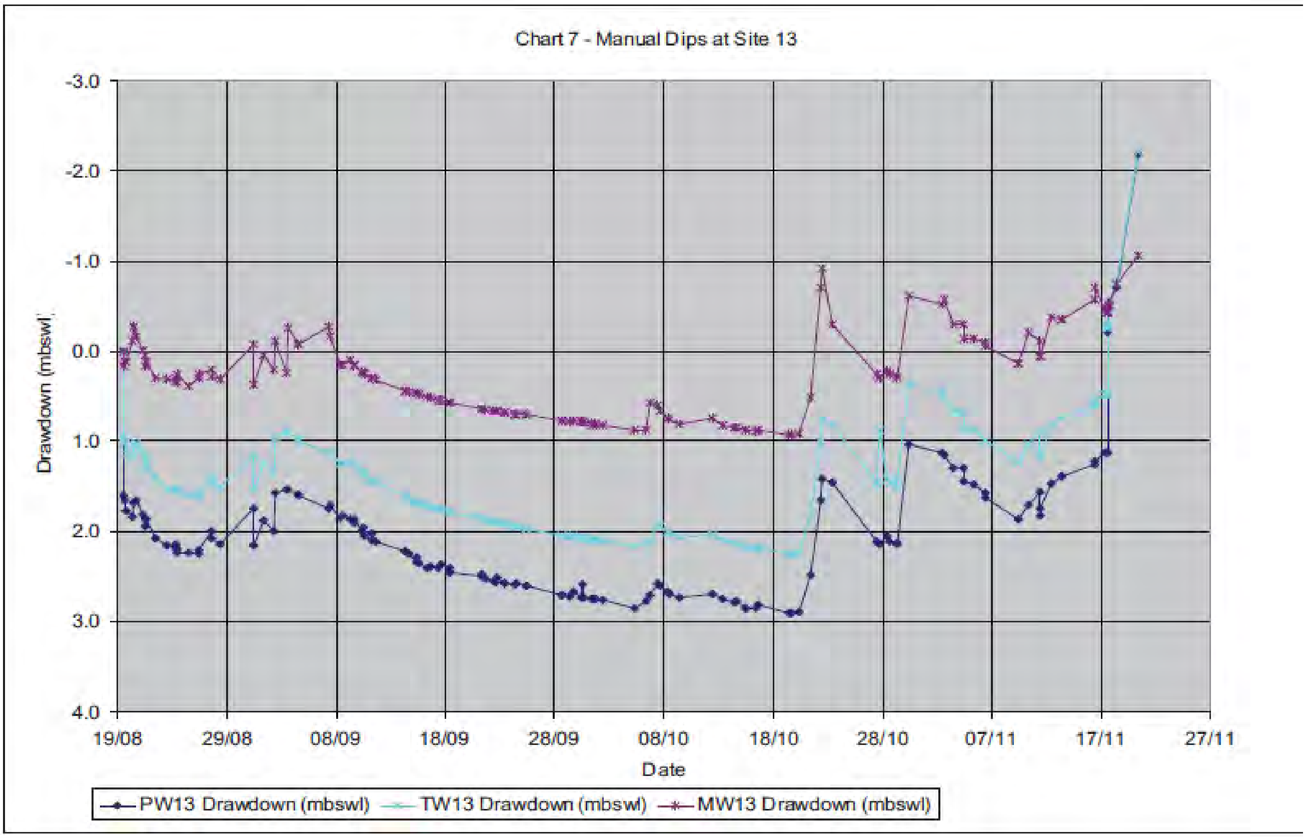


The levels in the production wells, trial wells (which are within 2m of the production wells) the monitoring wells and the river levels can all be plotted in relation to their distance from the pumping well. This produces a clear logarithmic relationship between distance from the wells and drawdown as shown on the chart below.

Chart 16 - PW13-PW16 Distance-Drawdown Relationship



The water levels are shown form a transect through the aquifer over time. The chart below shows the levels for PW13, TW13 (c. 2m from PW13), MW13 (halfway between the production well and the river). The chart below shows the greatest drawdown in the production well with less in the trial well and less again in the monitoring well, however the same pattern is clear. The pattern in the water levels is defined by the river level rather than the pumping regime, which was kept constant throughout the test.



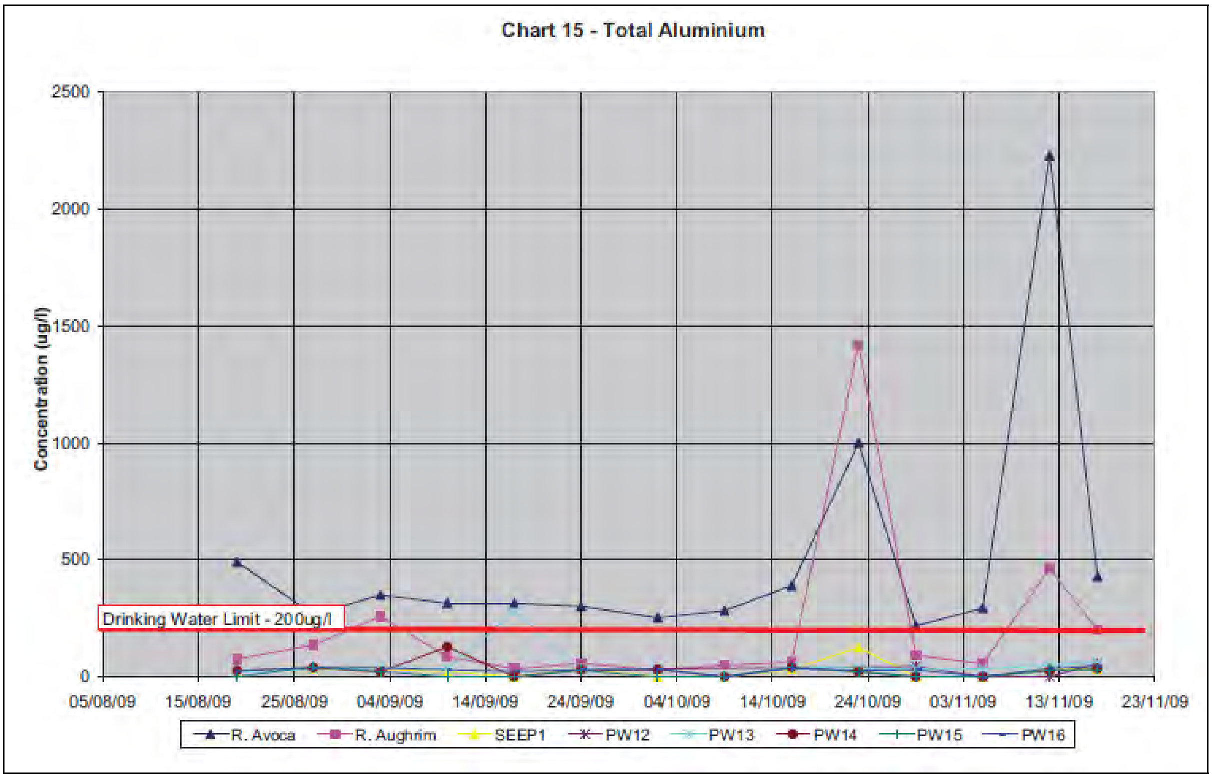
The test was successful in showing no reduction in the Production Well productivity during the course of the test. Riverbank filtration systems can often suffer from reduced yield due to entrainment of fines into the riverbed which result in clogging. This clogging reduces the hydraulic conductivity of the riverbed and the specific capacity of the wells subsequently decreases.

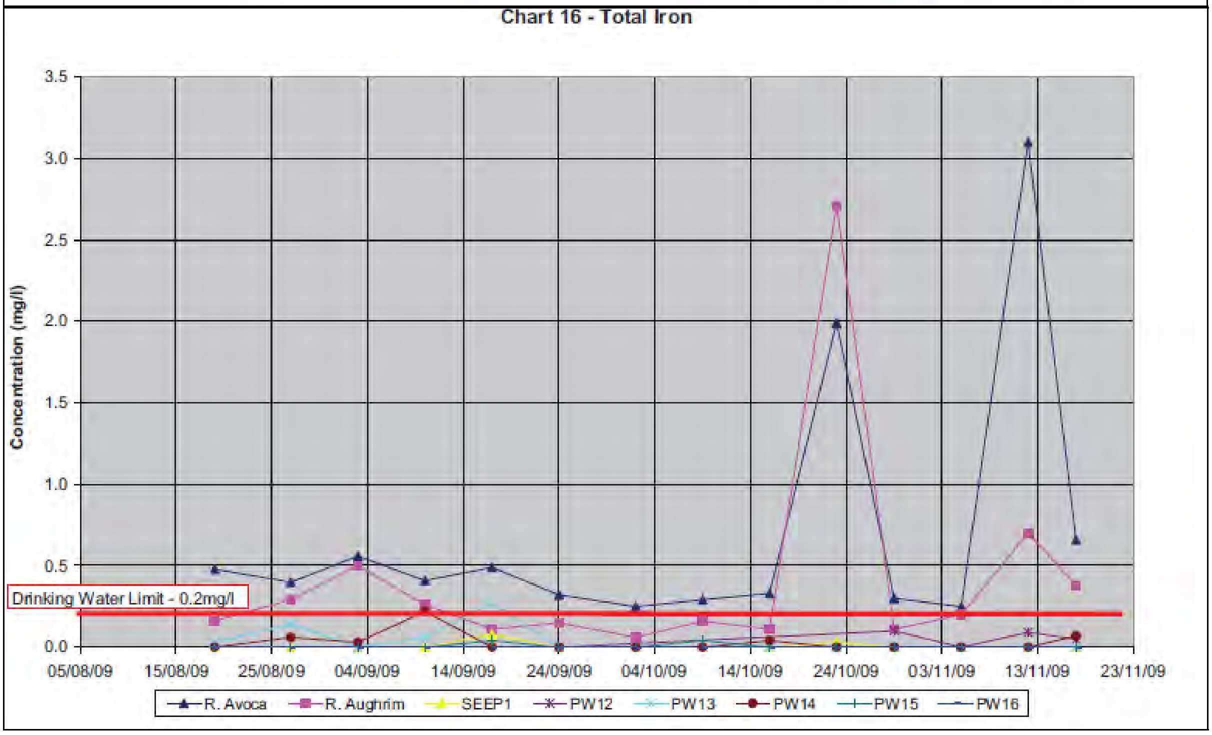
Water Quality

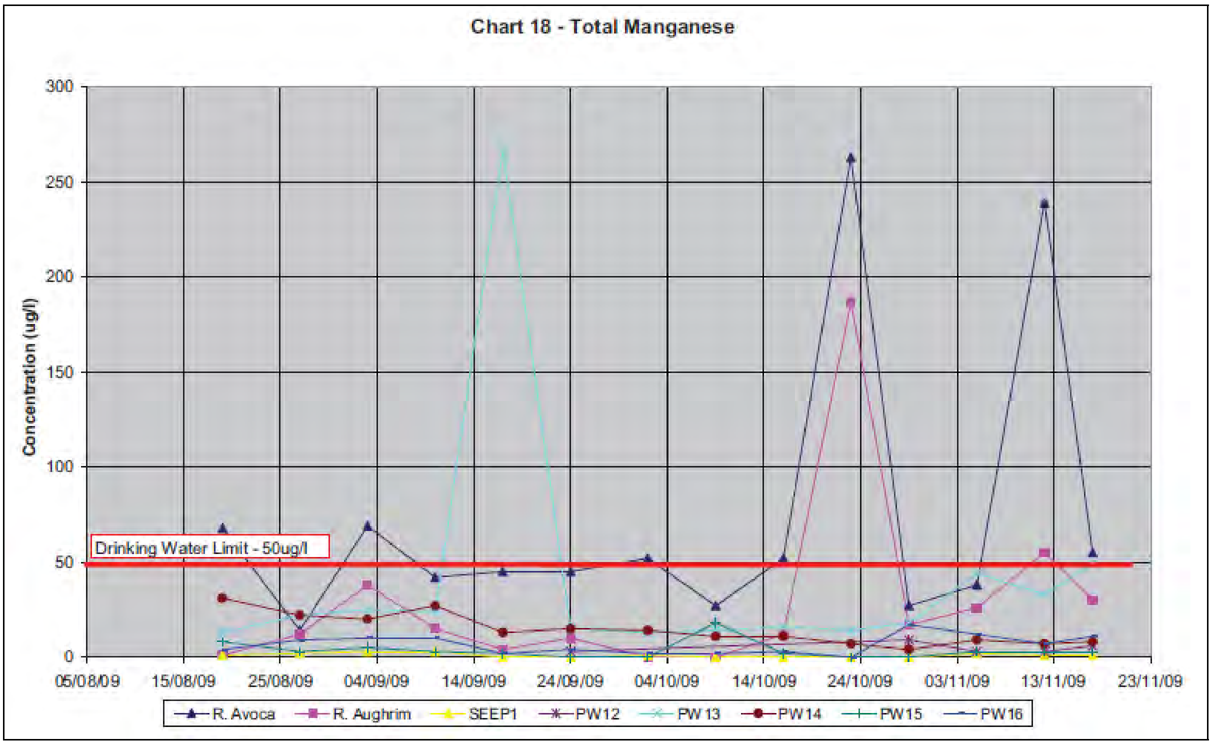
The other aim of the test was to determine if elevated metal levels in the R. Avoca would make their way to the Production Wells during operation. Riverbank Filtration Systems function was natural filtering systems and as a result the water quality is generally very good. The production well water was completely free from microbial contamination during the extent of the test despite very high level found in the river.

The key metal of concern was the elevated aluminium in the R. Avoca, which was above the drinking water limit. The chart below shows the Aluminium concentrations measured at all locations during the pumping test. This shows that Aluminium in the Avoca was consistently above the drinking water limits where as the concentrations in the wells were consistently below the drinking water limit. One erroneous elevated value was detected for PW13 however this was considered to be an anomaly.
The charts for Iron and Manganese, also elevated in the Avoca, are also presented below. These also show high levels in the R. Avoca but low levels in the production wells. The charts for all the metals show higher concentrations during flood events. This is thought to be linked to additional discharge from the mine adits following rainfall events.

Manganese level in PW13 began to rise during the last 4 weeks of the test. PW13 was the most productive and highest transmissivity well. This could be an indication of the development of a plume from the river towards the wells. It could be a sign that the Sand & Gravel between PW13 and the river had absorbed all the manganese possible with progressive amounts flowing towards the well. It is interesting that the same trend was not seen in the Aluminium or Iron concentrations.

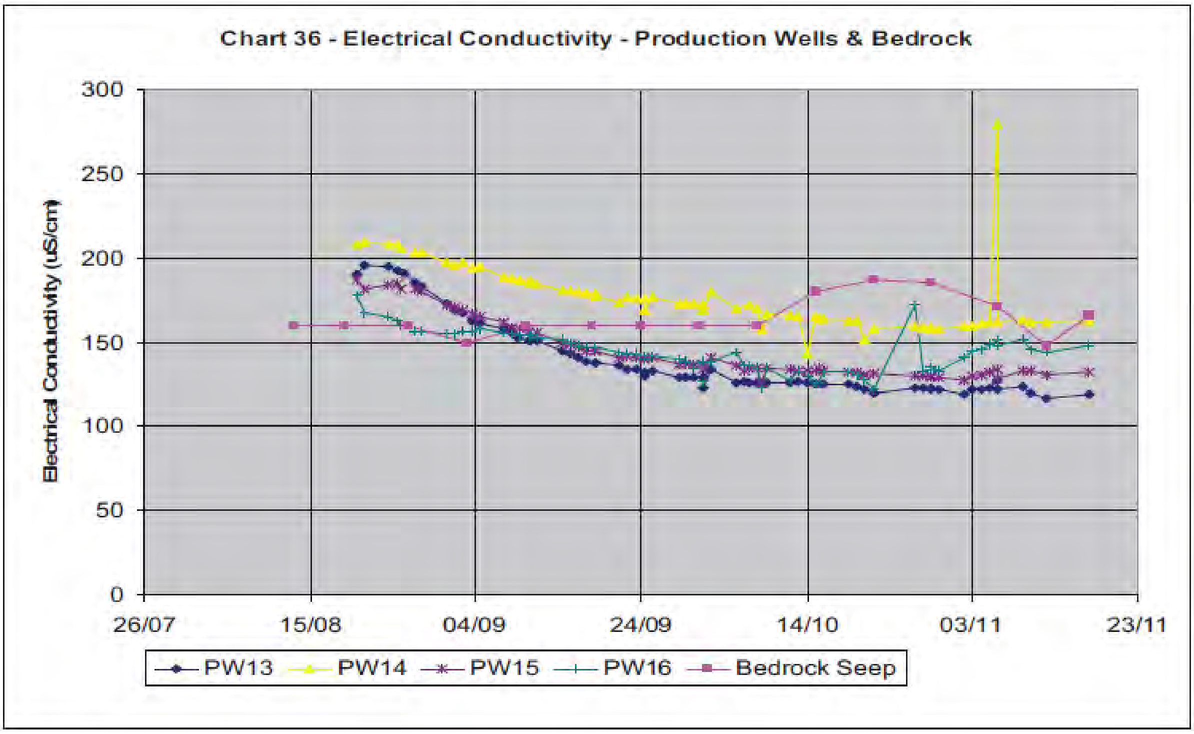






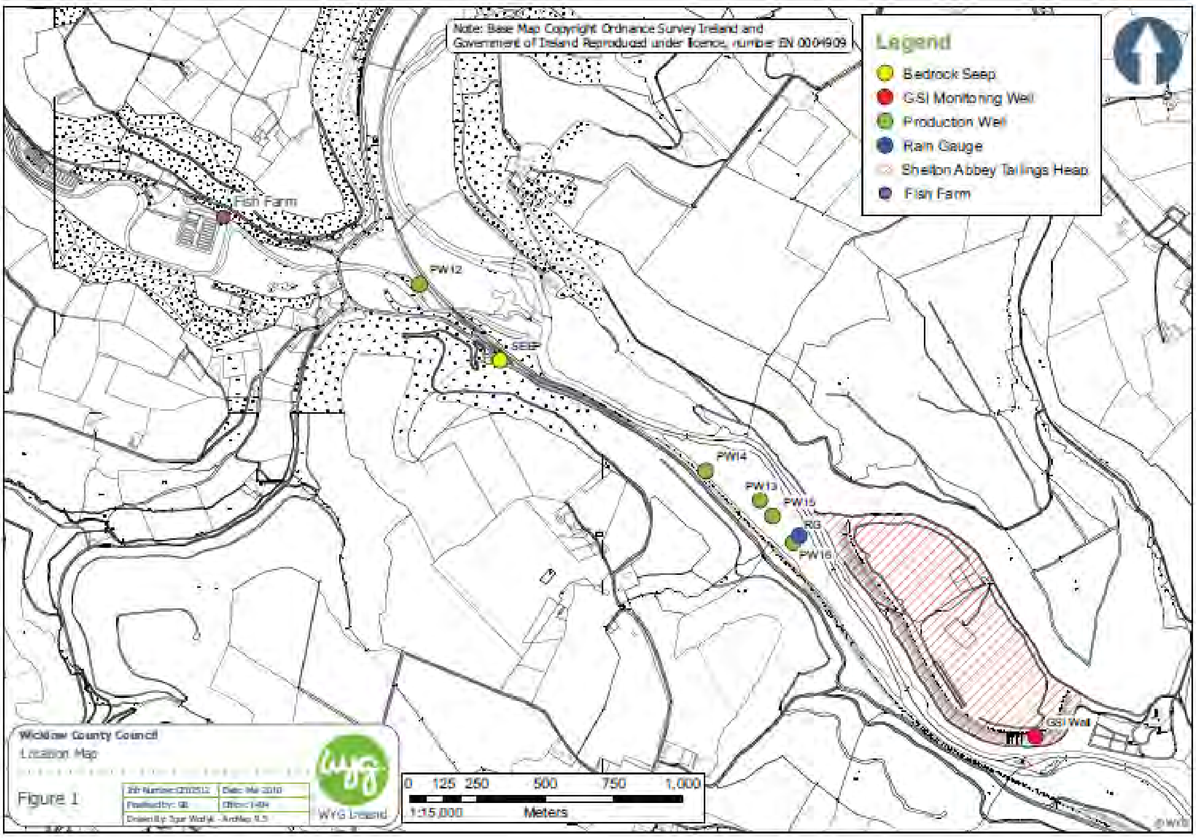
Groundwater modelling has shown that groundwater river water quality had largely stabilised after 40 days of the test. This is clear from the electrical conductivity results which are also graphed below. The reduction in conductivity during the test is a clear indication of river water (lower conductivity) mixing with the groundwater. The reduction in electrical conductivity stabilises halfway through the test when the flowpaths from the river to the wells are fully developed.

It is also interesting that the stabilised electrical conductivity in the wells can be related to the distance of the wells to the river and the pumping rate. Therefore PW14 which is the furthest distance from the river has the highest conductivity. PW16, while close to the river, has a lower pumping rate and as such a lower contribution from the river. The conductivity results can be used to derive a mass balance for the wells which shows that the contribution of river water to the wells is c. 75%. This ratio of groundwater contribution vs. surface water contribution closely matches the estimate based on the recharge estimates for the wells.

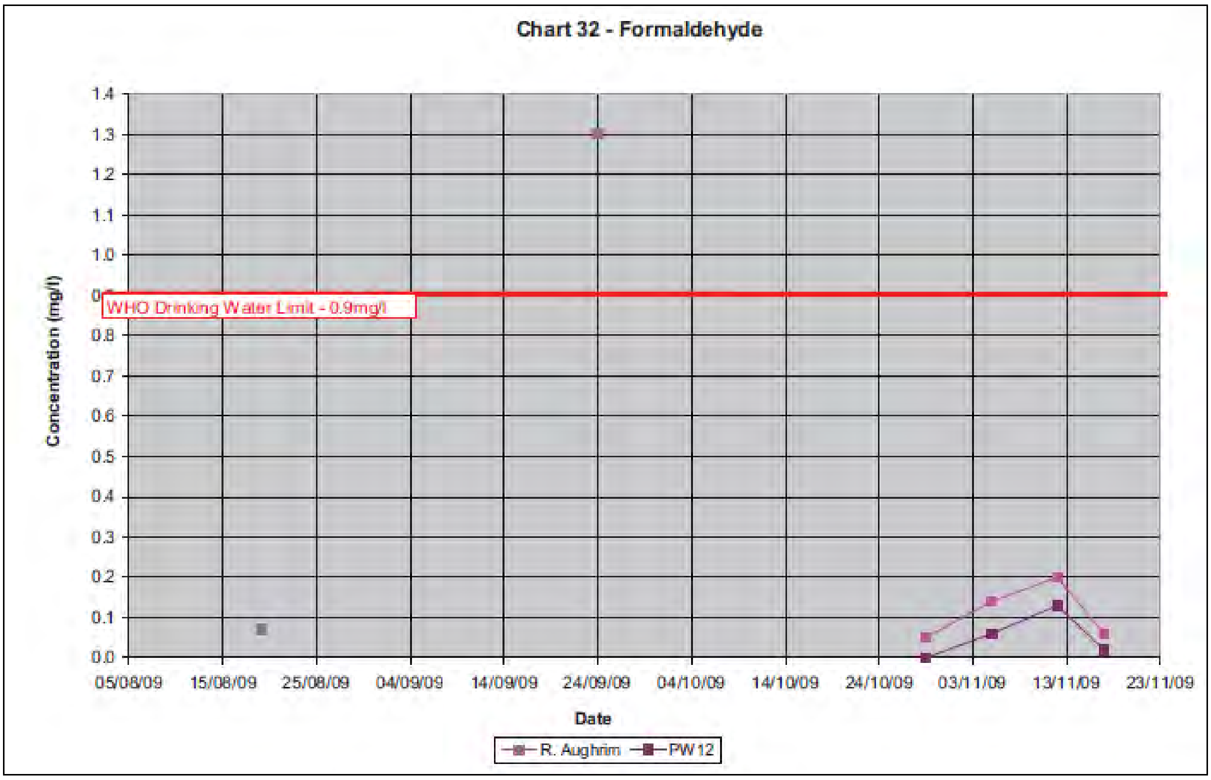


PW12 Water Quality

An additional concern for water quality of PW12 was the presence of a fish farm directly up stream of the well on the R. Aughrim. The location of the fish farm is shown on the figure below. The fish farm uses numerous chemicals and feed which are discharged directly into the river. The key chemical of interest, based on the quantities dosed and the potential toxicity to humans is Formaldehyde. This is used to kill microbes which infect the fish gills following high flows. Formaldehyde was samples for in PW12 and the R. Aughrim on a number of occasions towards the end of the test. The results are shown on the graph below.



The concentrations are well below the WHO drinking water limit for the parameter. It is however interesting that the concentration trend is similar in both samples with the concentration in PW12 being about half that seen in the R. Aughrim. This could be an indication that in the case of PW12 the well received 50% of its recharge from the R. Aughrim. The other 50% likely comes directly from the gravel aquifer and a small amount from the R. Avoca.



Groundwater Modelling

A 3D groundwater model was developed for the site to test a number of scenarios and confirm the zone of contribution and source protection areas. The scenarios tested included:

- Potential for contamination from the R. Avoca or Shelton Abbey Long Term pumping
- Potential for contamination from the R. Avoca or Shelton Abbey Long Term pumping with clogging of the riverbed

The model was developed using GW Vistas which is a GUI for the Modflow, Modpath and MT3D models. The model was developed with two layers. The upper layer represented the gravel aquifer and the lower layer representing the bedrock aquifer. The topography in the model was imported from the 100m DEM. Meteoric recharge was set to total effective rainfall. River level and base elevations were imported from a flood modelling project completed by WYG in the area. The river bed conductance was set so that the hydraulic conductivity of the bed sediments was equal to the gravel aquifer.

The aquifer parameters were taken from analyses completed on the pumping test results. A number of methods were used to estimate the aquifer parameters and these are summarised below. The Nueman 1974 method suggested a much lower vertical than horizontal hydraulic conductivity. This may be due to the layering observed in the gravel with some layer of very low permeability clays.

Table 15 - Aquifer Parameters derived for the 10 day pumping test.

Production Well		PW13	PW14	PW15	PW16	Average
Pumping Rate (m^3/d)		2231	1920	1627	503	
Steady State Drawdown (m)		2.44	3.74	2.82	1.11	
Saturated Thickness (m)		15.3	14.2	15.0	14.3	
Specific Capacity (m^3/d/m)		914	513	577	453	
Est. Transmissivity (m^2/d) *Logan Unconfined Approximation*		1147	715	767	573	
Hydraulic Conductivity (m/d) *Logan Unconfined Approximation*		75	50	51	40	54
Neuman 1974	Transmissivity (m^2/d)	1041	656	763	508	
	Horizontal Hydraulic Conductivity (m/d)	**68**	**46**	**51**	**36**	**50**
	Vertical Hydraulic Conductivity (m/d)	0.58	0.02	0.31	0.36	0.32
	Specific Yield	0.084	0.0083	0.082	0.04	
Theis Unconfined Approximation	Transmissivity (m^2/d)	1469	1648	1151	775	
	Storage Coefficient	1.3×10^{-3}	2.3×10^{-11}	4.4×10^{-4}	2.2×10^{-4}	

Table 16 - Summary of Hydraulic Conductivity Results

Method	PW13	PW14	PW15	PW16	Average
Logan Approximation (90 day Test)	60	45	49	33	47
Logan Approximation (10 day Test)	75	50	51	40	54
Particle Size Distribution	-	-	42.3	-	-
Distance Drawdown (Thiem-Dupuit)	51.1	36.9	42.6	21.1	37.9
Time Drawdown (Neuman 1974) (10 day test)	68	46	51	36	50
Well Average	63.5	44.5	47.2	32.5	**47.2**

The model was calibrated using water levels measured before and during the test. The model accurately represented the groundwater flow under both circumstances with little variation of the aquifer parameters used. The model was run as both a steady state and transient model.

The transient model was calibrated against the measured field conductivity data and was shown to represent the aquifer behaviour very well.

Figure 6 - Model Hydraulic Conductivity

Figure 8 - Model Water Levels; Scenario 1 Pumping

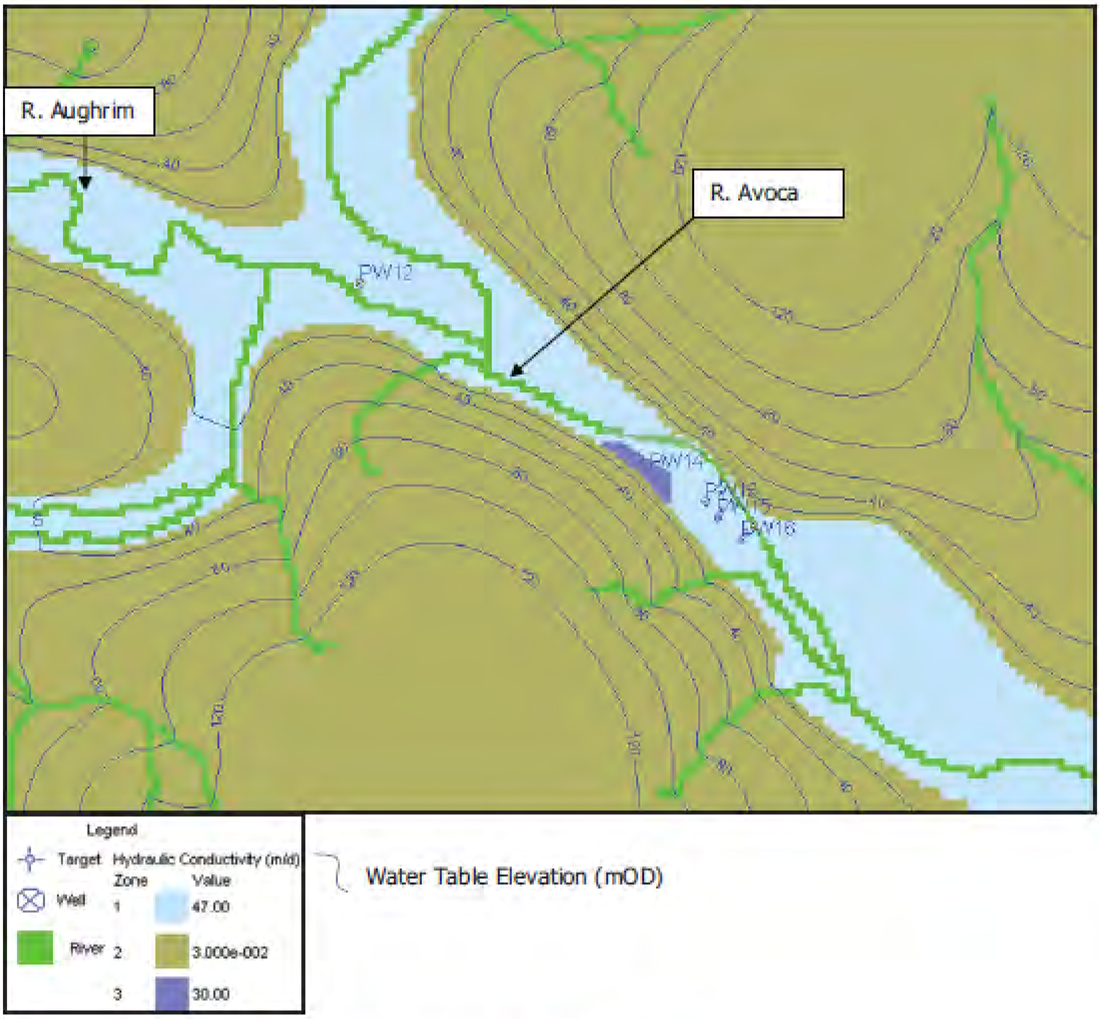
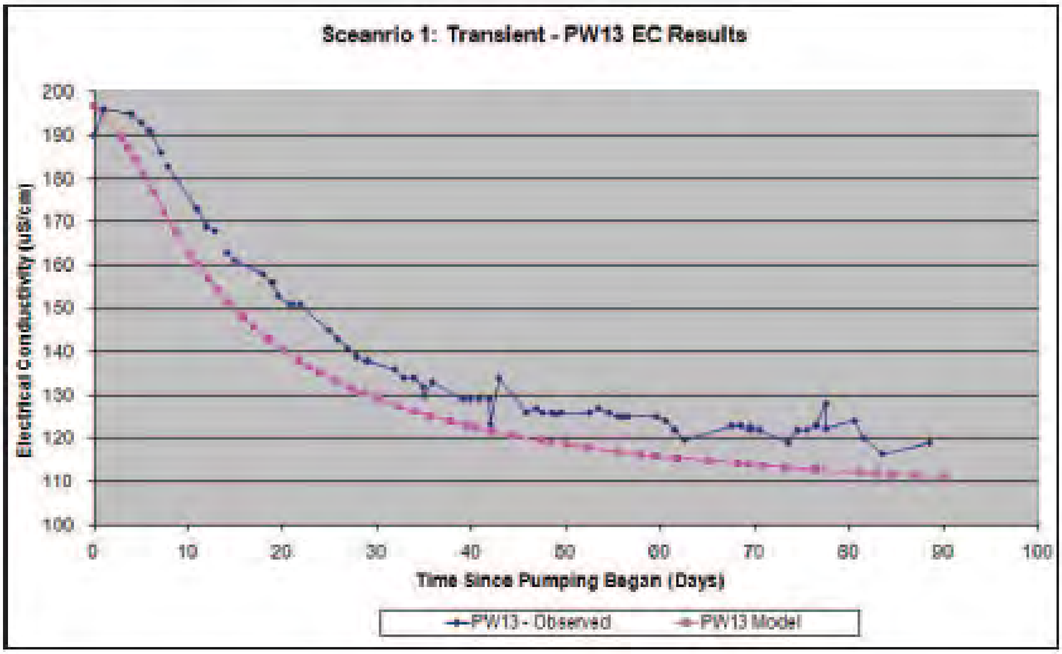


Table 19 – Scenario 1 Pumping Calibration Statistics

Statistic	Steady-State Pumping
Residual Mean	-0.19
Residual Standard Deviation	0.20
Residual Sum of Squares	**0.90**
Absolute Residual Mean	0.19
Minimum Residual	-0.03
Maximum Residual	0.54
Observed Range in Head	3.35
Res. Std. Dev./Range	0.06
Correlation Coefficient	**0.98**

Chart 28 - Scenario 1 Transient Model - PW13 EC Results



The MODPATH package was used to determine the ZOC for the wells and also the travel time to the wells. The results are shown in the figures below

Figure 10 - Scenario 1 - PW12 ZOC

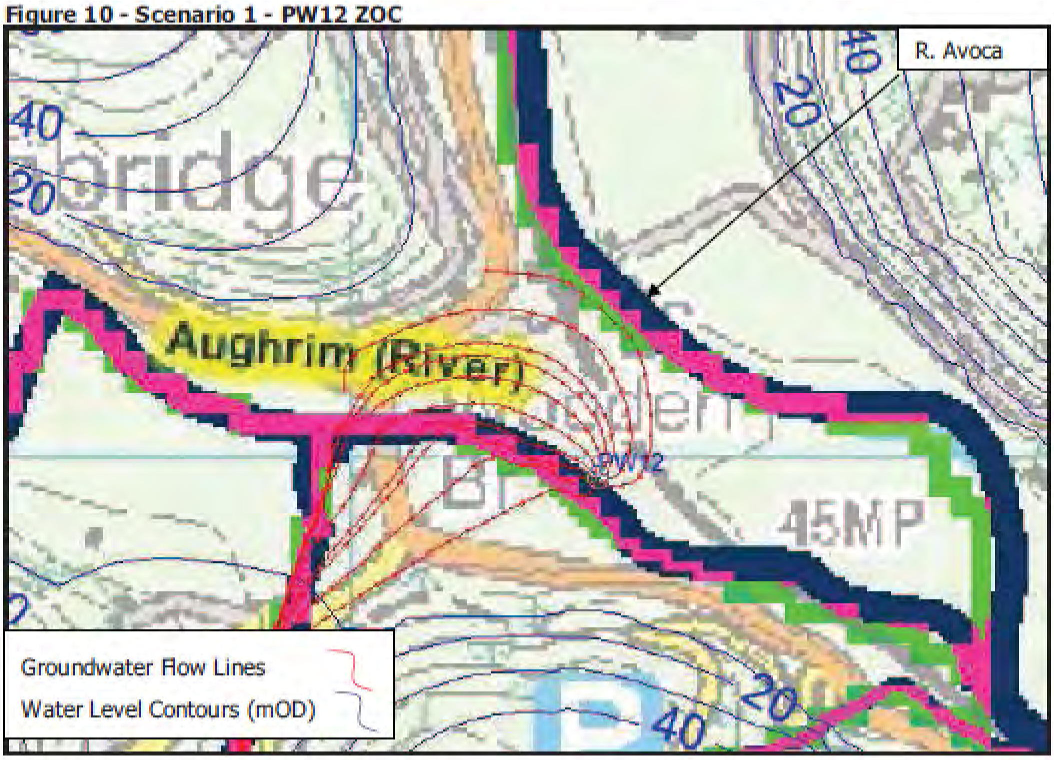
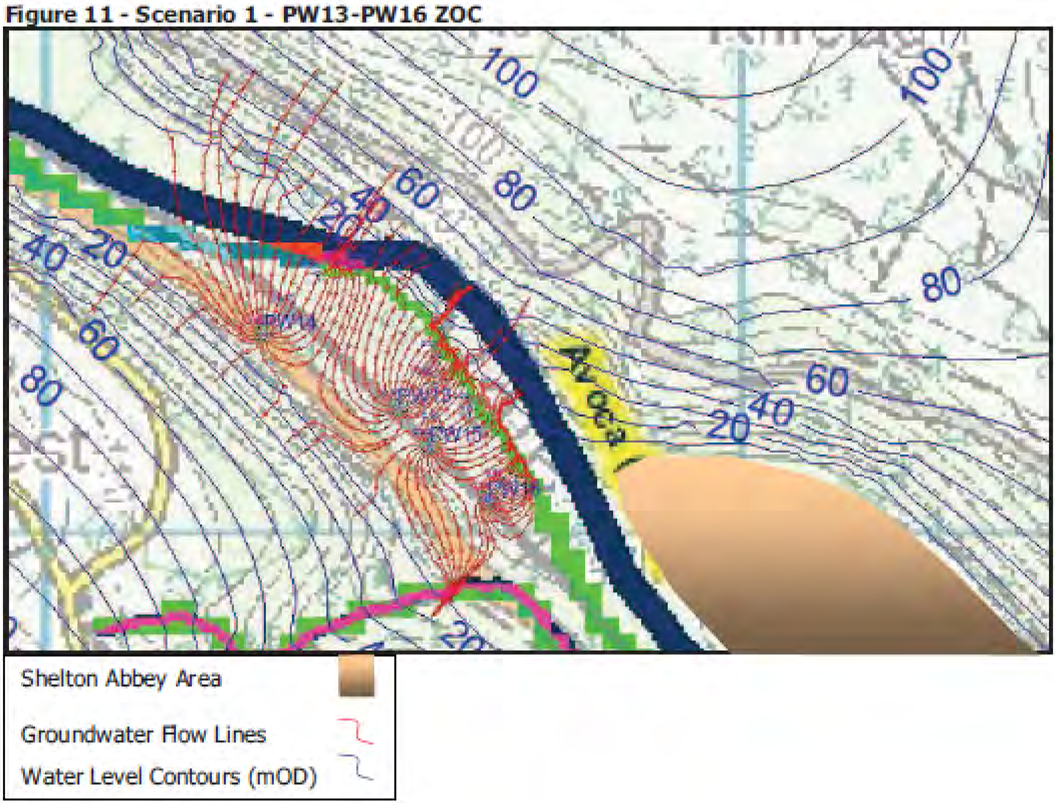


Figure 11 - Scenario 1 - PW13-PW16 ZOC

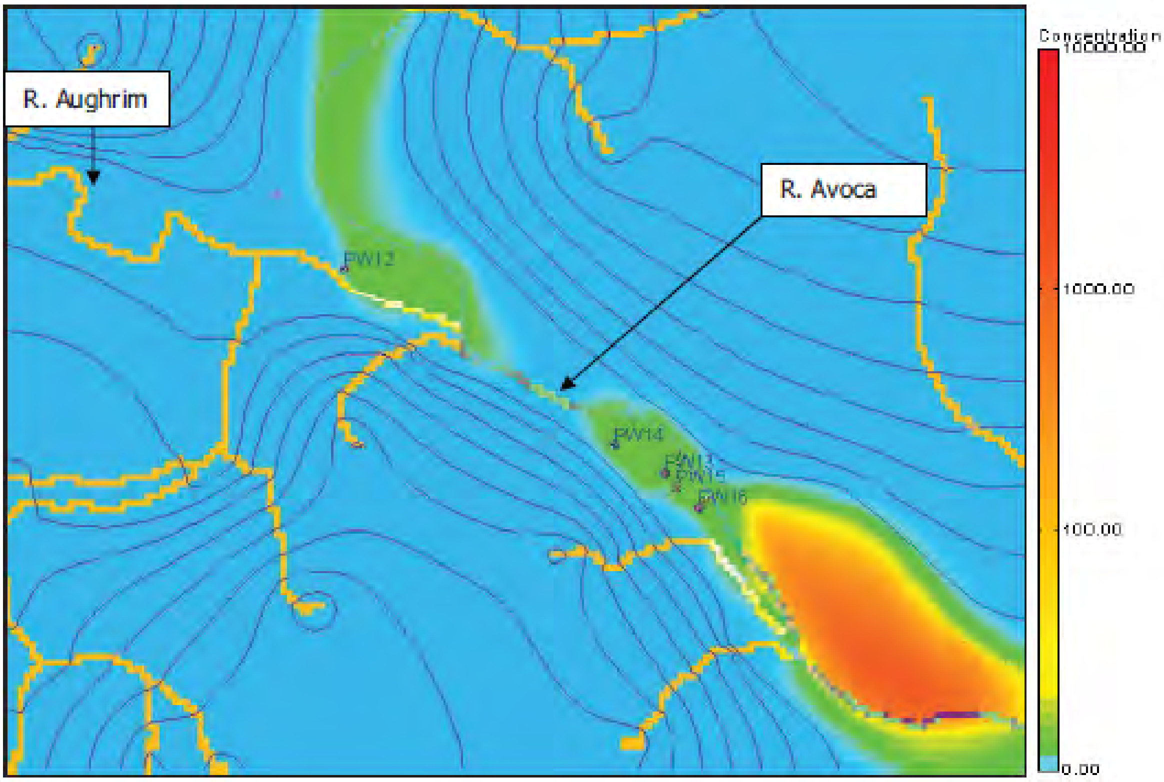


MT3D was used as to model a conservative contaminant through the model. For calibration purposes the electrical conductivity values were used. For contaminant modelling a normalised contaminant was used such that the background concentration in the aquifer and the recharge was 0. The concentration in the River Avoca was 100 and the concentration in Shelton Abbey was 10,000. This approach allows firstly the influence of the River but also the Shelton Abbey to be detected. The results of this modelling, which represents the scenario with no clogging of the river bed is presented below.

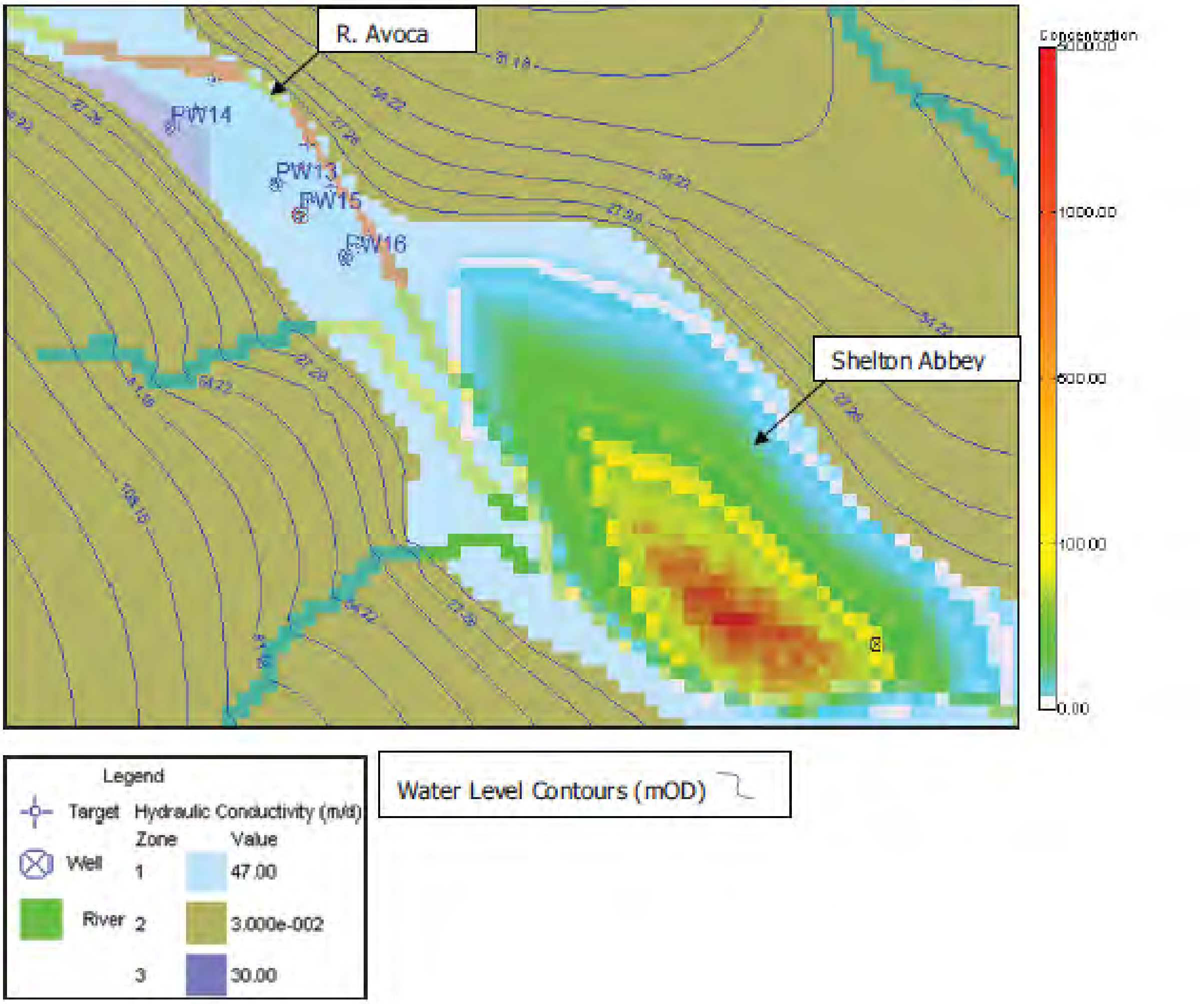
The green in the figure is indicative of the river water entering the aquifer downstream of meanders and it is clear it subsequently makes its way back into the River, e.g. upstream of the well field. This is a useful insight into groundwater-surface water interactions in the area. The model accurately represents the flow from the river towards the wells. The model shows that some wells have a greater contribution than others and this closely matches what was derived from observed data. The red, orange and yellow colours represent the high concentrations at Shelton Abbey. Under this scenario there is no migration towards the wells, even over very long periods of time.

The second scenario modelled involved reducing the hydraulic conductivity of the riverbed in the vicinity of the wells to assess what impact this would have on the yield of the wells and the water quality. The results are presented in the second figure below. They show only a minimal change in the groundwater flow direction down gradient. Also there is no appreciable reduction in the productivity of the wells. The cone of depression of each of the individual wells spreads out a little further past the zone of clogging to access the recharge at the base of the river. This results in some minor additional drawdown at the wells.

Figure 12 - Scenario 1: Water Quality Results



Scenario with river bed clogging



Former Mine Sites at Avoca, Co. Wicklow

Eibhlin Doyle (EMD) & Gerry Stanley (GSI)

The **Avoca Mines** were worked intermittently from 1720 to 1982. Mining was for copper and pyrite. Other metals which occurred in the orebody included lead and zinc. The Site extends in a linear fashion for some 4km in a northeast to southwest direction. The site has traditionally been divided into two parts East Avoca and West Avoca separated by the Avoca River. East Avoca, itself, is commonly divided into Connary, Cronebane and Tigroney while West Avoca comprises Ballymurtagh, the North Lode and Weavers Lode. Total copper production for the period 1720 to 1982 is estimated to have been 13.8 Mt @ 0.73% Cu. The site now comprises disturbed ground with many pits, shafts, adits and waste rock piles. There is significant pollution to the Avoca River from waters emanating from the mine. Estimated current reserves in West Avoca are 4.7 Mt at 0.68% Cu and in East Avoca 14.4 Mt at 0.60% Cu, giving a total of 19.4 Mt at 0.62% Cu.

SAFETY

We all have a responsibility to make this field trip as safe, enjoyable and incident free as possible. Participants are expected to have the experience and ability to look after themselves. The three elements that contribute to an enjoyable and safe field trip are **YOU**, the TERRAIN and the CONDITIONS.

Firstly, YOU: You don't have to be super fit to enjoy this trip but the more often you have been on field trips or hill-walking the more fit you are likely to be and this should lead to greater enjoyment both for yourself and the others on the trip. You should also be dressed appropriately and this too is your responsibility. You need to keep yourself safe and warm. The 'Layering System' will assist you stay as dry, cool or warm as possible throughout the field trip. Bring a suitable small rucksack to carry layers which you do not need at any particular time on the trip. Special attention should be paid to footwear. Walking or hiking boots are most appropriate for this trip. City shoes, runners, wellington boots or golf shoes are not suitable for this trip.

Secondly, the TERRAIN: The terrain on this trip is moderately difficult. There are steep inclines and declines and although we will be walking along pathways and tracks they are strewn with cobbles and boulders. Take your time and if necessary rest at appropriate times. The other factor in TERRAIN is the length of the trip over all. On this trip the total traversed distance is likely to be of the order of 5km. Again take a break if you need to do so.

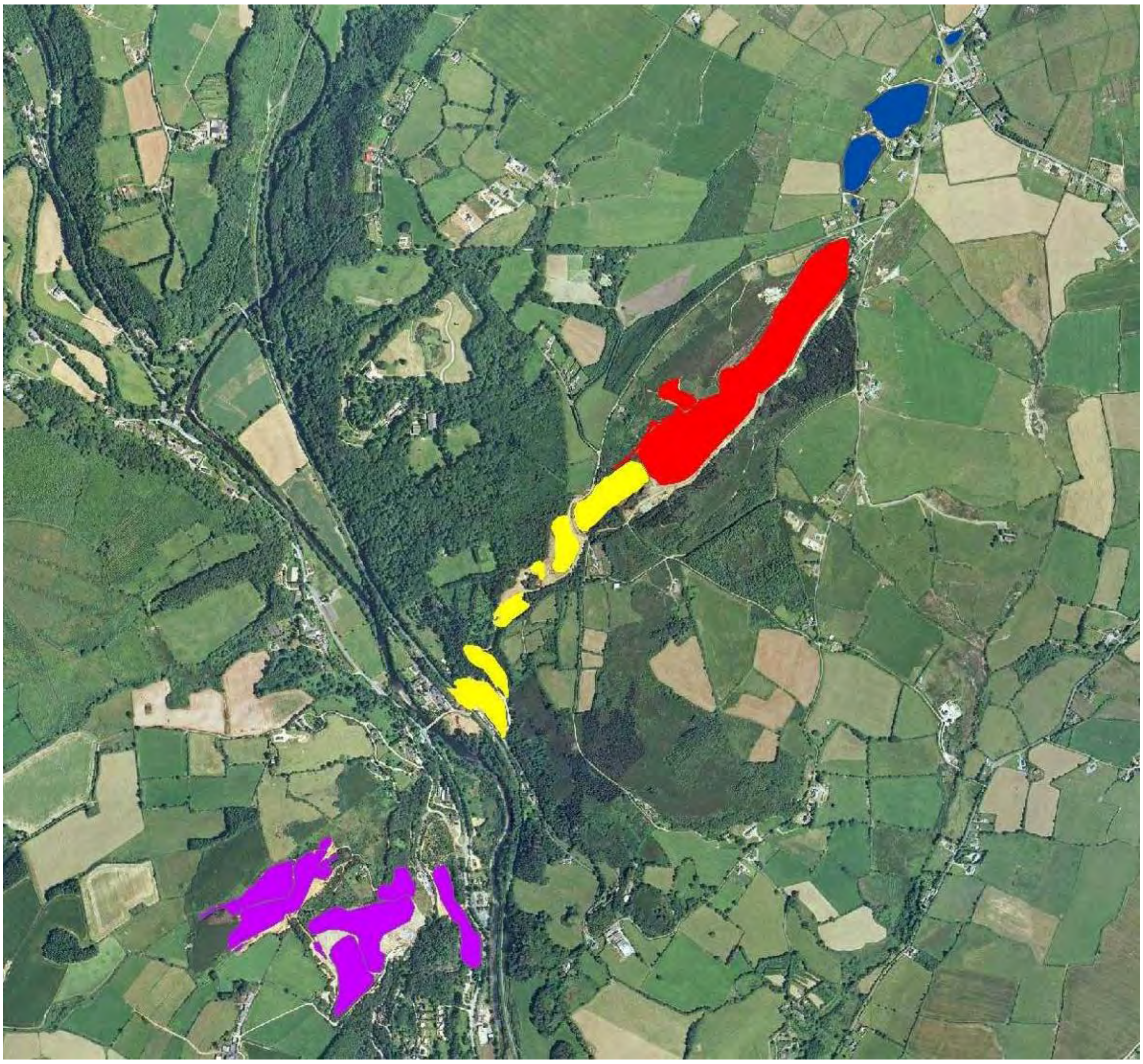
Thirdly, the CONDITIONS: Poor visibility, rain and high winds may turn the field trip into a dangerous experience for all participants. Plans may have to be changed before or during the visit to adjust to the weather conditions.

AVOCA DISTRICT

Mining History and Production

Copper mining began in Avoca about 1720 (Griffith, 1828) and there were mines at both Ballymurtagh and Cronebane, the latter employing 500 people, at a rate of 8d (pence) per day, mining copper and native silver that was found disseminated in the iron ochre gossans overlying the copper ore (Henry, 1752). Copper was also extracted from the mine water by precipitation and cementation. The acidity of this water was recognized at an early date (Henry, 1752) and not long after commencement of mining and discharge of large volumes of water into the Avoca river, the rich salmon fisheries of the river had been affected (Bayly, 1816).

Mining at Avoca took place in East Avoca – Connary, Cronebane, East Tigroney and West Tigroney; and in West Avoca – Weaver's, North and Pond (Ballymurtagh) (Figure 1).
Figure 1. The Avoca Mining District. Purple – West Avoca; Yellow – Tigroney; Red – Cronebane; and Blue – Connary. The latter three sites combined form East Avoca.



There were three major eras of mining in Avoca (Gallagher and O'Connor 1997). In the first, between 1720 and 1816, mining was carried on by private companies in both East and West Avoca. Little is known about the earliest copper mining, but generally the mines in East Avoca (Cronebane-Tigroney) were better managed, especially between 1787 and 1816 when an English company, the Associated Irish Mine Company (AIMC) held the lease. In this period, AIMC produced some 27,000 tonnes of copper ore grading 6.45% Cu.

The second era began around 1826 and lasted until the 1880s. West Avoca mine (Ballymurtagh) was developed and mined efficiently by the Wicklow Copper Mining Company, an Irish public company. Throughout this period, the mines on the eastern side of the river, which now included Connary, remained in private hands. Between 1826 and 1839, copper (as chalcopyrite concentrate) was the principal commodity produced ore but in 1839, when supplies of sulphur to the British market were interrupted which originally came from Italy, the Avoca mines switched to production of pyrites. Most mines continued to produce both copper and pyrites over the next 25 years until 1865 when the opening of the Rio Tinto mines in Spain provided the British market with cheaper sulphur supplies. Thereafter, production declined and by 1888 the mines were derelict, although most had been all but abandoned long before then. Between 1822 and 1888, up to 200,000 tons of copper ore and 2,400,000 million tons of pyrites were mined at Avoca.

The third major period of mining at Avoca was preceded during 1947-1955 by a State-sponsored assessment of the potential for mining which outlined some 14m tonnes of copper ore grading 1.12% Cu in West Avoca. Instead of selective mining of high-grade seams of copper ore, the modern approach was to bulk mine the low-grade ore. Between 1958 and 1962, Saint Patrick's Copper Mines Ltd., a Canadian company, extracted some 2,850,000t of ore grading 0.74% Cu by underground mining in West Avoca and also limited underground mining in East Avoca. The operation ceased in 1962, having been under funded from the outset. Avoca Mines Ltd. (AML) recommenced development and mining in West Avoca in 1969 and produced almost 8,900,000t of copper ore (0.73% Cu) before abandoning the mine in 1982 (Figure 2). This operation too was under funded and dependent for profitability of buoyant copper prices that only rarely prevailed. AML operated mainly underground at West Avoca but it was also responsible for excavating the open pit in West Avoca (Ballymurtagh) and for the open pit developments on the East Avoca site at Cronebane and Tigroney East.

Total copper production for the period 1720 to 1982 is estimated to be 13.8 Mt @ 0.73% Cu. Estimated current reserves in West Avoca are 4.7mt at 0.68% Cu and in East Avoca 14.4mt at 0.60% Cu, giving a total of 19.4mt at 0.62% Cu.

Figure 2. Avoca Mine during the mid 1970s (photograph by Bill Sheppard).

GEOLOGY

(After Vincent Gallagher, Peadar McArdle, Bill Sheppard, Dan Tietzsch-Tyler and Pat O'Connor)

Regional geology

Simply put, the regional geology of the Avoca area comprises a northeast trending belt of volcanic rocks (the Duncannon Group); flanked by meta-sedimentary rocks (the Ribband Group). Both these Groups are Lower Palaeozoic in age. To the west lies the Devonian Leinster Granite.

Most of the bedrock of southeast Ireland is comprised of Lower Palaeozoic rocks of the paratectonic Caledonides that were deposited subaqueously and later underwent multiphase deformation during an interval of nearly 200 million years from the early Cambrian to early Devonian periods (570 - 400Ma).

The geological history of the region began at its southeastern extremity over 600 million years ago when igneous rocks and sediments, deeply buried in the continental crust, underwent intense deformation and metamorphism under conditions of high temperature and pressure to form the gneisses of the Rosslare Complex. Extension and thinning of this crystalline crust led subsequently, in Cambrian times, to continental rift and gradual subsidence of the land surface to the northwest of the Rosslare area where a deep marine basin began to form, marking the beginning of the Iapetus Ocean. This ocean existed in southeast Ireland at least from c. 570 to 450 million years ago. It extended along a similar axis to that of the modern Atlantic Ocean. The Iapetus Ocean filled with clastic sediments derived from weathering of the continental landmasses to southeast and northwest. These sediments are today represented by the Bray, Cahore and Ribband Group rocks. The ocean reached its greatest extent at end Cambrian-early Ordovician times (c. 500 million years ago). Thereafter, subduction of the ocean floor led to gradual closure of the ocean. In the mid-Ordovician, volcanism was widespread above a subduction zone developed along the southeastern margin of the Iapetus. The Ordovician Duncannon Group is dominated by the products of these volcanic eruptions and includes the Avoca Formation, host to the Avoca ore deposits. Volcanic activity ceased around 450 million years ago and closure of the Iapetus followed. The Lower Palaeozoic geological history of southeast Ireland was completed with end-Caledonian mountain building, a final phase of crustal deformation and metamorphism marked by intrusion of the Leinster Granite 405 million years ago in the early Devonian.

Local geology

Geology and Mineralization

The Avoca deposit is hosted by the Avoca Formation, a northeast-southwest-trending sequence of 455 million-year-old Ordovician volcanic and sedimentary rocks. The formation is 2-4 km thick and dips steeply to the southeast. The rocks possess a steep bedding-parallel regional cleavage. A series of north-south faults offset the mineralized zones and they have been interpreted as possible feeder zones for mineralizing fluids (McArdle 1993).

The formation covers an area some 2-4km wide by 15km long and has been subdivided into three members (McArdle 1993) (Figure 3). The oldest unit is the Castlehoward Member which forms the western part of the formation, cropping out northwest of a line from the Meeting of the Waters to Kilmacoo. This member is 450-1200m thick and comprises sericitic crystal tuffs with felsic horizons. The Kilcashel Member (700-1050m) underlies the central part of the Avoca district and consists of chloritic tuffs, often silicified and altered, including both crystal and lithic tuff varieties. The Kilcashel Member rocks are notable for their high chlorite content. The youngest unit is the Tigroney Member (350-1800m), dominated by sericitic lithic and crystal tuffs and felsites, but also including chloritic crystal tuffs. The main ore zones at Avoca mine occur at the top of the Kilcashel Member at its contact with the Tigroney Member.

Volcanic rocks are interbedded with marine sediments in the Avoca Formation and the two rock types pass laterally into each other. The felsitic tuffs include vitric and ash tuffs. They have been interpreted as products of post-eruptive slumping of pyroclastic material on the sea floor, i.e. they were deposited by pyroturbidity currents (Downes and Platt 1978; McArdle 1993). The distinctive chloritic tuffs of the Kilcashel Member and of the mine sequences may have been formed by alteration of volcanic tuffs on the sea floor during the geothermal activity that gave rise to the mineralization (McArdle 1993).

The mineralization is found mainly within distinctive chloritic tuffs, interpreted as having formed by alteration of rhyolitic and intermediate tuffs on the seafloor during the hydrothermal activity that gave rise to the mineralization (McArdle 1993). Shearing is a distinctive element of the mineralization and is interpreted as having played an important role in the formation of vein-disseminated mineralization.

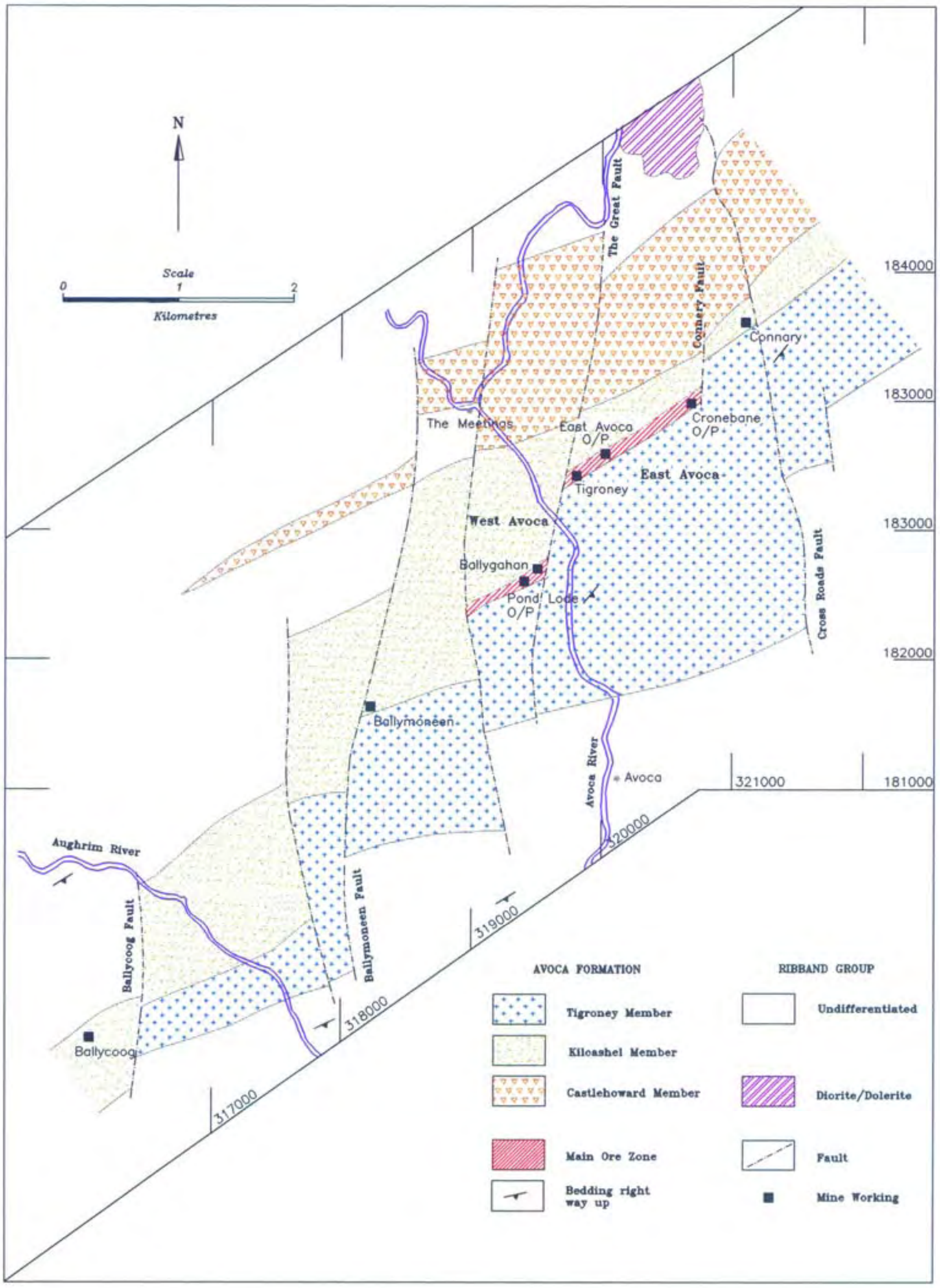


Figure 3. Geology of the Avoca mine area after McArdle (1993).

Three main primary ore types have been recognized on a macroscopic scale in the Avoca mine area:

1. In the pyritic zones or **banded sulphide ore** (Williams 1984) or **massive ore** (Platt 1973) bands of pyritic ore alternate with bands of sphalerite-rich ore and bands of chlorite and sericite (photo, right). Pyrite (FeS_2) is the dominant mineral; other minerals include chalcopyrite ($CuFeS_2$), sphalerite (ZnS) and galena (PbS). Magnetite (Fe_3O_4), hematite (Fe_2O_3), arsenopyrite ($FeAsS$), pyrrhotite (FeS), bismuthinite (Bi_2S_3) and native bismuth are minor, and gold rare. Such ore is typified by the Pond Lode and North Lode in West Avoca and the Main Lode in East Avoca.

2. In the siliceous zones **vein and disseminated ore** (Williams 1984) or **stringer ore** (Platt 1973) occurs; major pyrite, chalcopyrite, sphalerite and lesser galena occur within a siliceous matrix (photo, right). Arsenopyrite, pyrrhotite, bismuthinite, native bismuth, tetrahedrite ($(CuAgFe)_{12}Sb_4S_{13}$) and bournonite ($CuPbSbS_3$) are minor. The South Lode, the south branch of the North Lode in West Avoca and the hangingwall in East Avoca are examples.

3. The **lead-zinc ore** contains banded sphalerite, galena and pyrite with minor arsenopyrite and chalcopyrite in a chlorite matrix. The Lead-Zinc lode at West Avoca and the "kilmacooite" zones at Cronebane and Connary are representative of this ore type (Wheatley 1971).

Secondary or **supergene** mineralization includes breakdown products of pyrite, chalcopyrite, sphalerite and galena, such as hydrated iron oxides and covellite (CuS) (Wheatley 1971). Subsurface oxidation extends to a depth of about 60m below ground level at West Avoca (Wheatley 1971). In East Avoca, the top 30m of Cronebane Open Pit was a supergene deposit composed of chalcocite (Cu_2S), covellite and chalcopyrite. It was formed by the weathering of the chalcopyrite-pyrite-sphalerite-galena mineralization.

The Figures on the next three pages show the various mine features at East And West Avoca (Figures 4, 5, and 6).

EAST AVOCA - 1

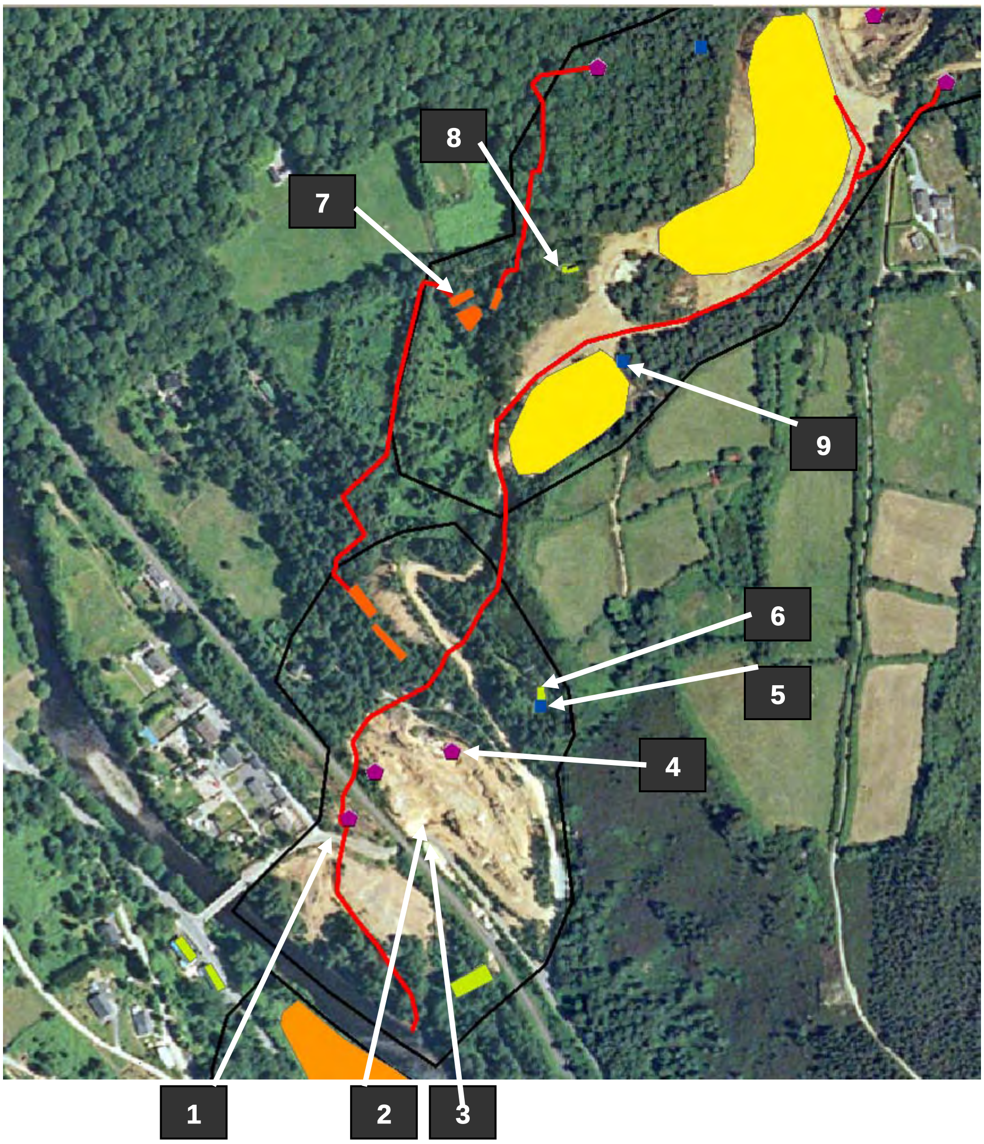


Figure 4. Mine features at East Avoca (Tigroney). 1 - Deep Adit; 2 - Ore bins; 3 - Flat rod tunnels; 4 - 850 Adit; 5 - Williams Shaft; 6 - Williams Engine House; 7 - Ochre pits; 8 - Baronet's Engine House; 9 - Farmer's Shaft.

East Avoca - 2

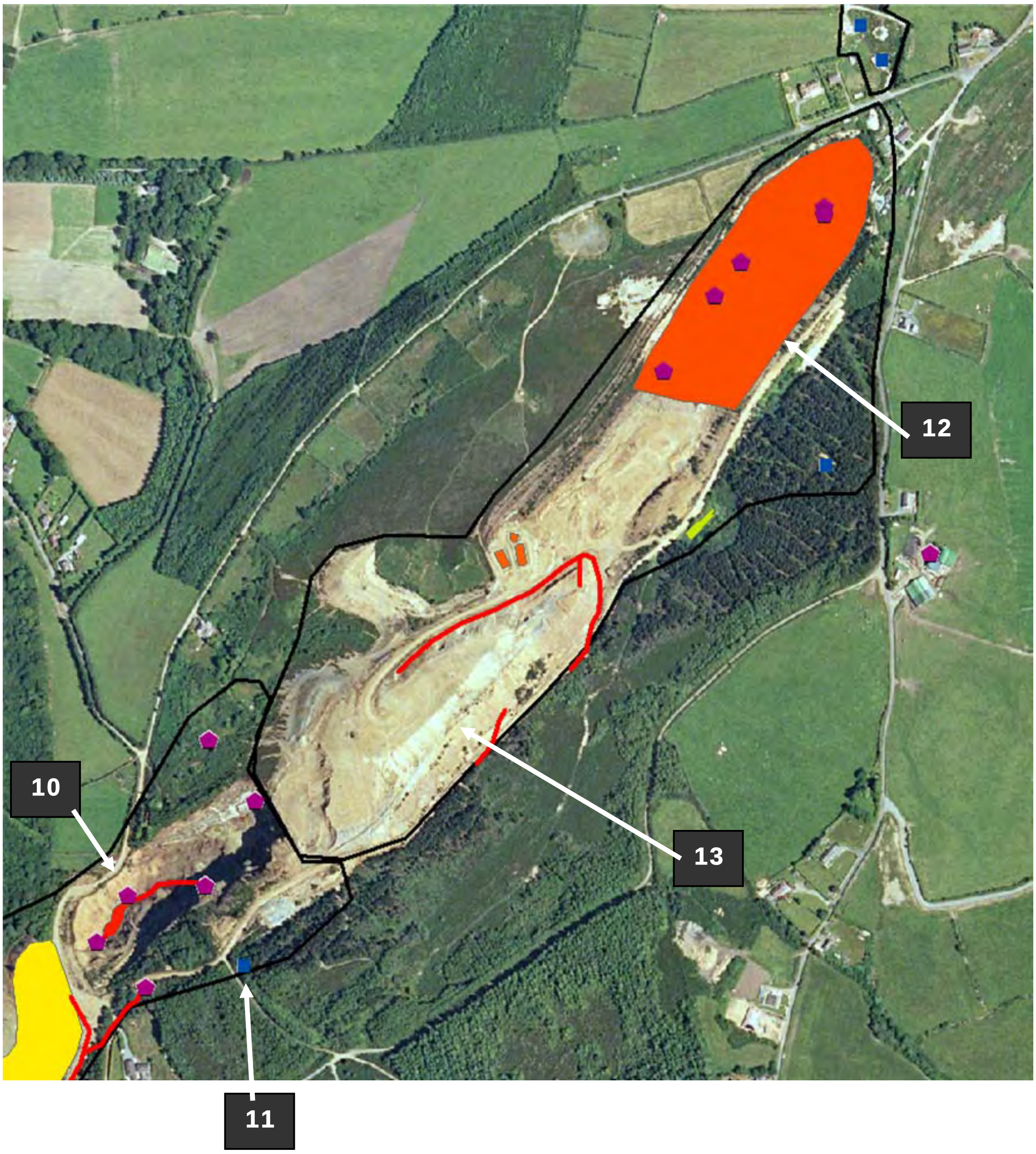


Figure 5. Mine features at East Avoca (Cronebane). 10 - East Avoca Open Pit; 11 - Cronebane Shallow Adit; 12 - Cronebane Pit; 13 - Mt. Platt.

WEST AVOCA – 1

Figure 6. Mine features in East Avoca. 14 - Road Adit; 15- Mine Office; 16 - Knight Tunnel; 17 - Ballygahan Shaft; 18 - Pond Lode Open Pit (Ballymurtagh); 19 - Twin Shafts (west); 20 - Twin Shafts (east); 21 - Twin Shafts Engine House (west); 22 - Twin Shafts Engine House (east); 23 - Tramway Arch; 24 - Tramway Engine House Chimney; 25 - Ballygahan Engine House; 26 - North Lode Open Pit; 27 - Whelan's Shaft; 28 - Spa Adit; 29 - Weaver's Open Pit; 30 - Emergency tailings.

REMEDIATION AND ENVIRONMENT

At the time of the Avoca operations little attention was paid to environmental issues associated with the mining operation. These days the situation is completely different and environmental matters are very important. There are environmental issues to be considered at each stage of the Mining Cycle but on this trip we will consider those that are relevant to the Closure or post operational stage.

Again there are differences between what I might call a planned closure as would happen at any of the currently operating mines in Ireland and an abandoned mine such as at Avoca. We will look at the latter case. Often such abandoned sites spawn many investigative research projects and the Avoca deposit is a good example with many studies having taken place over the past 25 years.

The principal issues for closure are:

- Water
  - Groundwater
  - Surface water
- Solids
  - Tailings
  - Waste rock piles
  - Soil
- Long term
  - After use
  - Rehabilitation
  - Monitoring
- Other
  - Subsidence
  - Visual
  - Socio-economic

On this trip we will address some of the issue associated with Water, Solid Wastes, Remediation and Heritage.

Water

Water at Avoca is acidic with pH measurement as low as 3.7 for water issuing from the mine site. The water also contains high concentrations of heavy metals, such as Cu, Pb and Zn. Table 1 provides some indication of the values recorded at Avoca.

	Pb (tot) µg/l	Zn (tot) µg/l	Cu (tot) µg/l	Cd (tot) µg/l	Cr (tot) µg/l
Deep Adit	1,272	39,130	1,154	105	3
Deep Adit channel	1,227	38,710	1,188	102	5
Deep Adit mix zone	237	8,306	323	22	5

Table 1. Chemistry of water discharging from the Deep Adit at Avoca.

The discharges from the mine have affected the quality of the receiving river and the EPA has described it as the most polluted river in Ireland. There have been many fish kills (Figure 7). The waters from the mine could be treated before they enter the river so that the river could recover. The Celtic Copper project was an Interreg funded project which investigated the Avoca deposit here in Ireland and the Parys Mountain closed mine in Anglesey. The two mines are similar in many respects.

Figure 7. Fish kill at Avoca on 23rd April 2007.

The Eastern Regional Fisheries Board led the study in Ireland and a pilot treatment plant was installed which treated the waters issuing from the mine. The pilot plant was situated in the County Council yard (Figure 8). The treatment essentially consisted of:

1. Aeration – to increase the pH
2. Addition of lime – to increase the pH which in turn facilitates the precipitation of metals
3. Addition of flocculent – to facilitate the separation of precipitated solids

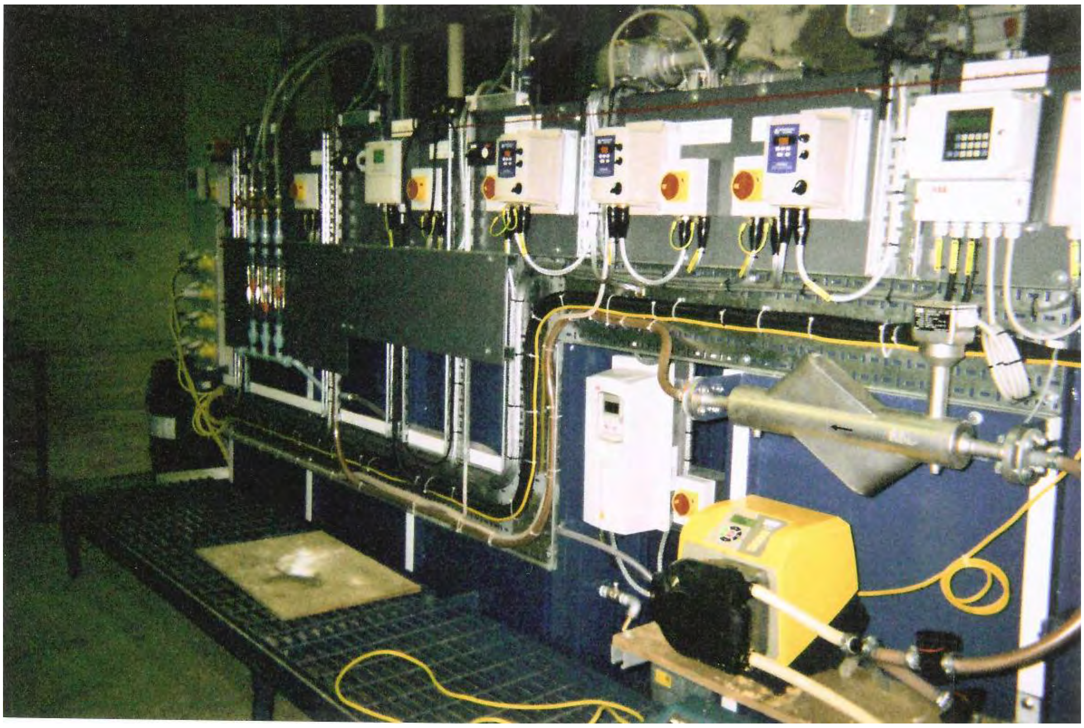


Figure 8. The pilot water treatment plant at Avoca.

The end result is water which can be released to the river plus a metalliferous sludge which must be stored at an appropriate waste facility.

Solids

Solid wastes comprise the waste rock dumps scattered over the Avoca site and tailings areas. The former are very visible while the latter are barely noticeable apart from the actual size of the Shelton Abbey facility which we will not visit on this trip.

As part of a recent national study on Ireland's historic mine sites the GSI carried out a characterization of many waste piles including several at Avoca. Characterization involves the identification and quantification of the various elements in the wastes. This was carried out using a field portable X-ray fluorescence spectrometer.

What elements cause us problems? There are several well known ones such as arsenic and lead. Table 2 summarises the known issues for humans and animals for a range of elements. These are the main elements but the scientific evidence for others is not so clear cut and is a matter for debate. Currently there are only standards or thresholds for drinking water and salmonid waters. There are no agreed limits for elements in soils or waste materials. Guidelines have been developed in some countries (the UK, The Netherlands, Canada and the USA) for some elements (Pb, Zn, As and a few others). There are no standards or guidelines for any elements in stream sediments.

As an example the results for Pb for Tigroney in East Avoca are illustrated in Figure 9.

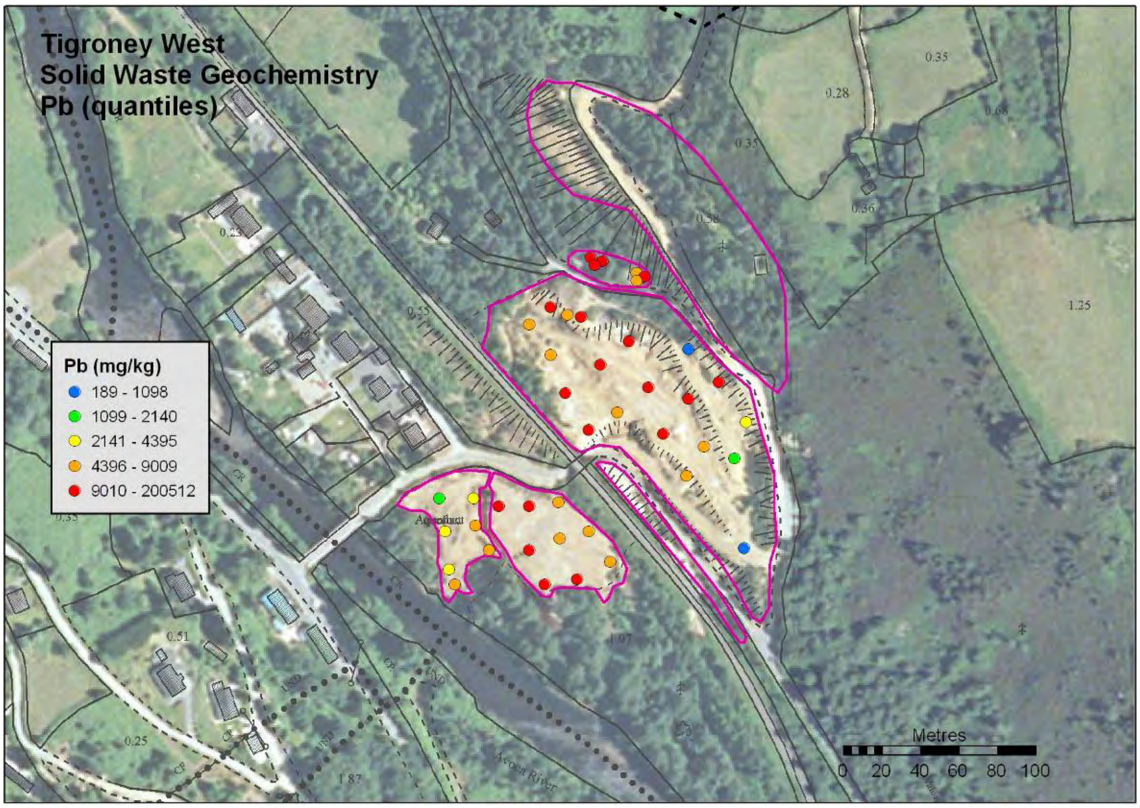


Figure 9. Pb results from field portable XRF for Tigroney, East Avoca.

Element	Known issues for humans	Other issues
Antimony	Pneumoconiosis Increased blood pressure Abdominal distress	
Arsenic	Carcinogenic (lung, liver, skin)	Decreased productivity in algae
	Birth defects	Shellfish bioaccumulate more than fish
Cadmium	Carcinogenic Kidney and liver damage	Affects aquatic plants and hence the entire ecosystem Kidneys in fish Skeletal deformities in fish Pancreas in marine crustaceans
Copper	Few issues	Affects fish and sheep Affects insects that fish eat
Lead	Accumulates in bones and teeth Restricts growth and development Hyperactivity, low attention span and low IQ (especially in children) Damages kidney function Birth defects	Affects gills in fish Reproductive effects in birds
Mercury	Neurologic Kidney damage	Easily accumulates in fish
Nickel	Carcinogenic (lung and nasal passage) Asthma Liver damage	
Selenium	Reproductive failure Birth defects	
Zinc	Few issues	Damage to gills, liver and kidneys in fish

Table 2. Some human and animal issues associated with different elements.

Revegetation

Little or no revegetation was attempted on any of the Avoca waste piles. However, there is some evidence that with a little encouragement plants would be able to grow on them – for example the builder's rubble dumped in around the site.

As part of the LIFE project in 1995 a series of revegetation trials were undertaken. Composted sewage sludge was tested as an ameliorant for two different scenarios: firstly, a mixture of non-phytotoxic mine waste and the sewage sludge; and secondly the use of various barriers over which an imported top soil was mixed with the sewage sludge. Phytotoxic mine waste is mine waste with little or no revegetation, low pH, high acid generating potential and high metal concentrations. Non-phytotoxic mine waste on the other hand had the opposite characteristics (successful natural revegetation, higher pH, lower acid generating potential and lower metal concentrations). There were two sets of trial plots, one at the North Lode and the second at Ballymurtagh Crest (Figure 10). Ballymurtagh Crest was the site for the barrier trials.

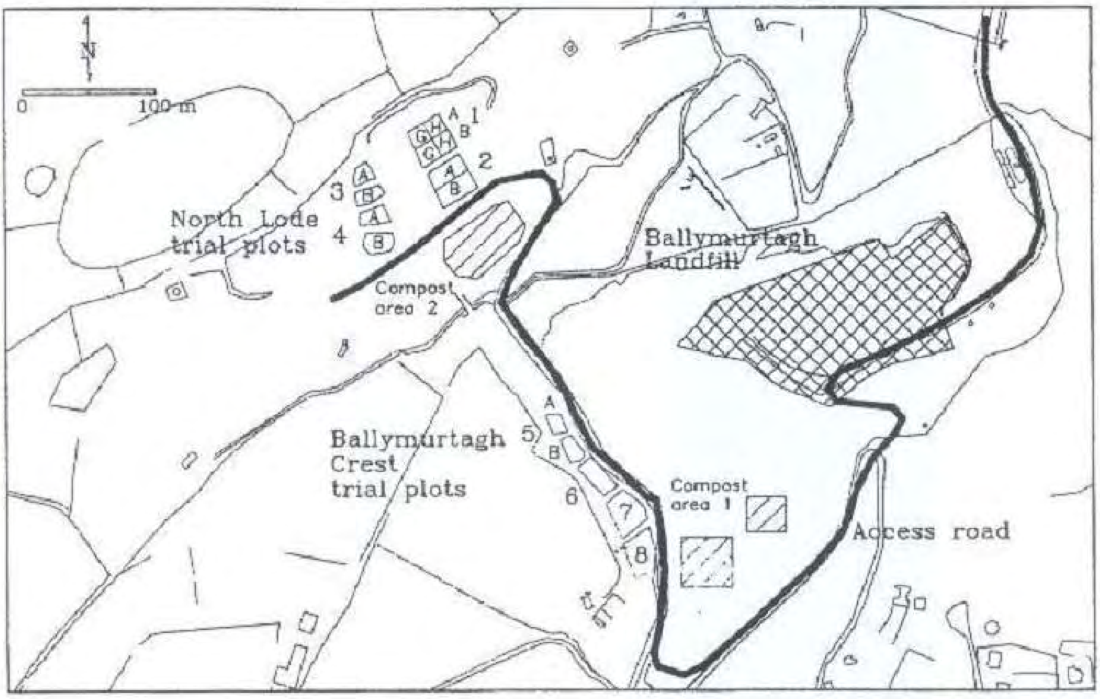


Figure 10. Revegetation trial plots at West Avoca.

HERITAGE

A feature of Avoca and some other mines was the manufacture of tokens. John Morris has written on the "Token Wars" at Avoca and an example of one is shown in Figure 11. Two sets of tokens were produced – the Cronebane tokens (by the Associated Irish Mine Company) and the Ballymurtagh Tokens (by the Hibernian Mining Company). All the Cronebane Tokens bear the date 1789 although they were produced during the period 1787 to 1797.

Figure 11. An Avoca Token.

There are many features, in various states of disrepair, remaining at Avoca (Table 3).

No.	Feature	Use	Constructed
		East Avoca	
1	Deep Adit	Drainage for East Avoca	Late 18th Century
2	Ore bins	Ore storage	1958 - 1962
3	Flat rod tunnels	"Transfer of power"	Not known
4	850 Adit	Mine entrance – drawing ore	1959 - 1962
5	Williams Shaft	Raising water	Mid 19th Century
6	Williams Engine House	Engine house	Mid 19th Century
7	Ochre pits	Ochre pits	Pre-mid 19th Century
8	Baronet's Engine House	A "drawing" shaft	Not known
9	Farmer's Shaft	Whim engine	Not known
10	East Avoca Open Pit	Extraction of ore	1978 - 1982
11	Cronebane Shallow Adit	Main access to Cronebane	Late 18th Century
12	Cronebane Pit	Extraction of ore	1970s
13	Mt. Platt	Waste pile	1970s
		West Avoca	
14	Road Adit	Drainage for West Avoca	Mid 19th Century
15	Mine Office	Mine office	1960s
16	Knight Tunnel	Main mine access	1955
17	Ballygahan Shaft	Drawing water and ore	Early 19th Century
18	Pond Lode Open Pit	Extraction of ore	1973 - 1979
19	Twin Shafts (west)	Drawing water; later for ventilation	Early 1850s
20	Twin Shafts (east)	Drawing ore; later for ventilation	Early 1850s
21	Twin Shafts Engine House (west)	Engine house for drawing water	Early 1860s
22	Twin Shafts Engine House (east)	Engine house for drawing ore	Early 1860s
23	Tramway Arch	Ore transport	1846
24	Tramway Engine House Chimney	Ore wagon haulage	1840s
25	Ballygahan Engine House	Not known	Not known
26	North Lode Open Pit	Extraction of ore	1850s
27	Whelan's Shaft	Not known	Not known
28	Spa Adit	Entrance to Weaver's Lode	Not known
29	Weaver's Open Pit	Extraction of ore	19th Century
30	Emergency tailings	Tailings disposal	1960s

Table 3. Extant heritage features at Avoca.

Wexford Ordovician Volcanics

G Baker – WYG

Introduction
The Ordovician bedrock in Co. Wexford and Waterford contains volcanic rocks with are grouped into the Duncannon Group. These volcanic rocks are considered a Regionally Important Fissured Aquifer (Rf). The Duncannon group contains the Campile formation which consists of pale coloured rhyolites and rhyolitic tuffs or agglomerates in gray and brown slaty mudstones with occasional andesites and andesitic tuffs or agglomerates (Tietzsch-Tyler & Sleeman (1994)). Rhyolites are fine-grained igneous rock, containing feldspar and quartz which are usually hard and flinty. Tuffs are rocks formed from volcanic ash, usually comprising silt to sand sized particles.

The rhyolites are extensively faulted and as a result are the most permeable unit of the Duncannon Group. However the individual rhyolite units thin rapidly and are confined by the interbedded sediments.

Depositional History
The continued subduction of the Iapetus Ocean in this period in the Upper Ordovician resulted in a major phase of volcanic activity with build up of a volcanic arc extending from Waterford to the English Lake District and Whales. In Leinster a number of volcanic centres interrupted sedimentation at different intervals with emplacement of rhyolites and rhyolitic tuffs that now make up the Campile formation. Occasionally andesitic lavas and tuffs were extruded at the surface and sheets of dolerite (gabbro in the larger sheets) were intruded at depth.

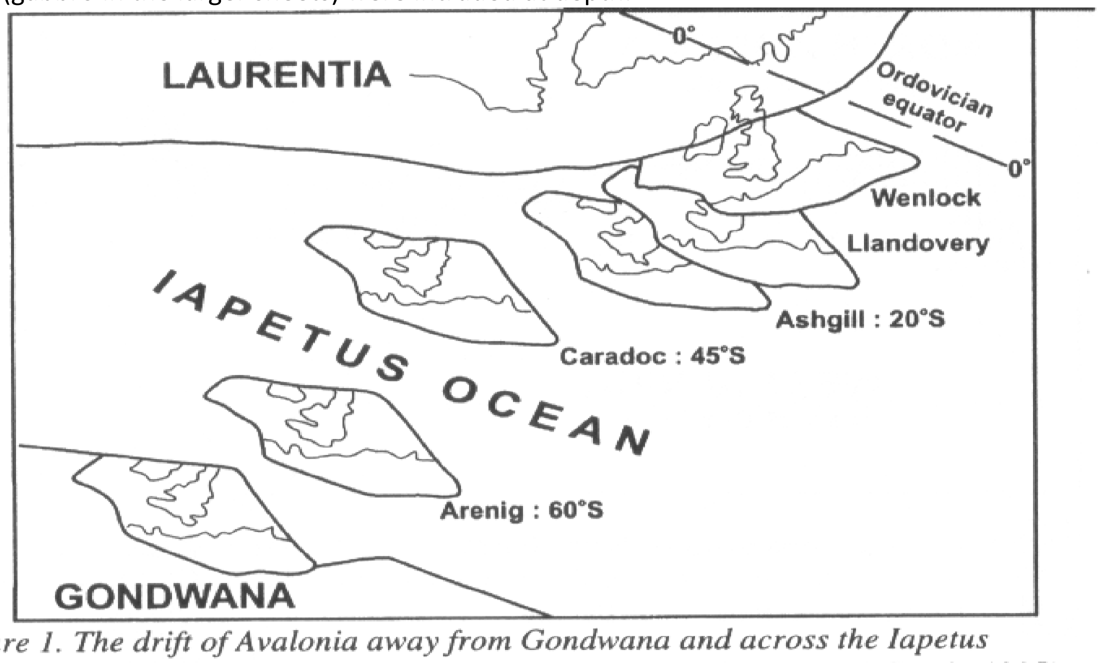
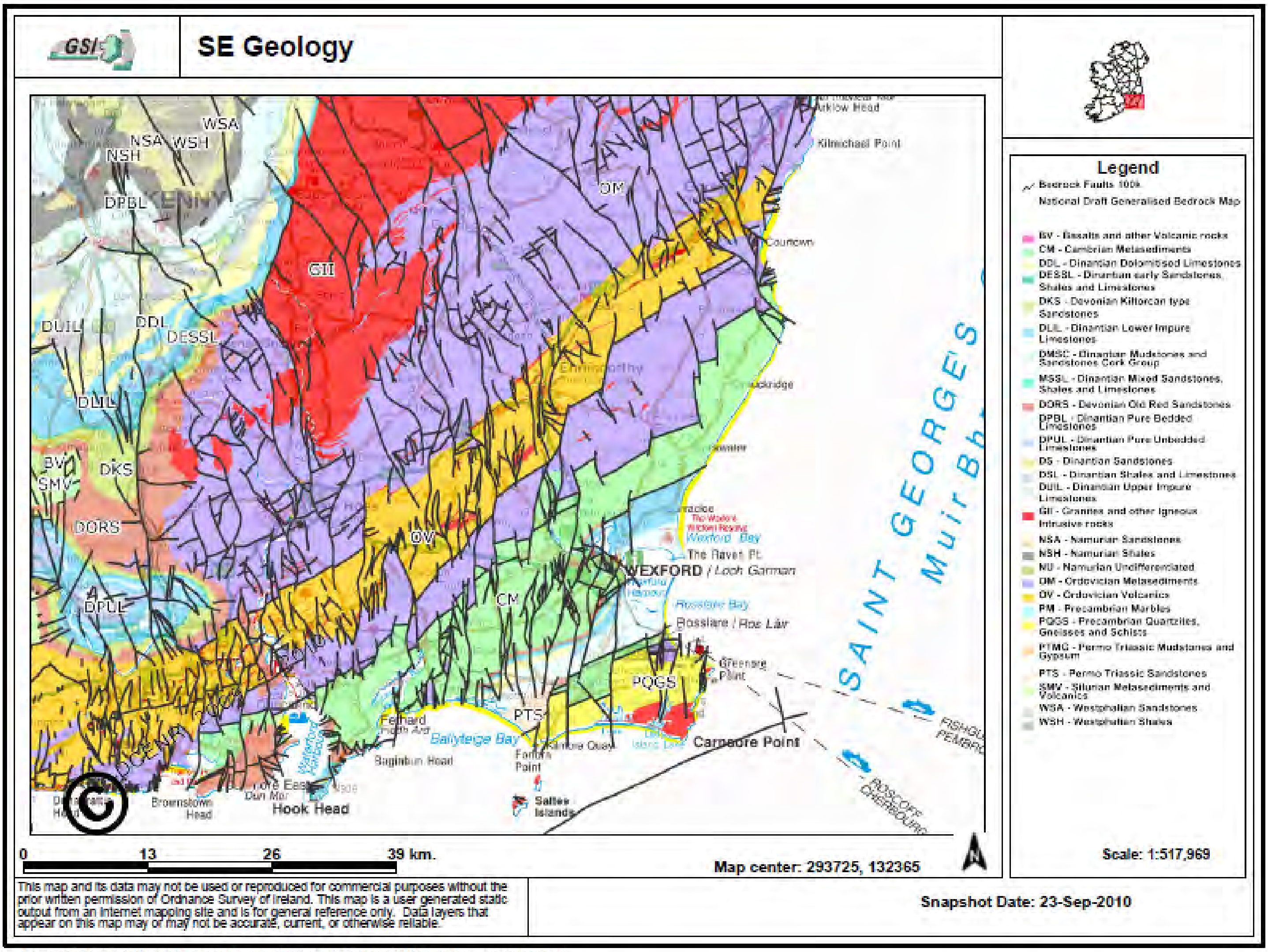


Figure 1. The drift of Avalonia away from Gondwana and across the Iapetus Ocean relative to a stationary Laurentia. (after Fig.5 in Pickering & Smith, 1995)

The predominant north-east to south-west elongation is partly due to later deformation. The rocks were deformed during the Caledonian orogeny and again in the Variscan, the latter being responsible for much of the faulting. Despite the considerable deformation the grade of metamorphism remained extremely low. The difference in lithological rheology (reaction/movement of matter under pressure) results in differences in response to the folding; most of the movement being taken up by the mudrocks, which are strongly cleaved, tightly folded and locally thrust and overturned, where as the more massive volcanic rocks appear to have been faulted and shattered. It is this shattering of the rhyolites which give rise to their permeability.



The volcanic horizons are not continuous. This will interrupt the groundwater flow field and as a result limit the flow of groundwater through the aquifer. Well yields are highly variable throughout the formation with some very high yields available where regionally extensive sections of rhyolite rocks are intersected.

The overall pattern is that the older rocks are basaltic to andesitic and the younger ones are dominantly rhyolitic. Hydrothermal activity associated with rhyolite intrusion and brecciation has been responsible for extensive vein formation, often quartz-feldspar, or quartz-sericite,

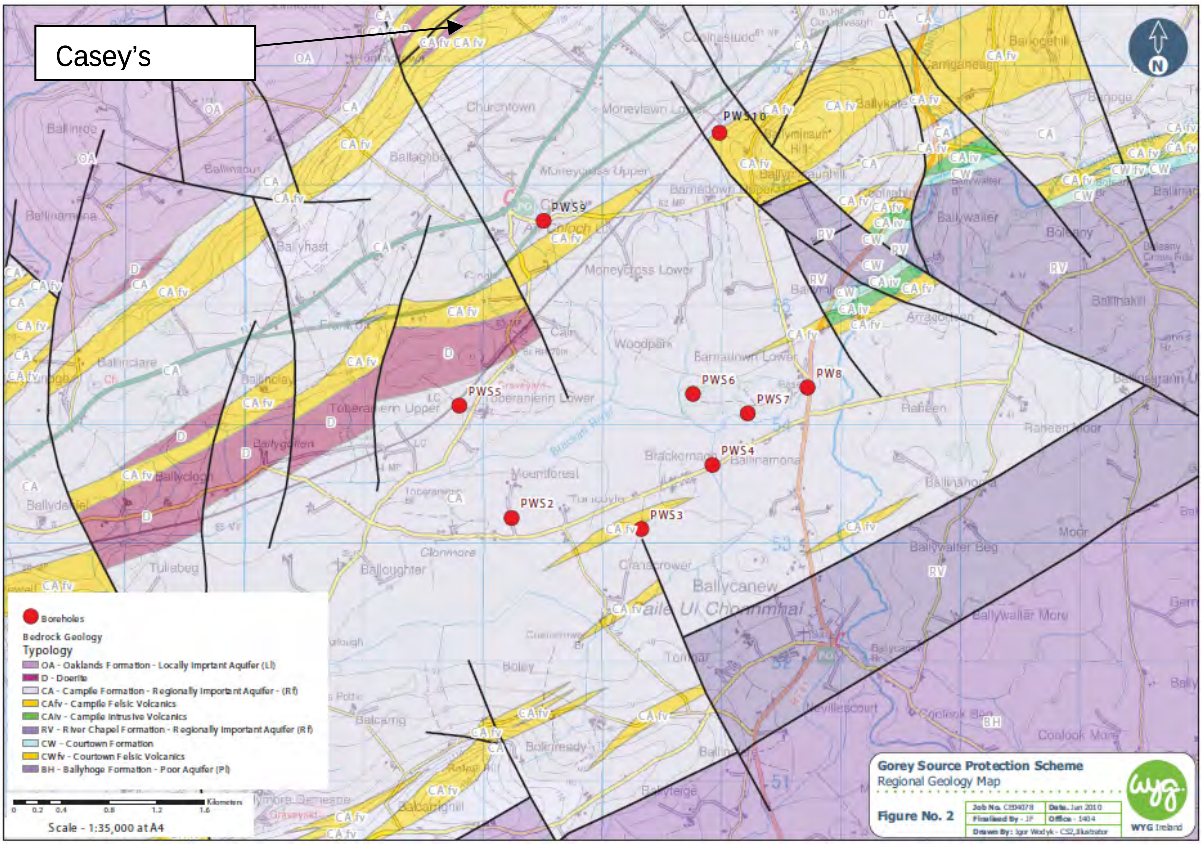
Vulnerability & Recharge

Large occurrences of rhyolite are particularly resistant to erosion while the sediments in between are not often seen. Consequently the rhyolites tend to be responsible to for the isolates hills formed within the outcrop of the Campile formation, including Tara Hill northeast of Gorey. Many of these smaller hills look similar to drumlins on the map however they are rock cored. These rock cored hills are key recharge areas for the large aquifer much of which can be underlain by thick deposits of low permeability till.

Gorey PWS – South Well field

WYG have been involved for a number of years in developing the South Well field of the Gorey PWS. A series of successful trial well locations were developed into production wells. The production wells are mostly 90m deep wells drilled into the rhyolites of the Campile formation. The well yields are quite variable, as shown in Table below.

Production Well	Depth to Bedrock (mbgl)	Well Yield (m^3/d)	Transmissivity (m^2/d)
PWS2	14	654	40
PWS3	12	348	78
PWS4	26	2370	173
PWS5	13.5	307	18
PWS6	19	1699	121
PWS7	20	429	136
PWS8	No Data	1550	328
PWS9	12	850	184
PWS10	22.5	1500	386

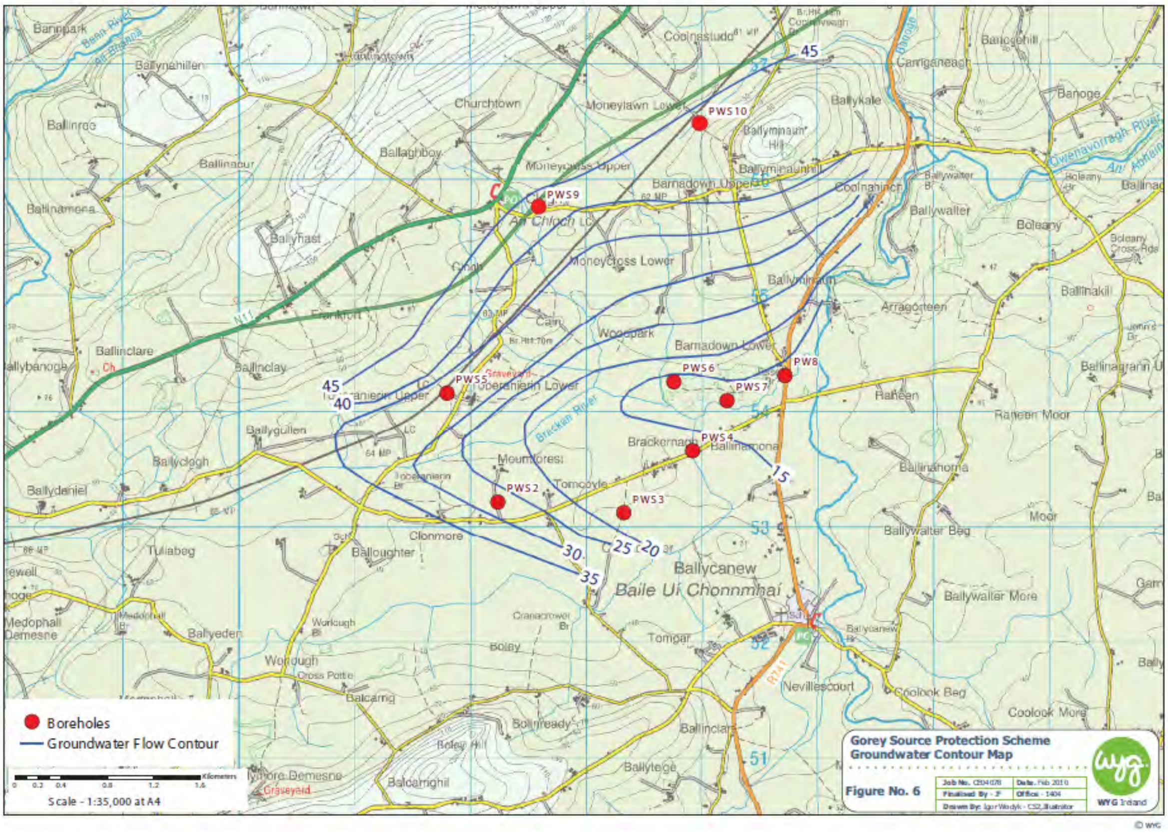


The majority of the wells were drilled with an air-rotary drilling rig however PWS9 & PWS10 were drilled successfully, but rather slower, with a mud drilling rig. PWS9 is drilled into an unmapped gravel aquifer which directly overlies the volcanic and is in turn overlain by low permeability clay. An extensive period of flushing was allowed for in PWS9 to ensure drilling muds were removed from the well and the gravel aquifer was sufficiently developed.

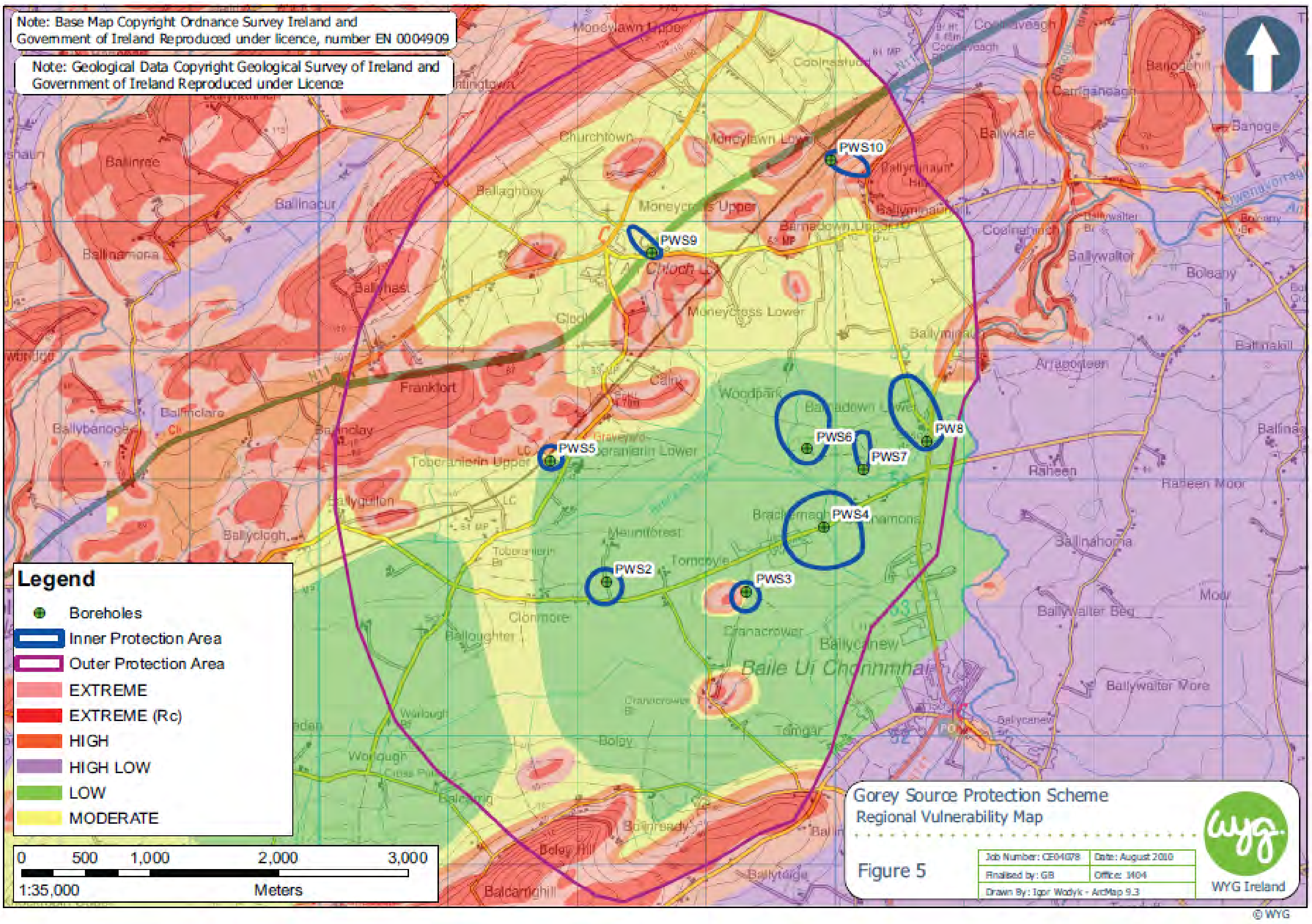
WYG have complete individual and simultaneous pumping tests on the production wells to determine the sustainable yield of the well field. The results of the pumping tests have been analysed to determine the transmissivity of the aquifer. The main method used for determination of the transmissivity was the Theis recovery method. The estimated transmissivity values are shown in Table above. This is indicative of a very productive aquifer. The storativity of the aquifers was not determined as in many cases observation wells were not available for monitoring during the test.

The aquifer is predominantly confined in the vicinity of the production wells by the overlying low permeability Irish Sea Till. This confinement provides good protection to the wells from nearby potential contaminant sources. The hydrochemistry at the wells confirms the confined state of the aquifer with clear denitrification and elevated iron and manganese.

A regional groundwater flow direction map was developed for the purposes of defining the groundwater flow direction and the source protection zone to the wells. The groundwater flow direction is locally towards the tributaries of the R. Bracken and ultimately towards the R. Owenavorragh to the east of the well field.



A revised vulnerability map was developed for the area by WYG, based on the depth to bedrock and permeability information. This map (shown in the figure below) shows the vulnerability ranges from extreme to low, with area of extreme vulnerability in the rock cored hills around the periphery of the valley and moderate and low vulnerability towards the centre of the well field. The recharge area for the production wells is quite large as there recharge in the moderate and low vulnerability areas is very low. A composite outer source protection area was delineated for the production wells in the well field. This was done as when individual source protection areas were initially defined they were found to overlap.



Inner source protection areas were based on modelling results with the USEPA model WHPA which used analytical modelling of the uniform groundwater flow field to determine travel time based protection areas around wells.

Casey's Quarry, Gorey, Co. Wexford.
Casey's quarry is a rock quarry which extracts from the Campile formation. The quarry uses all rock extracted from the site for a variety of purposes including, road stone, tar-mac and building blocks. The quarry owner is currently assessing the long term future development of the quarry. WYG have been asked to assist with assessing the hydrogeological aspects of any future quarry development. The quarry is located within the Campile formation. The quarry has some excellent exposures of the Rhyolite aquifer. There are sections of columnar-jointed rhyolite visible.

At present the site has extracted quite deep with the floor of the quarry being at 104m. The elevation at the ground surface at the top of the quarry is c. 135mOD. The deepest section of the quarry acts as a sump from which collects surface water and groundwater. Following rainfall events seepages can be seen along the side of the sump.

The sump is drained on a regular basis however the rate of abstraction or the duration is not recorded. The sump water is discharged to a local stream to the north of the quarry. This stream is a tributary of R. Bann. The R. Bann subsequently flows southwest towards the Slaney River. As such the quarry lies on the surface-water and groundwater divide between the R. Slaney which discharges to the Irish Sea at Wexford and the R. Owenavorragh which flows north east to discharge to the Irish Sea at Courtown.

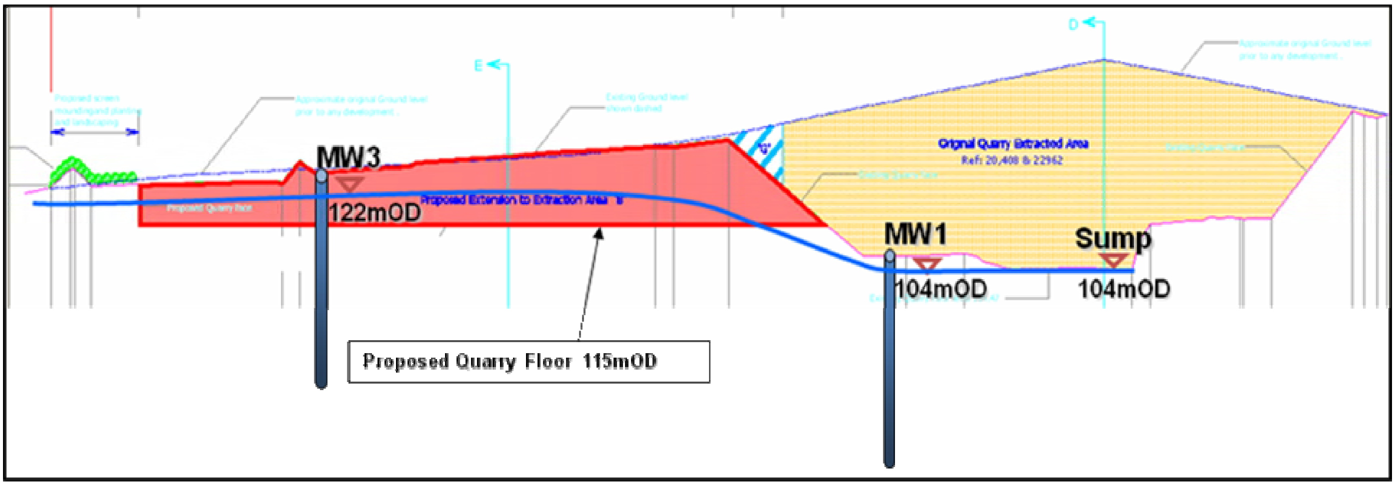
As part of the quarry assessment WYG propose to monitor the pumping from the sump to determine what the current dewatering rate in the quarry is. This will be used to help estimate the potential increase in dewatering rate associated with any further development of the quarry.

There are currently 3 pumping wells at the quarry. One at the entrance at the base of the hill, one located near the site office and one at the back of the site. These wells are used in conjunction with water pumped from the sump for the various on-site water requirements in the quarry such as dust-suppression system, wheel wash facilities and some processing works.

A short 3.5 hour pumping test was completed on the well at the back of the quarry. The recovery of the well was analysed and suggested a transmissivity of $81m^2/d$. This is quite a high transmissivity and suggests the aquifer is very productive. The value is comparable to the transmissivity estimates from some of the production wells in the Gorey South Well field.

Three additional monitoring wells were drilled in August 2010 by WYG. The wells have been surveyed into ordnance datum. One of the wells (MW1) was drilled near the floor of the quarry. The water level in this well is 104mOD, which is c. 2m below the ground level at this point and comparable to the water level elevation in the sump. This is a clear indication that the water in the sump is representative of the water table at that point.

The water levels in MW2 & MW3, which are located in the proposed future development area for the quarry, suggest the water table is at 122mOD at the end of August. The water table is therefore c. 7m below ground level. The quarry developer plans to extract below this depth. As a result there will be an increase in the dewatering at the quarry.



WYG plan to complete pumping tests on MW2 and MW3 to determine the aquifer parameters in the vicinity of these wells. The quarry exposures show a definite variability in the lithologies, faulting and veining over small areas. There could be considerable variability in the permeability of the aquifer between the different well locations.

An additional concern with the quarry is that it is located on the boundary of the outer protection zone of the Gorey South Well field. Further work is required to assess the potential impact of future quarry development on the well field.

Groundwater Vulnerability

M Spillane, M Kabza, O Murphy – Tobin Consulting

INFORMATION TO BE PROVIDED AT THE FIELD SITE

Copper Coast Geopark and Local Mining History

T. Keating – Geopark Geologist
D Cowman – Local Historian

The Copper Coast
European and Global Geopark
under the auspices of UNESCO

The Waterford coast from Tramore in the east to Stradbally in the west are mainly composed of Ordovician age rocks. The excellent coastal rock exposures display spectacular volcanic features that have attracted the attention of volcanologists since the 19th. Century. During the middle to the upper part of the Ordovician period, about 450 million years ago, this area formed part of the southeast margin of the ancient Iapetus Ocean and was the site of intense activity related to a volcanic arc situated at the Avalonian continental margin.

The area between Fenor and Stradbally is today called the Copper Coast because it was a very important copper mining district from 1824 –1908. Copper was extracted from a large number of copper bearing lodes called veins that trend NW-SE through the Ordovician rocks. The main copper ore present is Chalcopyrite (copper iron sulphide) which has a Copper content of about $35^{o}/_{o}$ and this is found within steeply dipping with quartz veins. The veins are up to 20m thick and the Tankardstown lode was mined to depths in excess of 400m. Some mines extended under the sea bed. The quartz veins often possess brecciated wall rock suggesting they may have been emplaced during the deformation of the Ordovician rocks.

The development of copper mining in the Bonmahon district resulted in many mines and engine houses which in their heyday (1824-1878) employed up to 1300 people. The coastal setting of the mines was a major advantage as the copper ore was loaded directly onto ships and transported to smelters in south Wales. In recent years the local community in collaboration with the geological Survey of Ireland have been very active in conserving the geoheritage of the area and promoting geotourism. This initiative resulted in the Copper Coast being designated a European Geopark in 2001 and Global Geopark status in 2004.

Location 1:
Tankardstown

Guide – Des Cowman

At the centre of the Copper Coast in County Waterford lie the 19th century mines of Bunmahon-Knockmahon-Tankardstown. The mines here were deep under the sea so pumping was a major operation.

The copper mines thrived from 1825 to 1875 before closing down, devastating the area. Most of the mining families headed into the unknown and were directed to the Copper Country of Michigan's Kewenaaw Peninsula and later to Butte, Montana

The Copper Coast was so named because of the rich copper deposits which were discovered and extensively mined during the 19^{th}.Century, occurring in the form of extensive, relatively thin, steeply dipping “veins” or “lodes”. The veins were composed mainly of Quartz and Chalcopyrite (a common type of copper mineral). Secondary copper minerals are also common in places.

Beautiful bright green and bright blue staining from the copper carbonate minerals Malachite and Azurite (the rarer of the two) are well exposed along the cliffs of Knockmahon strand but particularly in the walls of the “Copper Yard” at Stage Cove.

Location 2:
Stage Cove

This site was also the centre of a flourishing copper mining industry.
You can still see evidence of this activity. -
-The wall of the storage yard and remnants of the cobbled floor
-Adits in the cliff face where miners explored copper veins

There is also evidence of coastal erosion - slumping has exposed a beautiful section through the Ice Age sediments.

SUMMARY OF THE GEOLOGICAL HISTORY OF THE SITE, WHICH RESULTING ROCKS ARE VISIBLE HERE (My = Million years):

460 My – Bunmahon volcano – andesite, ash and tuff – Mainly grey/green coloured rocks.
The Copper Coast lies on the floor of a deep ocean, in a position close to the South Pole and experienced its first volcanic episode.

450 My – Kilfarrasy volcano – rhyolite, ash and tuff – Mainly grey/cream coloured rocks.
The Copper Coast lies on the floor of a deep ocean and experienced its second volcanic episode.

360 My – Desert conditions – sandstone and conglomerate – Mainly red/ purple coloured rocks.
Over the last 90 million years, through continental drift, the Copper Coast has been brought to the surface and to a position close to the Equator. The climate is bone dry and rivers snake their way

1.6 My – Ice Age – glacial till – mainly brown/muddy colour rocks – Several episodes of deep freeze and global warming alternate during the Ice Age. The glaciers gouged out the landscape and broke the underlying rocks on their way. Once they melted, the glaciers dropped their load of boulders and sand e.g. the glacial till.

10 000 years ago – Since the end of the Ice Age till now, the sea is recycling the material from the cliffs

The different rock formations of Stage Cove

Ice, Fire and Water Sculpture,
by Colette O'Brien

This sculpture was commissioned to illustrate the common geological theme to the four Geoparks: "Ice, Fire and Water".

Fire for the volcanism (Copper Coast, Vulkaneifel), Water for the sea (Copper Coast), lakes (Vulkaneifel,Bergstrasse), cave system(Marble Arch) and Ice for the Ice Age that shaped the modern landscape of all geoparks.

Supported by **Members of**

BUNMAHON DISTRICT (Information supplied by G Stanley – GSI)

Background information

Mine Name: Tankardstown, Stage Cove, Knockmahon

Mine District: Bunmahon

Alternative Names:
Bonmahon

Elements of interest:
Cu

Project Prefix: BUN-

County:	**Townland:**	**Grid Reference:**
Waterford	Knockmahon	E243962, N98996

The Bunmahon mine district is located 15km west of Tramore on the Waterford coast. It comprises numerous individual sites among which Bunmahon, Tankardstown, Stage Cove and Knockmahon (Fig. 1) were the most important. All are located within a 5km-long stretch of coastline. The district has a significant physical mining heritage, principally in the form of the recently conserved Tankardstown engine house complex (photo, right). The district is the focal point for the Copper Coast European Geopark.

Production and Mining History

Mining at Bunmahon may have taken place as early as the Bronze Age. According to Cole (1922) systematic mining began in the Bunmahon district in 1730 but it was only after the Mining Company of Ireland (MCI) began exploring in 1824 that extensive development occurred. For 50 years between 1828, when the company declared the vein system economic, and 1878 MCI mined continuously at Bunmahon (Tietzsch-Tyler 2005). Over the 30 years when the mines were being operated profitably (1834-46 and 1851-68) annual output ranged up to 7,000 tons of 10-13% copper ore. In the other, unprofitable years production was as low as 100-270 tons of 4-5% copper ore (Tietzsch-Tyler 2005). Total profits in the good years were £331,126 (average: £11,000 per annum) far outweighed total losses in the bad years of £47,757 (average: £1,447 per annum) (Tietzsch-Tyler 2005).

Mining initially began in Knockmahon where dressing floors were established with water-powered pumping and ore dressing (Tietzsch-Tyler 2005). During the 1830s and 1840s the mining was focused on Stage Cove, where five stream engines were erected for pumping and winding. Ore dressing continued at Knockmahon. The workings at Stage Cove extended under the sea but were eventually abandoned as sea water began to flood them. Subsequently, Tankardstown, less than 1 km to the east, was established as the centre of mining by 1850. Steam engines at the other two sites were dismantled and brought to Tankardstown. A tramway was also built to bring ore to the ressing floor at Knockmahon.

GEOLOGY AND MINERALIZATION

The Bunmahon mineralization is hosted by volcanic rocks of similar age to those that host the Avoca ores. However, in contrast to the essentially contemporaneous volcanism and mineralization at Avoca, the Bunmahon mineralization is hosted by quartz veins that are younger than their host rocks. The host rocks are chiefly members of the Ordovician Duncannon Group which consists of a variety of acid and intermediate volcanic rocks, shales and limestone as well as intrusive igneous rocks (Fig. 2). OBrien (1959) considered the mineralization to be pre-Devonian because an unmineralized Devonian Old Red Sandstone (ORS) basal conglomerate overlies one of the mineralized veins unconformably. However, many veins are situated on north-south faults which cut the ORS, suggesting a Devonian or post-Devonian age for mineralization (Sleeman and McConnell 1995). The mineralized veins contain fragments of brecciated wallrocks, suggesting they were emplaced during active deformation, and some are sheared. They occupy steeply-dipping faults consistently oriented NNW-SSE and intersect the coast where they are exposed in cliff sections (Wheatley 1971). All of them are repeatedly offset by cross-cutting faults and these, together with numerous problems relating to rent and taxation, contributed to the eventual cessation of mining in 1878. The veins are up to 20 m thick and have been traced to depths of 300 m (Cole 1922) and along strike for more than 2 km. At least five major lodes or vein complexes were exploited. Chalcopyrite was the main ore.

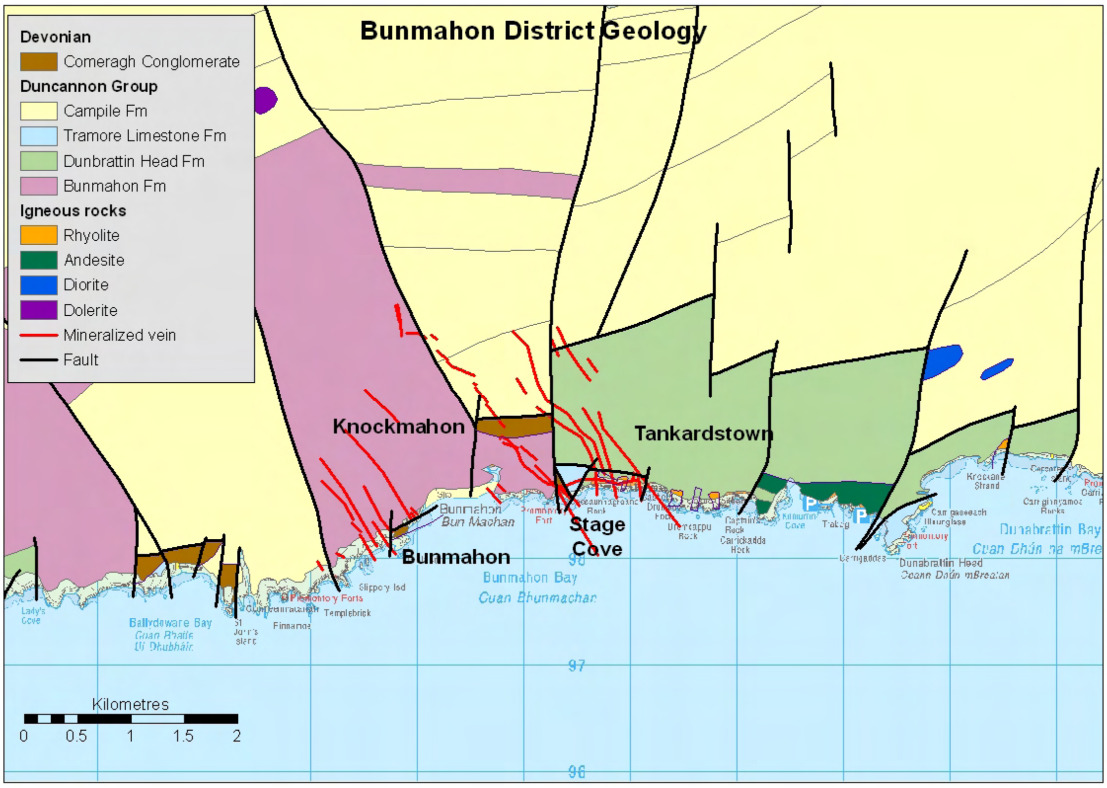


Fig. 1 Bunmahon District geology

There are few modern accounts of the geology of the mineralization at Bunmahon. The following description is based on Wheatley (1971). The mineralization consists of two distinct types: (i) siliceous veins with disseminated chalcopyrite and pyrite (Cu lodes) and (ii) siliceous veins with sphalerite, galena and minor chalcopyrite and pyrite (Pb-Zn lodes). The Pb-Zn lodes occur as shallow veins, averaging 1 m in thickness, but they are subordinate to the Cu lodes which average 3 m in thickness and extend to depths in excess of 300 m. Gangue material is mostly quartz but calcite, dolomite and barite are common constituents of the Pb-Zn lodes. Chalcopyrite fills the interstices between quartz grains and has a grain size of 0.2 - 1.0 mm. Pyrite is present in both veins and wallrock. A crude pattern of metal zoning has been noted with a Cu-rich zone centred on the Stage and Tankardstown Lodes and an outlying zone of Pb-Ba mineralization.

Site Description and Environmental Setting

Three sites were visited in the course of the HMS-IRC project, Knockmahon, Stage Cove and Tankardstown. The Tankardstown site has been subjected to a major conservation effort and is now a visitor attraction, with signage that describes the history and operation of the site. It is not considered further in this report. The remaining two sites include dressing floors and have been assessed geochemically.

The Bunmahon area is today well populated with a significant growth in recent years in the number of single houses. Many of these are located close to the sites of former mine workings, particularly shafts (Fig. 2). The scenic Waterford coast is also popular with tourists and the designation of the area as a Geopark has enhanced the attraction of the area. The land along the coast is mainly used for farming, both pasture and tillage.

The Knockmahon site (Fig. 2) was the main processing area for the Bunmahon district during the MCI operations. Processing plant included an engine house, crusher, hoppers, stamps and buddles. Numerous mine buildings were also on site including the magazine and the extant remains of the MCI Directors' house, mine manager's house and count house (Tietzsch-Tyler 2005). The cobbled remains of the dressing floor can still be seen near the site of the former crusher (photo, right). The site of the dressing floor is partly overgrown by gorse and grass but there are large areas of unvegetated solid mine waste of various textures and colours that marks the site of the former stamps and buddles. A large fan of waste that silted up the river channel during mining (Tietzsch-Tyler 2005) has been reclaimed as a flat, grassy area in use as a pasture field.

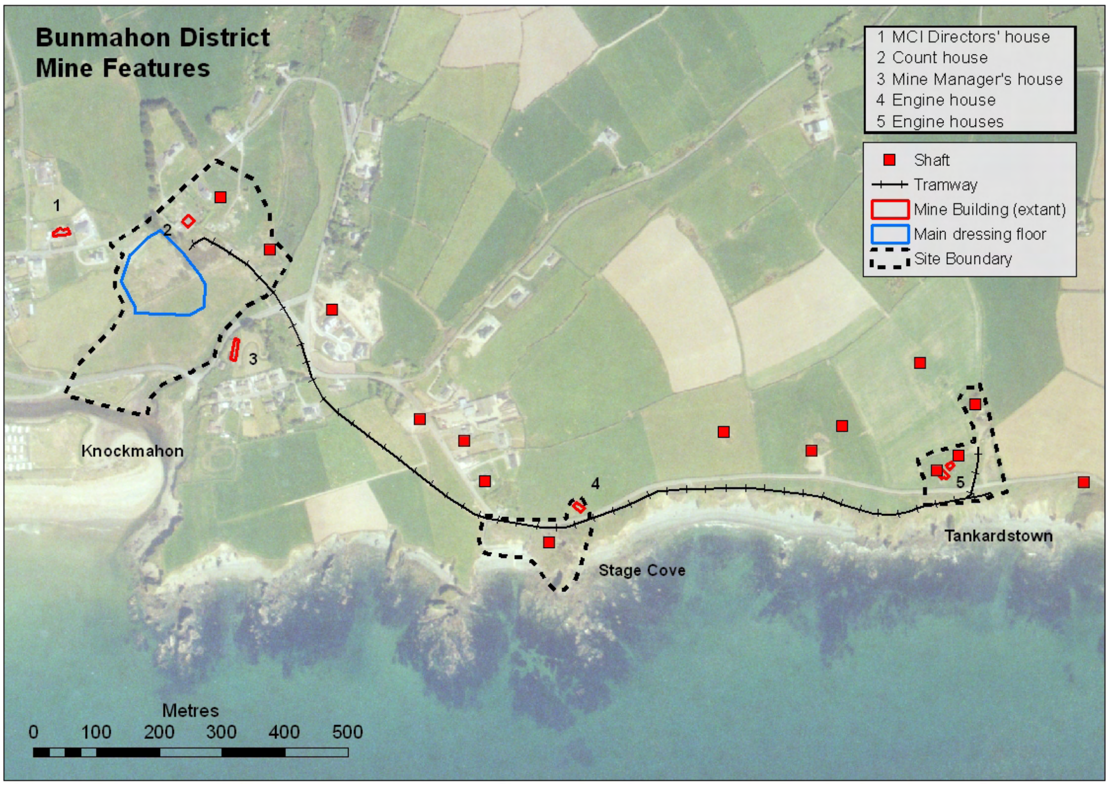


Fig. 2 Bunmahon District Mine Features

Stage Cove was a smaller site but still had a substantial engine-house complex (Tietzsch-Tyler 2005). Much of the site is grassed over. One ruined engine house remains on the landward side of the road while only a vague outline of the site of the remainder of the complex remains on the seaward side. Also on the seaward side of the road are the walled, cobbled processing yard and some shafts. There is an adit in the cliff-face below the yard. There are no apparent solid waste heaps at Stage Cove but, as it was a processing yard, several XRF analyses of "soil" were carried out.

The Tankardstown site has been the subject of a major conservation project in recent years. The site has been cleared of overgrowth and the buildings made safe through structural repairs. Excavations revealed many of the features linking the buildings, allowing a fuller interpretation of the operation of the site. Fencing and signage have been installed. The site is now a major locus for the Copper Coast Geopark. The walled yard contains the partially restored pumping engine house (photo, right), the ruins of the winding engine house, a restored chimney and the foundations of the boiler houses (Tietzsch-Tyler 2005). The three shafts on the site are filled in. No mine waste was identified on the site and no geochemical assessment was carried out at Tankardstown.

Solid waste was analysed mainly at Knockmahon, with some additional work carried out at Stage Cove (Fig. 3). Table 1 shows the estimated areas and volumes of the waste investigated for scoring under the HMS-IRC Site Scoring system.

TABLE 1 BUNMAHON SOLID WASTE HEAPS: AREA AND VOLUME

Waste ID	Area (m^2)	Volume (m^3)
BUN-PROC01	2787	2787
BUN-PROC02	704	352
BUN-PROC03	25105	25105
BUN-PROC04	1593	797

Geochemical Assessment

1. Surface water

No surface water samples were collected at Bunmahon. No mine water discharges were observed on any of the sites investigated. Some adits in the sea cliffs are known to discharge small flows of into the sea and the cliff faces below the adits are stained blue-green from the copper in the water.

2. Groundwater

Groundwater samples were not collected in the Bunmahon area. Leachate from a composite sample taken from the processing waste at Knockmahon had high levels of dissolved Cu (308 µg/l) and low levels of other metals such as Pb (8 µg/l), Zn (29 µg/l) and As (9 µg/l).

3. Stream sediments

One stream sediment sample was collected downstream of the Knockmahon site, near the mouth of the river (Fig. 3). Another sample was collected in 1990 about 500m upstream of the site as part of the GSI Regional Geochemical survey. In both cases, the fine (<150 µm) fractions was analysed. In addition, a <2 mm-fraction was collected at the downstream sampling site to compare with the fine fraction. The upstream sample had relatively low Cu and Pb concentrations but elevated Zn (Table 2). The fine fraction of the downstream sample had a high concentration of Cu (2677 mg/kg) and low concentrations of other elements of interest (Table 2). Somewhat surprisingly, given the tendency of metals to concentrate in the fine fraction of stream sediments, the coarser (<2 mm) fraction has an even higher concentration of Cu (4909 mg/kg). There is thus a clear indication in the data of significant downstream contamination of stream sediments as a consequence of mining at Knockmahon. The concentration of Cu recorded is well above the recommended limits for livestock (100 mg/kg).

Table 2 Stream sediment geochemistry, Bunmahon

mg/kg	**Cu**	**Pb**	**Zn**
GSI-903018 (u/s)	114	64	590
BUN-SS001 (d/s) <150 µm	2677	27	131
BUN-SS001 (d/s) <2 µm	4909	83	129

4. Solid waste

Twenty three *in-situ* XRF analyses were carried out in the district, 20 on the waste at Knockmahon and three in the copper yard at Stage Cove (Fig. 3). The waste contains high concentrations of Cu relatively high As and Pb (Table 3). Spectral analysis of the data suggests the samples analysed also contained elevated Mo but this element was not analysed quantitatively.

Three areas of solid waste have been defined at Knockmahon (Fig. 3). BUN-PROC01 is the main area of processing waste and includes mainly fine, red-brown waste (photo, right) that occupies the area where buddles and stamps were located. The second area of waste (PROC02) is located in the area where ore was unloaded from the trams, probably cobbed on the dressing floor and then run through the crusher. The waste in this part is generally covered by coarse, pebbly material but beneath this there is fine red-brown waste. The third area (PROC03) is the large flat grassed area in the floodplain of the river where, according to the reconstruction of Tietzsch-Tyler (2005), a fan of waste developed from the outwash from the processing area. The material analysed here was mainly soil at the base of the grass root layer.

The highest concentrations of Cu (1697 – 4737 mg/kg; median: 3650 mg/kg) were measured in PROC01 (Fig. 3). One spot in PROC03, closest to the main processing area, had a measured Cu concentration of 4043 mg/kg but other measured concentrations were lower, perhaps not surprisingly since soil was analysed rather than mine waste. Nevertheless, the concentrations of Cu measured in the other four samples in PROC03 (109 – 813 mg/kg) were much higher than the concentrations measured in soils in the region (maximum 68 mg/kg) for the National Soils Database (Fay *et al*. 2007). Concentrations of Cu measured in PROC02 were generally in between those for PROC01 and PROC03. The median concentration of As in the processing waste in PROC01 was 268 mg/kg (range: 87 to 660 mg/kg), much higher than that for PROC02 and PROC03 (combined median: 56 mg/kg).

Measured element concentrations in the copper yard at Stage Cove were in the lower range for Bunmahon (Fig. 3), Cu ranging from 647 to 1190 mg/kg and As from 24 to 175 mg/kg.

The highest Cu concentrations measured in mine waste at Bunmahon are in excess of soil guideline limits for children. Those for As exceed limits for both adults and children (Table 3.1.2, main report).

Table 3 Summary statistics, *in situ* XRF analyses, Bunmahon

mg/kg	Cu	Pb	Zn	As
n	23	23	23	23
Minimum	109	27	0.0	16
Maximum	4737	481	91	806
Median	1943	111	46	175
Mean	2229	151	40	235

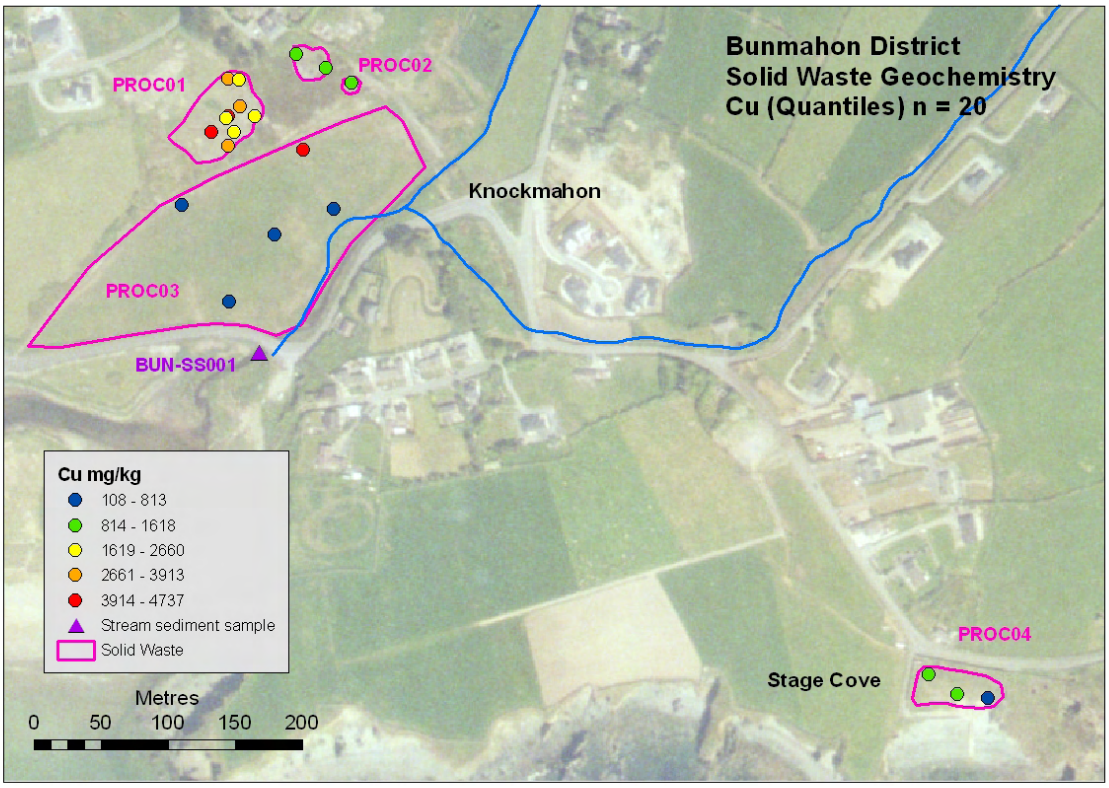


Fig. 3 Distribution of Cu in solid waste samples, Bunmahon

5. HMS-IRC Site Score

The HMS-IRC Site Score for Bunmahon is 14 (Table 4), a low score that reflects the relatively small amount of waste on the site and the absence of high concentrations of high-relative toxicity elements such as Pb, As, etc. No surface water samples were collected so there is no evidence of any impact by the mine site on the chemistry of surface water in the nearby river. The absence of any discharges of mine water to the river limits the potential for such impact, particularly since the most metal-rich waste (PROC01) is some distance from the river, reducing the possibility of contamination by diffuse groundwater flow. However, the stream sediment data do indicate an observed release from the site to the river.

Table 4 HMS-IRC Site Score, Bunmahon

Waste	PROC01	PROC02	PROC03	PROC04	Stream Sediment	Total
1. Hazard Score	12	12	12	11	1	48
2. Pathway Score						
Groundwater	1.75	1.20	1.21	0.80	-	4.96
Surface Water	2.94	2.86	2.76	0.18	-	8.73
Air	0.01	0.00	0.00	0.00	-	0.01
Direct Contact	0.02	0.00	0.13	0.02	-	0.17
Direct Contact (livestock)					0.14	0.14
3. Site Score	**5**	**4**	**4**	**1**	**0**	**14**

Fig. 4 shows the contribution of the different pathways to the total site score at Bunmahon. Pathways are the routes by which receptors are exposed to the hazard. The surface water pathway dominates the scoring (62.3%), largely because of the proximity of the river to the Knockmahon site and the fact that the stream sediment data indicate an observed release to the surface water pathway from the mine waste. Leachate data from PROC01 also indicate an observed release to groundwater but no data are available for the other waste heaps. Hence, the groundwater pathway contributes just 35.4% of the total though this might have been significantly higher if leachate data were available for the other waste heaps.

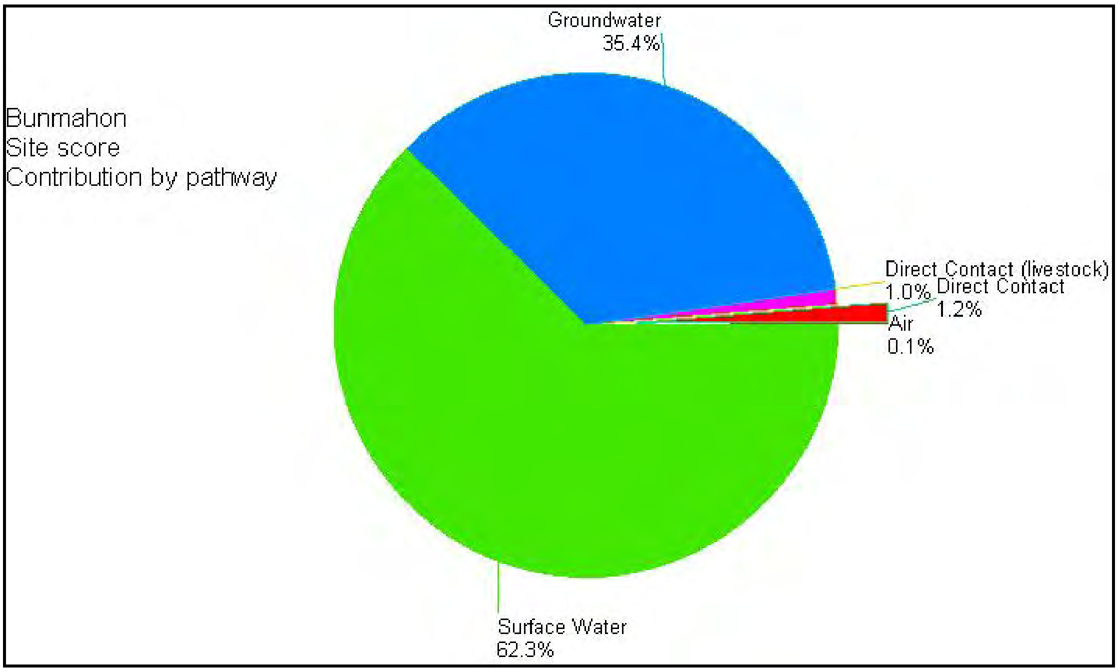


Fig. 4 HMS-IRC Site Score, Bunmahon: contribution by pathway

6. Geochemical overview and conclusions

Bunmahon was a highly productive and profitable mine district in the 19th century. Only limited mine waste remains on the three sites investigated for the HMS-IRC project, with most found on the old processing area at Knockmahon. High concentrations of Cu, in excess of recommended limits, were measured in both processing waste and in stream sediment downstream of the mine. Among other elements measured, only As is present in significant concentrations. The total site score is 14, placing Bunmahon in Class V.

References

COLE, G. A. J. 1922. Memoir and Map of Localities of Minerals of Economic Importance and Metalliferous Mines in Ireland.

Sleeman, A.G and McConnell, B. (1995) Geology of East Cork – Waterford. A geological description of East Cork, Waterford and adjoining parts of Tipperary and Limerick to accompany the bedrock geology 1:100,000 scale map series, sheet 22, East Cork-Waterford. Geological Survey of Ireland.

Tietzsch-Tyler, D (2005). Historical Reconstruction Drawings of the Copper Coast Mines, Co. Waterford. *Journal of the Mining Heritage Trust of Ireland*, 5, 29-46.