British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Applied geoscience for our changing Earth

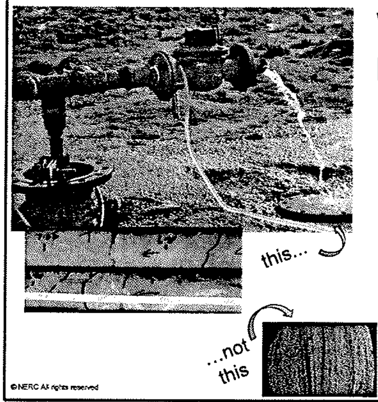
An overview of low productivity bedrock aquifers in Scotland

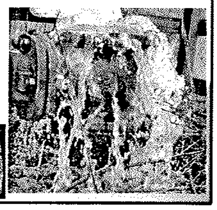
Classifying and understanding in order to manage

Brighid Ó Dochartaigh & Alan MacDonald
British Geological Survey

What is low productivity?

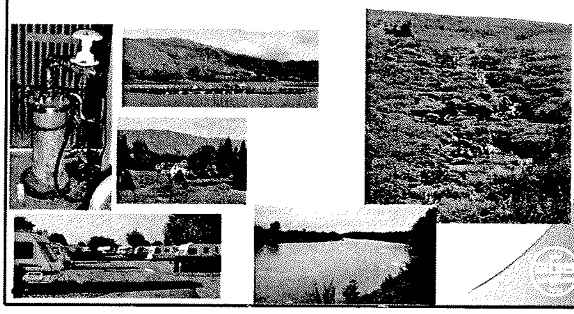
Borehole yields < 1 l/s; & usually < 0.5 l/s



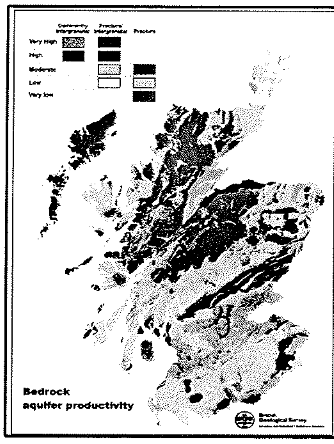


Why are low productivity aquifers important?

- Private (small and large), public, & small industrial water supplies.
- Support surface water flows and ecosystems; affect flooding



Aquifer productivity map 2004

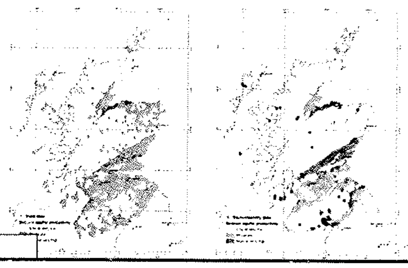


Based on **geology**, **limited hydrogeological data**, and extrapolation using **expert judgement**

MacDonald et al. 2004. BGS Report

Aquifer properties

- 2 year project
- Collated **quantitative data** on ~3,400 groundwater sites
- Few pumping test (T, S or Sc) or lab core (K, Φ) data
- Yield (Q) data most common



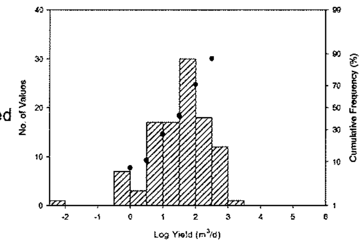
- Relatively few data points from low productivity aquifers
- Of these, few 'traditional' aquifer properties data

	No. of sites with data		
	Transmissivity	Specific capacity	Borehole yield
Ordovician / Silurian	-	5	94
Precambrian / Cambro-Ordovician	11	18	47
Igneous	-	17	88

Yield data

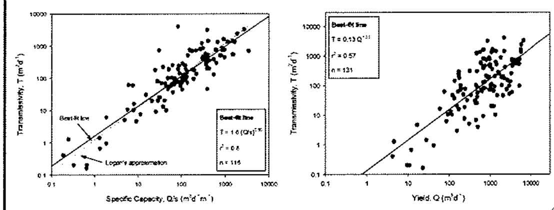
E.g. Precambrian, Cambro-Ordovician & igneous aquifers

- Log normally distributed
- Median yield 0.35 l/s
- Probably biased to higher yielding sites
- Occasional higher yields – mainly springs



Statistical analysis

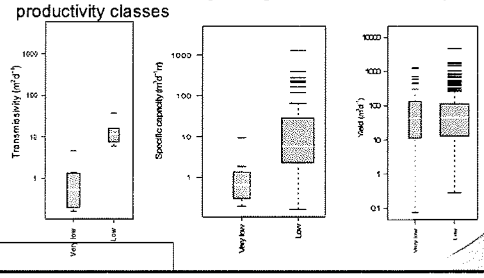
- Both Sc and Q are good proxies for T:



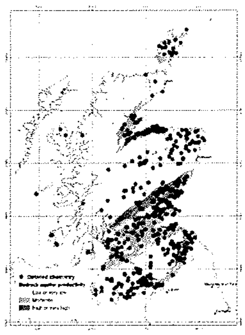
Graham et al. 2009. QJEGH 42.

Aquifer properties & aquifer productivity map

- **Good agreement:**
- Clear correlation between median T & Sc values and aquifer productivity class
- Q less useful for distinguishing between low and very low aquifer productivity classes



Natural groundwater chemistry

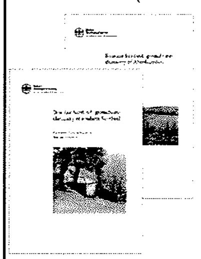


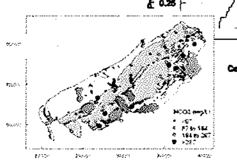
- Baseline Scotland
- 6 year BGS/SEPA project
- Rigorous sampling procedure
- Few but increasing samples from low productivity aquifers:
  - >150 detailed chemistry analyses
  - >50 residence time analyses

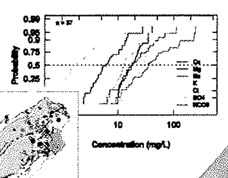
So far:

http://www.bgs.ac.uk/data/baselineScotland/

- Detailed interpretations from Lower Palaeozoic (southern Scotland), Dalradian (Aberdeenshire)
- Preliminary evidence from Devonian and Carboniferous volcanics (Central Belt) and Southern Highland Group







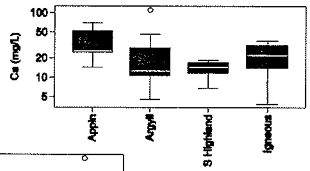
Low productivity aquifer chemistry

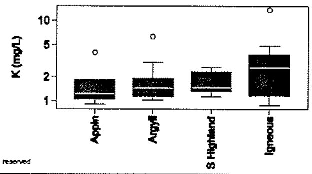
- Natural chemistry is more **variable** than high productivity aquifers, but often **predictable**
- Key **controls** are
  - bedrock & overlying superficial lithology
  - compartmentalised flow systems
  - residence time
  - redox
  - Also: recharge altitude, maritime influence
- Chemistry indicates that groundwater flow is dominantly through **fractures** and **well mixed** in top 50 m

Major ion chemistry

E.g. Precambrian and igneous aquifers in Aberdeenshire

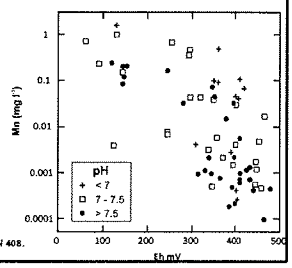
- Often predictable
- Often related to bedrock geochemistry
- Residence time also important





Trace element chemistry

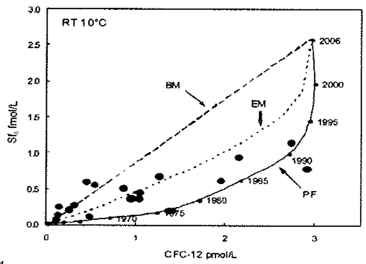
- Less predictable than major ion chemistry
- Key controls are Eh and pH
- Groundwaters typically oxic in southern Scotland and Aberdeenshire, but early indications of often anoxic waters from Southern Highland Group & volcanics
- What controls Eh & pH? Ongoing studies suggest superficial deposits, e.g. peats



Homoncik et al. 2010. STOTEN 408.

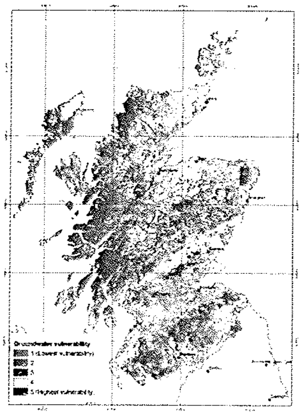
Groundwater age

- Generally no evidence of palaeowater
- But often several decades old



Management issues for low productivity aquifers

- Essential role in supporting ecosystems and river flows
- Not heavily, but relatively widely used for supply
- Large & remote areas – logistically and technically hard and expensive to measure, understand and monitor
- Variable physical and chemical properties – do we need more data to properly characterise?



Groundwater vulnerability

- 2003 – map developed in response to Water Framework Directive requirements
- Vulnerability controlled by pathway from ground surface to water table
- Opposite of 'traditional' groundwater vulnerability – low productivity aquifers are most vulnerable

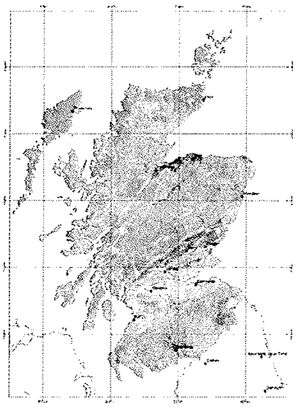
http://www.sepa.org.uk/water/monitoring_and_classification/assessment_tools/interpretation_of_the_maps.aspx

Low productivity aquifers:

- Fractured, with thin superficial cover ➔ easy, rapid pathways to saturated zone with little attenuation
- Limited recharge and storage volumes, and short, compartmentalised flow systems ➔ relative volumes of groundwater (and baseflow) are small

Groundwater in low productivity aquifers is rare (low volume) and highly vulnerable – and therefore needs special protection?

Aquifer vulnerability?



- Combining groundwater vulnerability with aquifer productivity
- But keeping them separate – not making economic judgements on groundwater value

Summary

- Low productivity aquifers cover most of Scotland
- Fewer data than for high productivity aquifers – need different investigation tools
- Yield is a good proxy for physical aquifer properties
- Chemistry interesting – variable but can be predictable
- Management challenging; different needs to higher productivity aquifers

lots already done; lots more to do!

Thankyou

Monitoring poorly productive bedrock aquifers in the Republic of Ireland

An Overview

Donal Daly, EPA
Henning Moe, CDM Ireland
Matthew Craig, EPA

epa

CDM

Acknowledgements

The concepts described in the paper were developed during interaction between the Groundwater Section, Geological Survey of Ireland, the WFD Working Group on Groundwater and the EPA.

The monitoring point installations were funded by the Department of Environment, Heritage and Local Government and administered by Carlow County Council

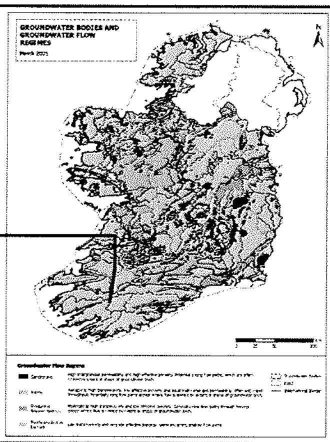
The drilling and well installations were undertaken by Aquadrill

Organisation and supervision of the well installations was undertaken by CDM and OCM staff.

David Ball acted as an advisor to the EPA

Groundwater Flow Regimes

Source: GSI



Poorly productive aquifers

Underlies ~65% of country

Context

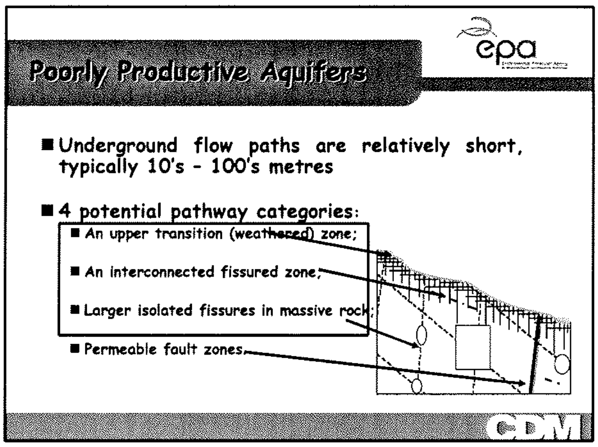
- ~65% of land surface of the Republic of Ireland is underlain by "Poorly Productive Aquifers" (PPAs)
- 25% (~60) of monitoring points (MPs) in the total network (220) are located in the PPAs
- These MPs are relatively high yielding wells and springs located along localised zones of high transmissivity - geological faults.
- Therefore, the 'mass' of PPA bedrock being monitored is small

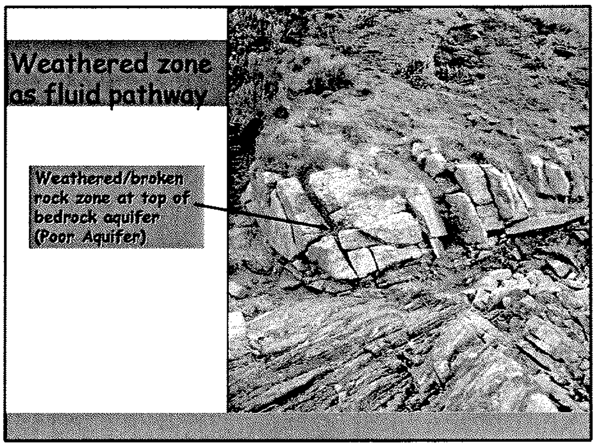
Context (2)

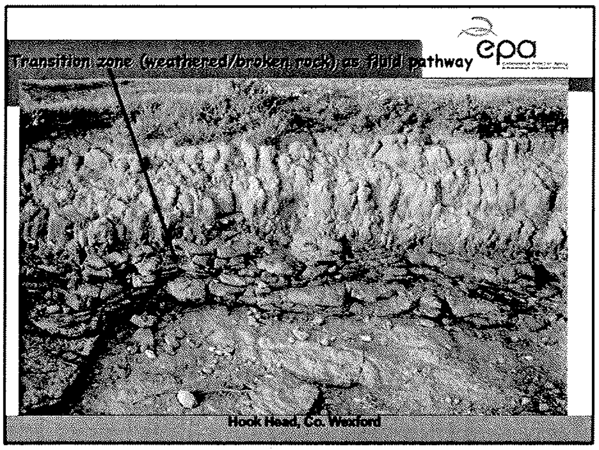
- Little hydrogeological investigation has been undertaken in PPAs
- Therefore, our understanding of flow processes is poor.
- Depending on the rock type, groundwater in bedrock is estimated to be providing between 15-30% of average river flows
- Many watercourses in PPA areas are classed as less than good status.
- In some of these areas, the land is 'dry' and the stream density is low.

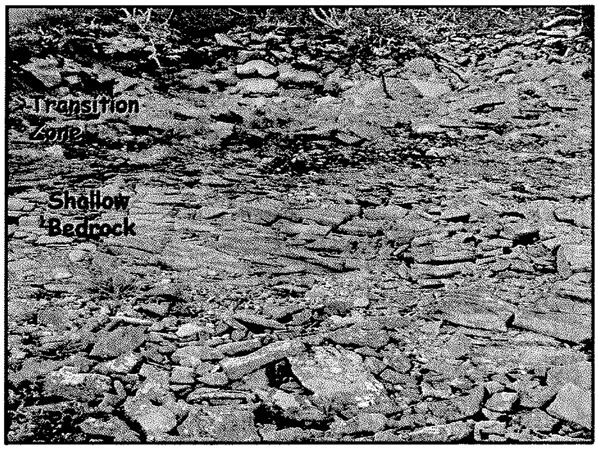
Context (3)

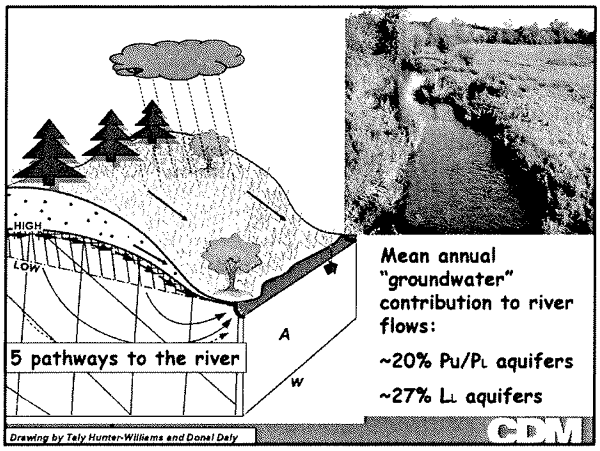
- Issue 1: What role has groundwater in contributing pollutants to surface water in these areas?
- Issue 2: What are the hydrogeological characteristics of PPAs?
- Issue 3: How much attenuation occurs along underground pathways?
- Issue 4: Where are the "critical source areas" in catchments underlain by PPAs?
- Issue 5: How should they be monitored?

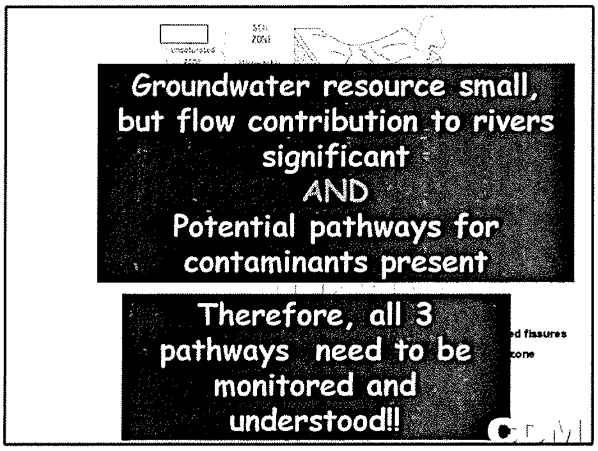

Poorly Productive Aquifers
epa
Underground flow paths are relatively short, typically 10's - 100's metres
4 potential pathway categories:
An upper transition (weathered) zone;
An interconnected fissured zone;
Larger isolated fissures in massive rock;
Permeable fault zones.
CDM


Weathered zone as fluid pathway
Weathered/broken rock zone at top of bedrock aquifer (Poor Aquifer)


Transition zone (weathered/broken rock) as fluid pathway
epa
Hook Head, Co. Wexford

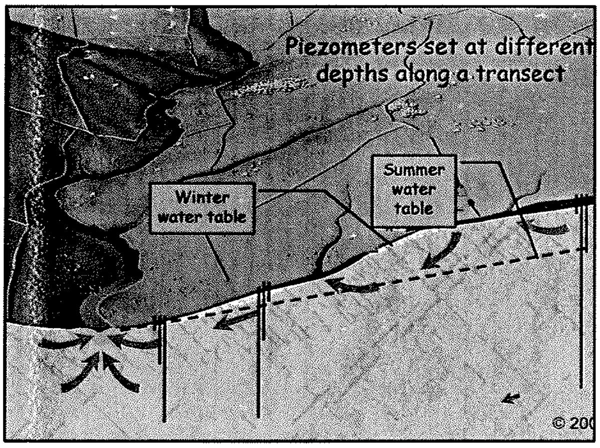

Transition Zone
Shallow Bedrock


HIGH
LOW
A
W
5 pathways to the river
Mean annual "groundwater" contribution to river flows:
~20% Pu/Pl aquifers
~27% Ll aquifers
Drawing by Taly Hunter-Williams and Donal Daly
CDM


Groundwater resource small, but flow contribution to rivers significant
AND
Potential pathways for contaminants present
Therefore, all 3 pathways need to be monitored and understood!!

Our Monitoring Approach

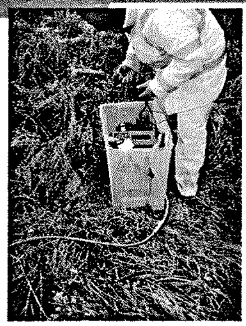
- Six poorly productive typology settings: impure limestones; ORS; granites; highly metamorphosed rocks; weakly metamorphosed rocks.
- Piezometers set at different depths in specially drilled boreholes.
- 3 well clusters, with 3-4 wells in each, along a transect in each setting.
- Hydraulic testing undertaken.
- Data loggers installed.
- Water samples taken; levels monitored.

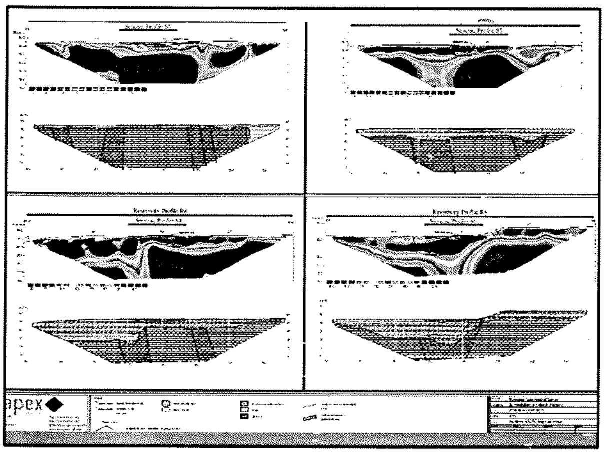


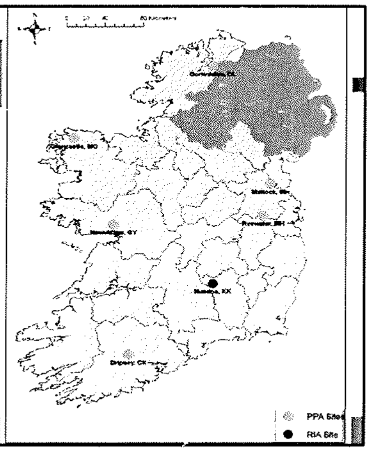
Siting of Suitable Locations

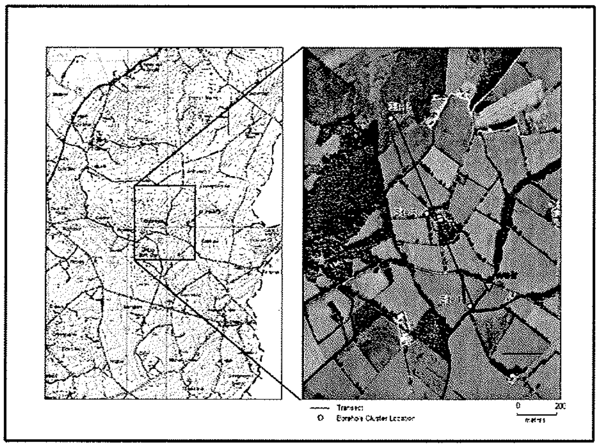
Surface Geophysical Surveys

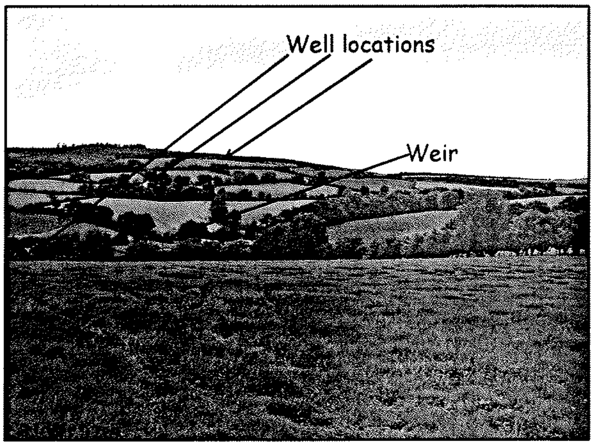
Two subcontractors used:
1. QUB
2. Apex

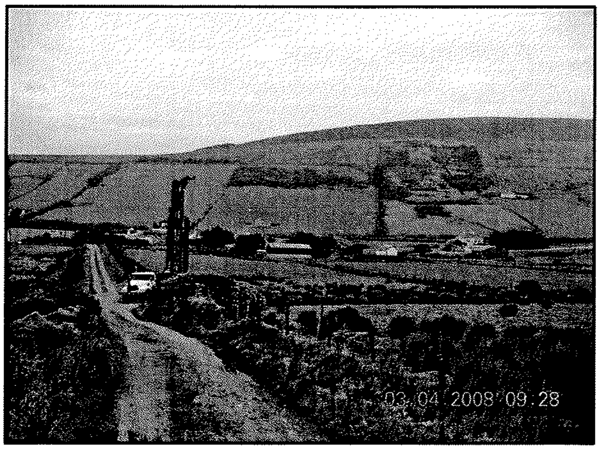









Well locations
Weir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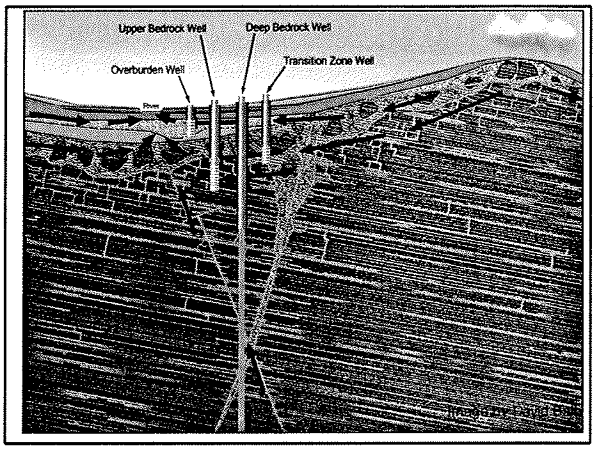
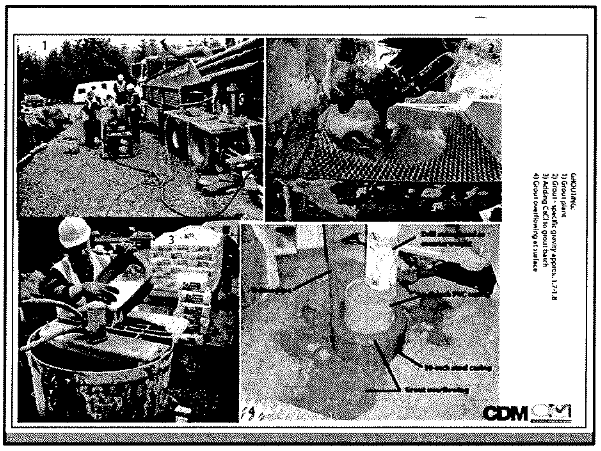
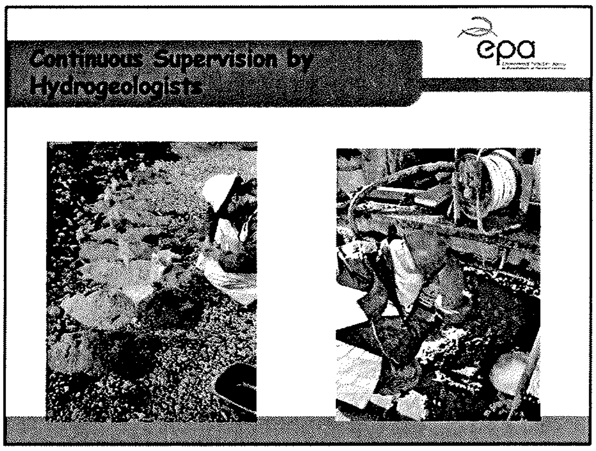
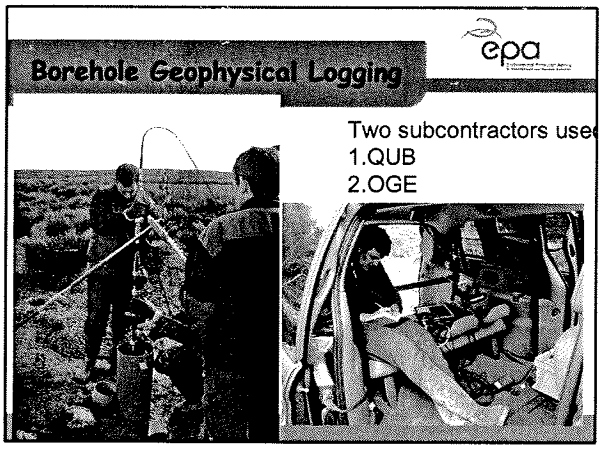
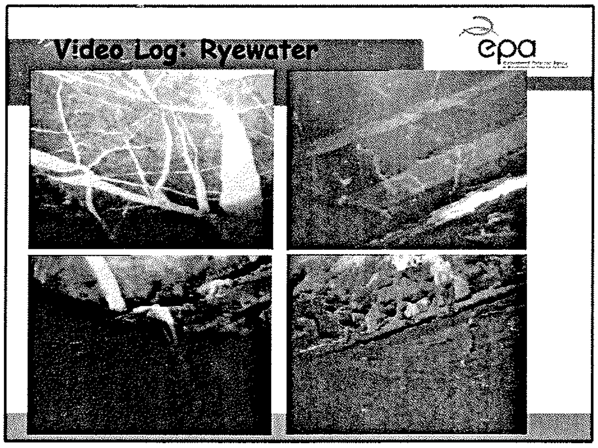
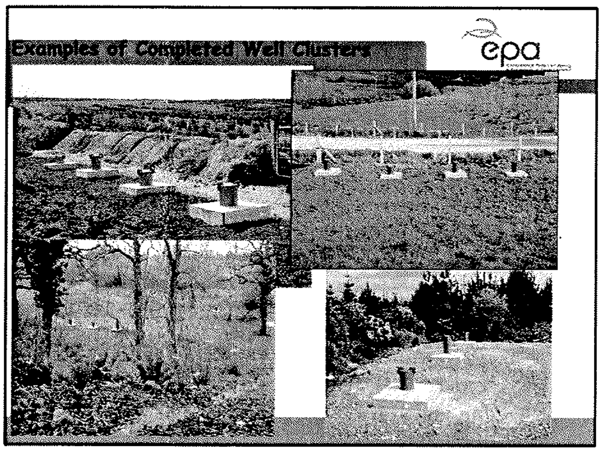

Upper Bedrock Well
Deep Bedrock Well
Overburden Well
Transition Zone Well

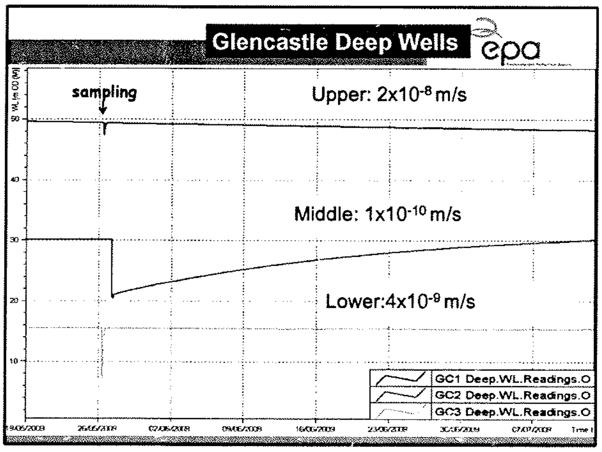

CDM

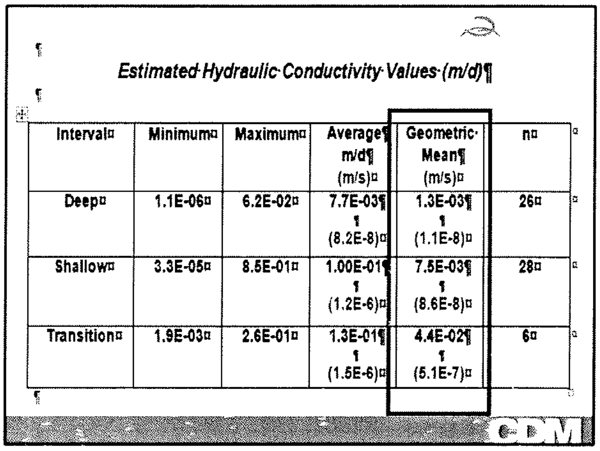

Continuous Supervision by Hydrogeologists
epa





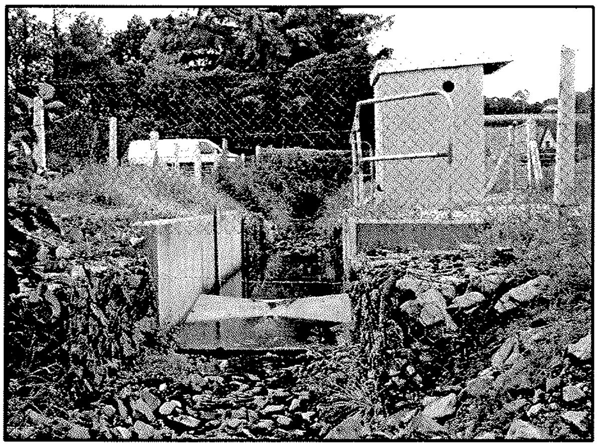






Estimated Hydraulic Conductivity Values (m/d)

Interval	Minimum	Maximum	Average m/d (m/s)	Geometric Mean (m/s)	n
Deep	1.1E-06	6.2E-02	7.7E-03 (8.2E-8)	1.3E-03 (1.1E-8)	26
Shallow	3.3E-05	8.5E-01	1.00E-01 (1.2E-6)	7.5E-03 (8.6E-8)	28
Transition	1.9E-03	2.6E-01	1.3E-01 (1.5E-6)	4.4E-02 (5.1E-7)	6



GW Chemistry

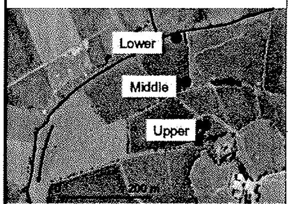
- Between 3 - 4 samples/year
- Dedicated tubing
- Pumps cleaned between sites
- Flow through cell - Purged until parameter stablisation

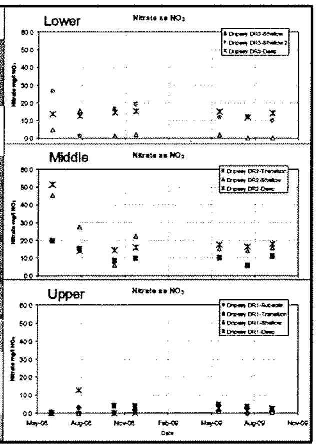
Chemical Analysis Suite	Parameters Analysed
Basic Monitoring Suite	**Field Analysis:** pH; Dissolved Oxygen; Temperature; Conductivity; Redox **Laboratory Analysis:** pH; Conductivity; Colour; Alkalinity; Total Hardness; Nitrate; Ammonium; Nitrite; Total Phosphate; Molybdate Reactive Phosphorus; Iron; Manganese; Sodium; Potassium; Chloride; Calcium; Sulphate; Silica; Cadmium; Arsenic; Zinc; Mercury; Lead; Magnesium; Copper; Boron; Aluminium; Nickel; Chromium; Total Organic Carbon; Fluoride; Barium; Molybdenum; Silver; Cobalt; Strontium; Beryllium; Antimony; Turbidity; Uranium; Total Coliforms & Faecal Coliforms (E-Coli)
Pesticides **(New Village)**	**Laboratory analysis:** Atrazine; Simazine; MCPA; 2,4-D; Isoproturon; Mecoprop; Chlortoluron; Glyphosate; Bentazone; Cypermethrin; Dieldrin; DDT; Lindane; Diuron; 2,6-dichlorobenzamide (BAM) & Total Pesticides

- Pesticides at NV
- Radon (RPII) at NV/GC

Dripsey - Nitrate

- Dairy Farming

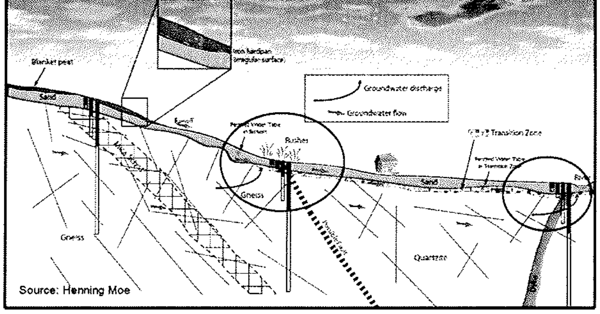




Summary

Characteristic	Newvillage	Glencastle	Dripsey	Mattock	Ryewater	Gortinleive
Low-K	✓	✓	✓	✓	✓	✓
Discrete inflows	✓	✓	✓	✓	✓	✓
Transition zone	✓	✓	✓	N	Y/N	✓
Vertical gradients	✓	✓	✓	✓	✓	✓
Upward flow near river	✓	✓	✓	N	✓	✓

Conceptual Model - Glencastle



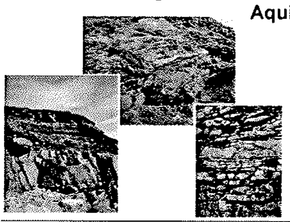
Finally - Assessing the Data

- The QUB Research funded by the Griffith Geoscience Programme will enable a far greater understanding of the hydrogeological characteristics of PPAs.
- EPA will continue to monitor, evaluate and report on the data collected.

Griffith Geoscience Award

Queen's University Belfast

Multi-disciplinary Characterisation of Groundwater Flow Regimes in Low Productivity Hard Rock Aquifers

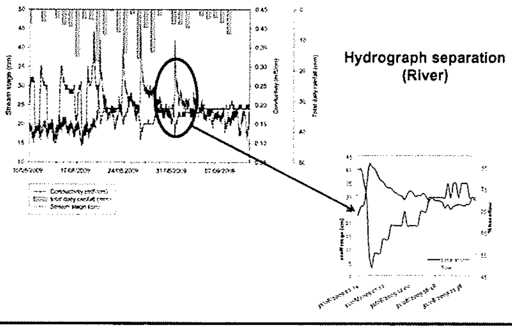


Geological Survey of Northern Ireland

Griffith Geoscience Project
Groundwater Group at QUB

- Dr. Rachel Cassidy
- Dr. Jean-Christophe Comte
- Dr. Ray Flynn
- Dr. Ulrich Ofterdinger
- Katarina Pilatova
- Janka Nitsche

Griffith Geoscience Project
PP4 - Hydrograph



Hydrograph separation (River)

Griffith Geoscience Project
Overview

- Project Objectives
- Methodology of Investigation
- Study Catchments
- First results - Gortinlieve, Co. Donegal & Mount Stewart, Co Down.
- Conclusions
- Perspectives

Griffith Geoscience Project
Objectives

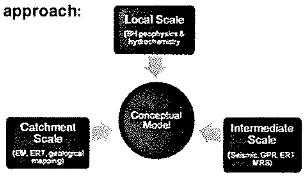
- **Main Objectives of the Project include:**
  - Characterisation of key groundwater flow components
  - Investigation of processes governing groundwater contributions to catchment run-off
  - Characterisation of geological structures and hydrogeological units
  - Development of conceptual model(s) for groundwater flow within poorly productive (incl. bedrock) aquifers
  - Development of numerical groundwater flow models for poorly productive aquifers

Griffith Geoscience Project
Methodology

- **The research activities under the Griffith project are used as a combined investigative approach, and include:**
  - **Borehole and Surface Geophysics**
    - to characterise aquifer heterogeneity(ies) & typology *(incl. relevant structural subsurface features)*
  - **Discontinuity Analysis**
    - To characterise fracture patterns at surface and subsurface level
  - **Hydraulic Well Testing**
    - to characterise aquifer parameters
  - **Hydro- & Geochemistry**
    - to characterise groundwater-surface water mixing processes and rock-water interaction processes
  - **Stable Isotopes**
    - to characterise groundwater flow components, recharge processes & groundwater contributions to surface water flow

Griffith Geoscience Project
Methodology

- **General Methodology**
  - **Characterisation using geological, geophysical and geochemical data**
  - **An integrated approach:**

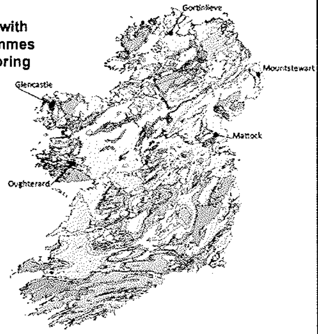


  - **Cross-comparison and evaluation of techniques**

Griffith Geoscience Project
Study Catchments

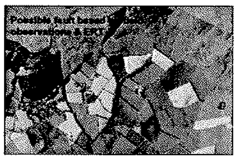
Field sites selected in collaboration with EPA/GSI & GSNI Monitoring Programmes to make best use of available monitoring installations

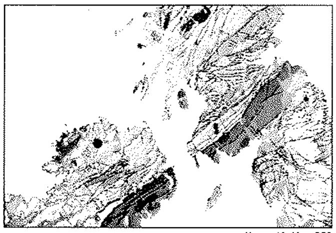
Poorly Productive Aquifer Field Sites	
Mount Stewart	Ordovician/Silurian Greywacke
Gortinlieve	Dalradian Metasediments
Glencastle	High Grade Metasediments
Mattock	Ordovician/Silurian Greywacke
Oughterard	Granite



Griffith Geoscience Project
Gortinlieve, Co Donegal

Geological map





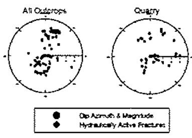
Map modified from BGS

Geology	Single Unit: Southern Highland Group (Dalradian) Pelitic & psammitic schist, phyllite & marble
Catchment	~2km²
Features	NE/SW trending fault

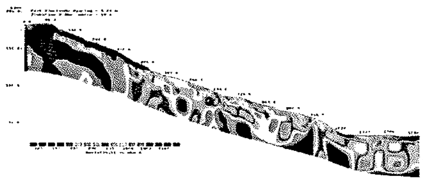
Griffith Geoscience Project
Catchment Scale Survey

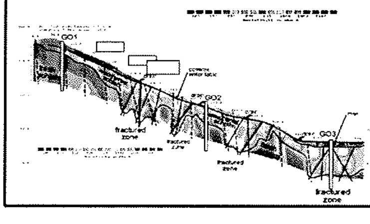
Digital Elevation Model

Outcrop Fracture Analysis

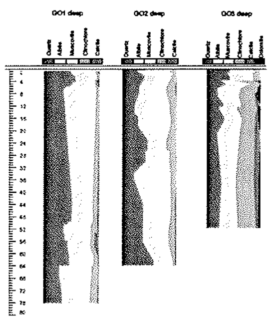


Griffith Geoscience Project
Gortinlieve - ERT



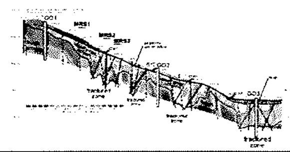


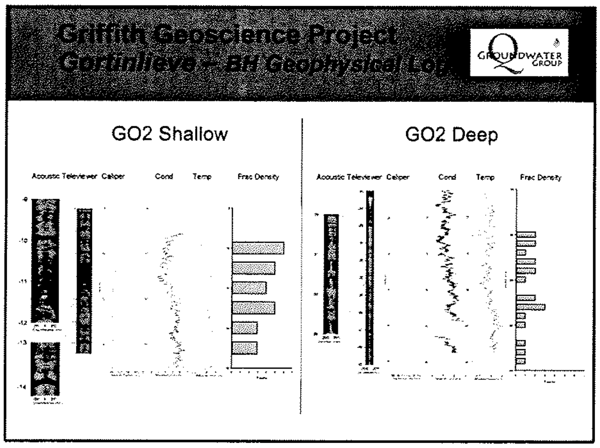
Griffith Geoscience Project
Gortinlieve - XRD

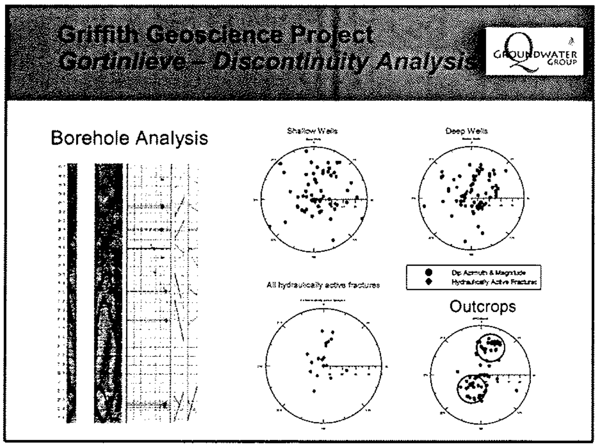


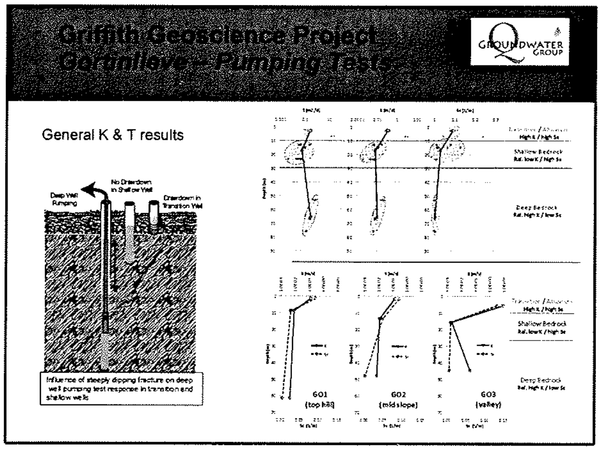
Mineral assemblages - taken from core cuttings

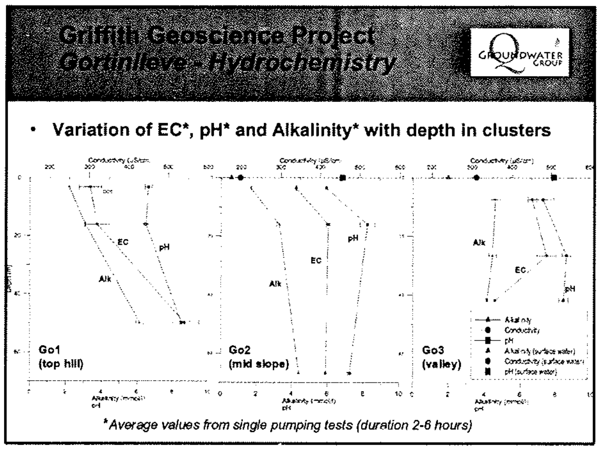
Quartz, Feldspars, Mica, Chloride, Calcite & Dolomite

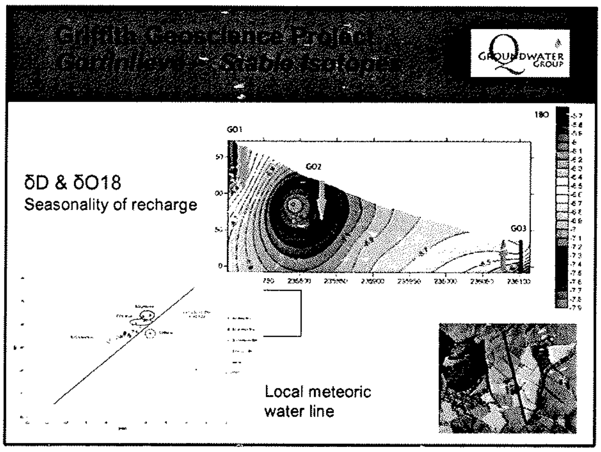


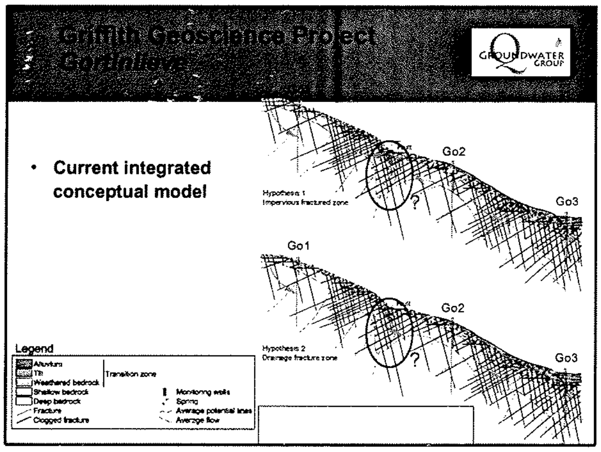

Griffith Geoscience Project
Gortinlieve – BH Geophysical Log
GO2 Shallow
GO2 Deep
Acoustic Televiewer Caliper
Cond
Temp
Frac Density


Griffith Geoscience Project
Gortinlieve – Discontinuity Analysis
Borehole Analysis
Shallow Wells
Deep Wells
All hydraulically active fractures
Outcrops

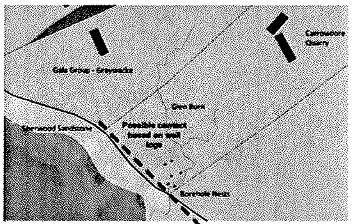

Griffith Geoscience Project
Gortinlieve – Pumping Tests
General K & T results
No Drawdown in Shallow Well
Deep Well Pumping
Drawdown in Transition Well
Shallow Bedrock
Deep Bedrock
GO1 (top hill)
GO2 (mid slope)
GO3 (valley)


Griffith Geoscience Project
Gortinlieve - Hydrochemistry
• Variation of EC*, pH* and Alkalinity* with depth in clusters
EC
pH
Alk
Go1 (top hill)
Go2 (mid slope)
Go3 (valley)
*Average values from single pumping tests (duration 2-6 hours)


Griffith Geoscience Project
Gortinlieve – Stable Isotopes
δD & δO18
Seasonality of recharge
GO1
GO2
GO3
18O
Local meteoric water line

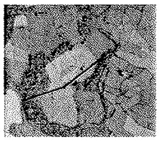

Griffith Geoscience Project
Gortinlieve
• Current integrated conceptual model
Go1
Go2
Go3
Hypothesis 1
Hypothesis 2
Legend
Transition zone

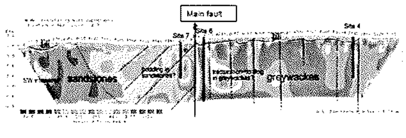
Griffith Geoscience Project – Mount Stewart, Ards Peninsula



Geology	Silurian Gala Group Greywacke; Southern Uplands-Longford-Down Terrane Permian/Triassic Sherwood Sandstones
Catchment	~5km^2
Features	Sandstone/ Greywacke contact

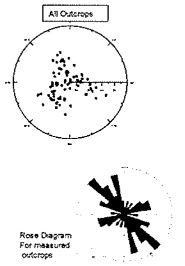
Griffith Geoscience Project Mount Stewart – Preliminary Results ERT



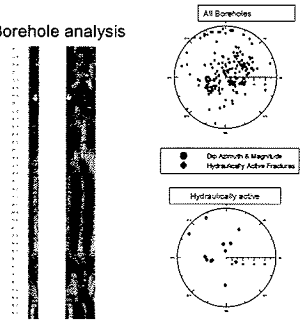


Griffith Geoscience Project Mount Steward – Preliminary Results Discontinuity Analysis

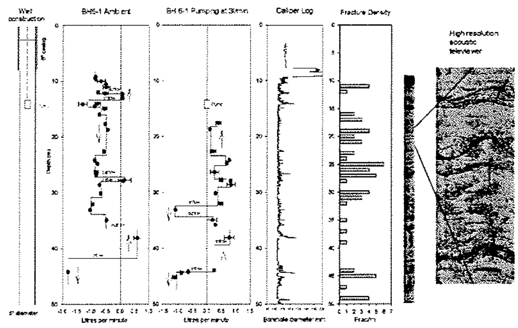
Outcrops analysis



Borehole analysis

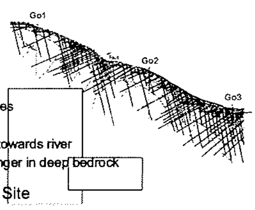


Griffith Geoscience Project Mount Stewart – Preliminary Results Flowmeter logs



Griffith Geoscience Project – Conclusions

- Study catchments with different (hydro)geological features
- Multi-method and multi-scale investigations
- Definition of provisional conceptual model for Gortinlieve catchment
  - Fracture density decreasing with depth
  - Deep fracture zones
  - Fault zone (permeable/impermeable)
  - 2 main fracture sets
  - Transition zone (rel. high K)
  - Steeply dipping hydraulically active fractures
  - Upward flow into river in valley
  - Clay-clogged factures in shallow bedrock towards river
  - Short residence time in transition zone, longer in deep bedrock
- Preliminary results for Mount Stewart Site



Griffith Geoscience Project Perspectives

- Future field work:
  - Packer testing
  - Resistivity & Gamma BH logs
  - High resolutions geophysical methods (seismic, GPR)
  - Heatpulse flowmeter
  - Event-based sampling (with EPA STRIVE Pathways)
  - Isotopic analysis (H^3 - Tritium)
- Re-appraisal of current models for complex and hardrock aquifers
- Numerical modelling of groundwater flow

Griffith Geoscience Project *Overview*

GROUNDWATER GROUP

Thank you for your Attention !

Acknowledgements

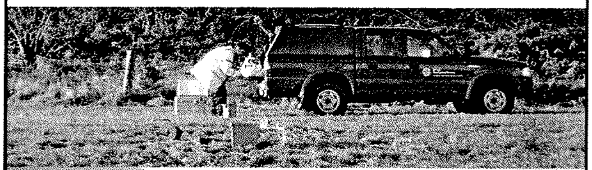
- EPA
- GSNI
- GSI – Groundwater Section
- Griffith Geoscience Research

Based on research grant-aided by the Department of Communications, Energy and Natural Resources under the National Geoscience Programme 2007-2013. The views expressed in this study are the authors' own and do not necessarily reflect the views and opinions of the Minister for Communications, Energy and Natural Resources.

British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

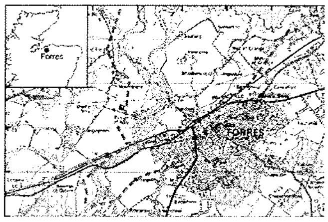
Applied geoscience for our changing Earth 175

A method for measuring the permeability of low permeability superficial deposits



Alan MacDonald, Lou Maurice, Clive Auton, Helen Bonsor
BGS Edinburgh Wallingford and Keyworth

Background: Flooding in Forres



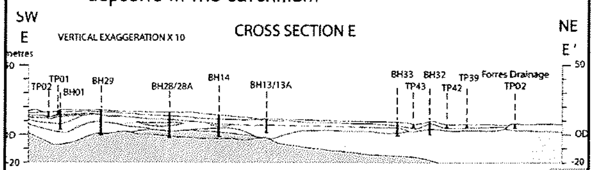
Destructive flooding in 1997, 2001

Muckle Spate of 1829

Background: Flooding in Forres

Designing new flood alleviation schemes

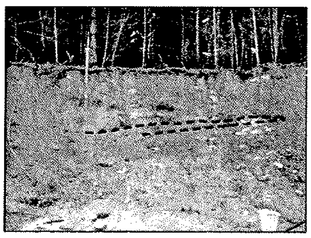
Must characterise the permeability of the saturated *and unsaturated* superficial deposits in the catchment



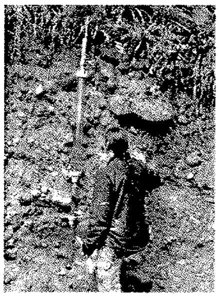
The Moray method

1. Describe field method
2. Results, reliability
3. Compare permeability with engineering data
4. Conclusions

Moray method 1: use geologists to identify type sections at outcrop



Moray Method 2: the Guelph permeameter



Usually used for soil measurements

Measures saturated permeability *insitu*

Maintains a constant head in an auger hole

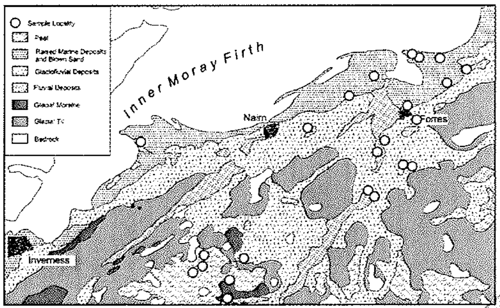
Measure the flow required to maintain head

Range 0.001 - 30 m/d

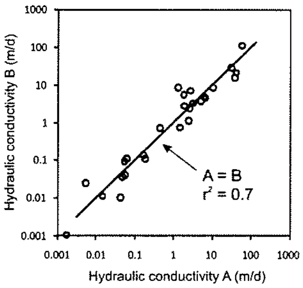
Test takes 1 hour

Moray Method 3: field method

Sample locations



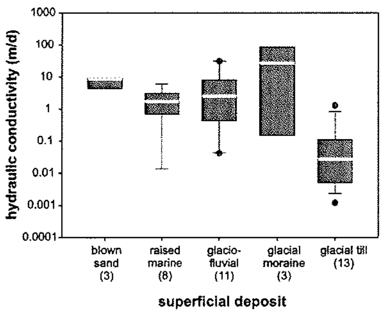
Results: repeatability



Results at same site highly correlated

Always within same order of magnitude.

Results: data



Distinct populations

3 orders of magnitude within same type

Internal variations accounted by mappable geology

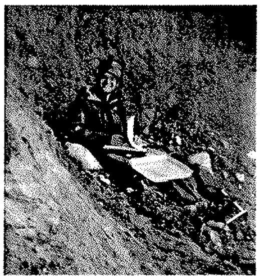
Results: comparing to engineering data

Grain size analysis

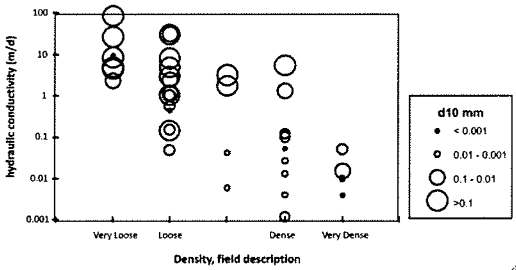
Density and cone resistance

Field description BS5930

Undertook detailed statistical analysis

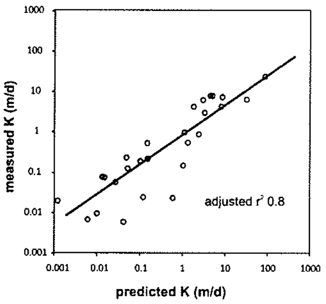


Results: comparing to engineering data



D10 and density the only independent predictors

Results: comparing to engineering data



D10 and density the only independent predictors

D60 or material description of main fraction (SAND, GRAVEL etc) had little predictive power

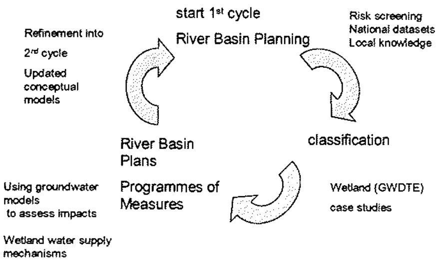
Conclusions

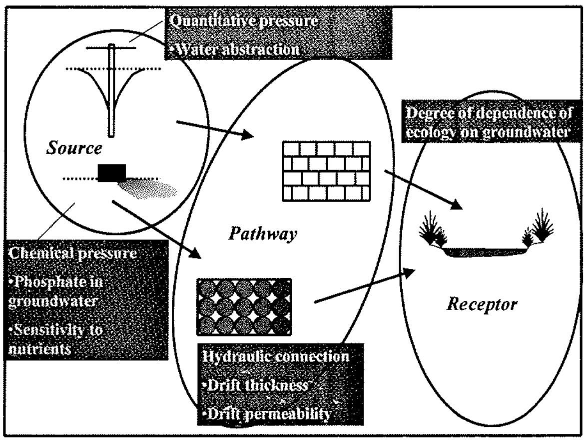
- Permeability of superficial deposits increasingly important to characterise
- Moray method proved rapid and gave repeatable data
- Useful addition to the hydrogeologist's toolbox
- Better than estimating from bulk material description

Outline

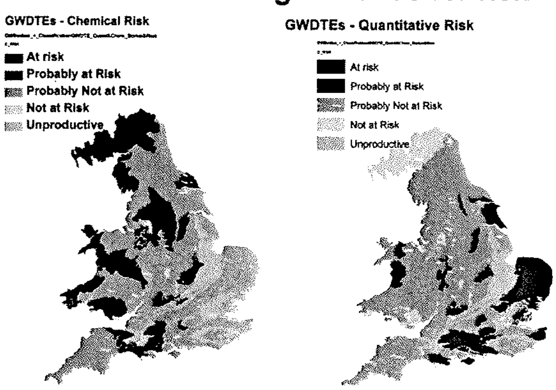
- Risk screening
- Field investigation
- Results
- Interpretation
- Conclusions

How we assessed wetlands for WFD





Results of screening wetlands for risk



Further investigations

Reason for high risk?

- Site unfavourable – Not groundwater → Ecological surveillance needed
- Site favourable
- Site unfavourable – groundwater → Ecological and/or hydrological investigation needed

Further investigations

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- Site unfavourable – Not groundwater → Ecological surveillance needed
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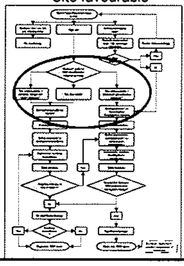
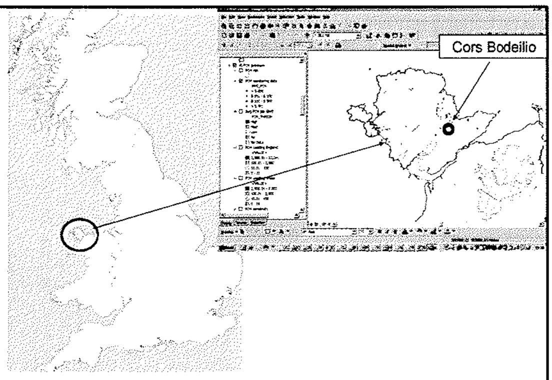
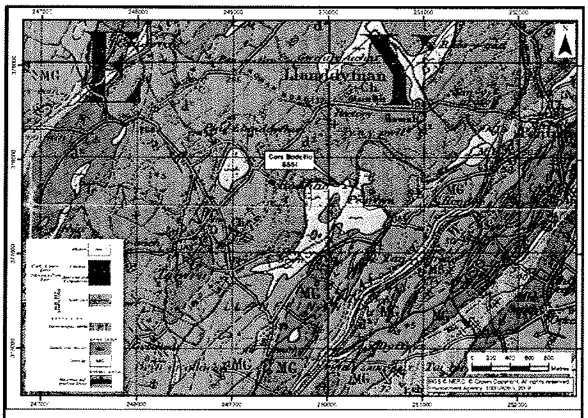
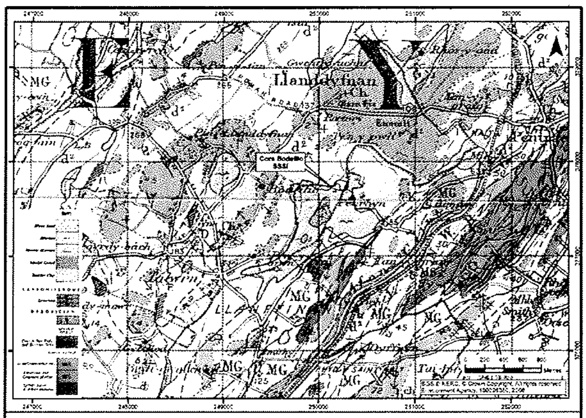




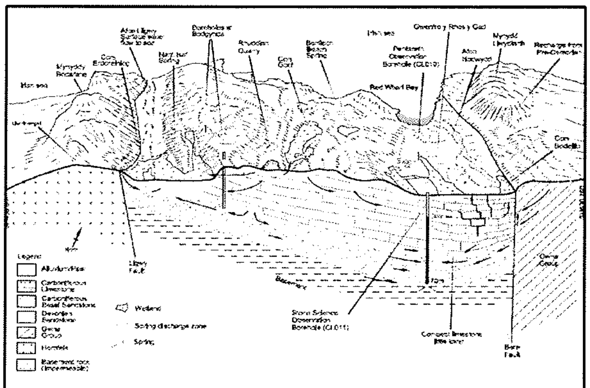
Study area



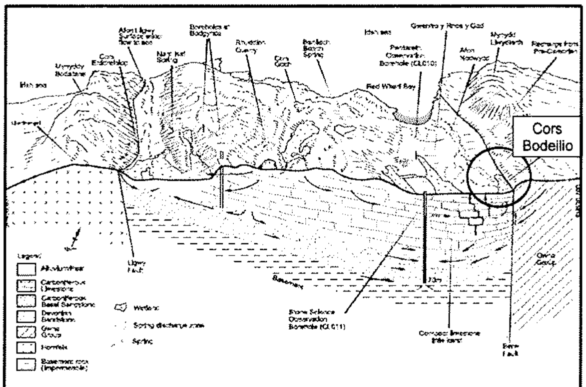
Solid & alluvial drift geology in the vicinity of Cors Bodeilio



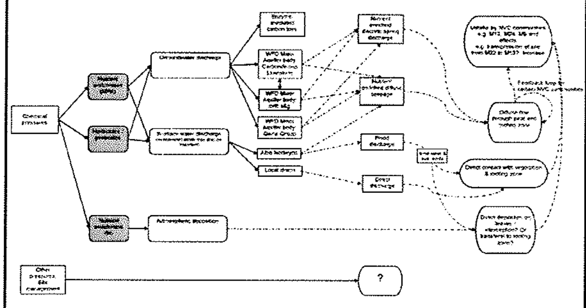
Drift geology in the vicinity of Cors Bodeilio



Conceptual model – schematic cross section

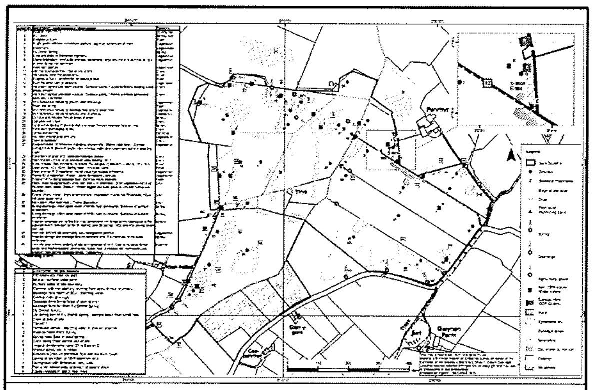


Conceptual model – schematic cross section

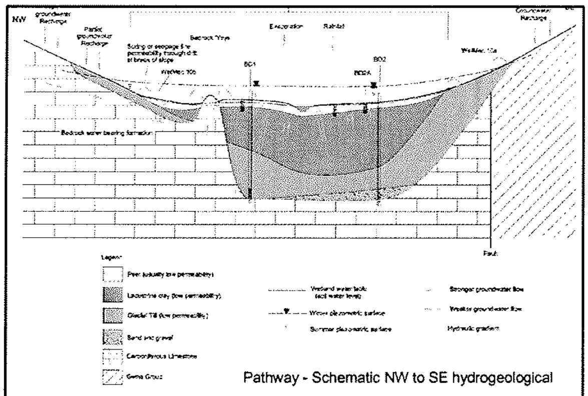


Cors Bodeilio Source-Pathway-Receptor linkages

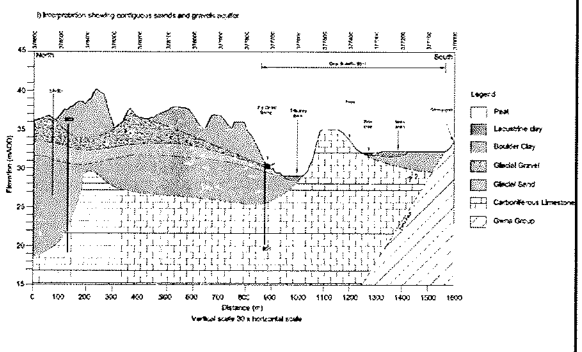
Field investigation – Cors Bodeilio

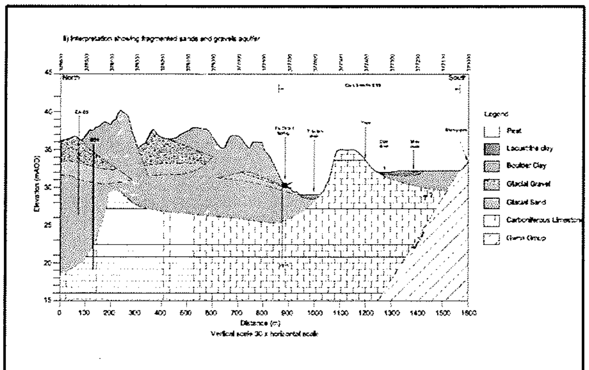


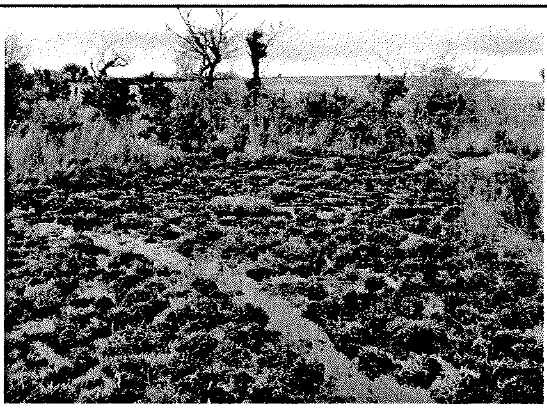
Hydroecological water features and locations of Vegetation Survey Quadrats



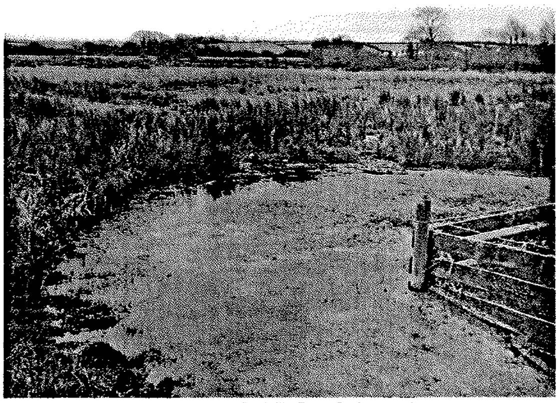
Pathway - Schematic NW to SE hydrogeological cross-section Cors Bodeilio





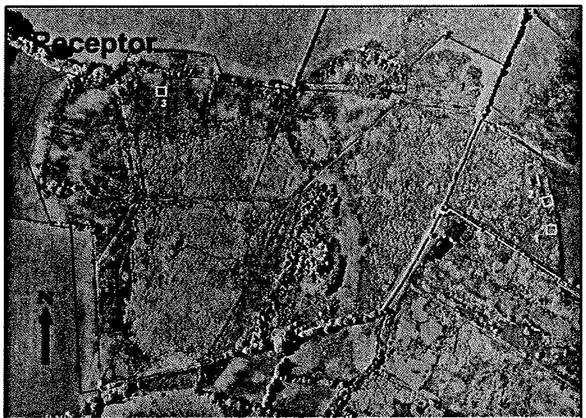


Cors Bodeilio - Discrete flush behind Fly Orchid Spring

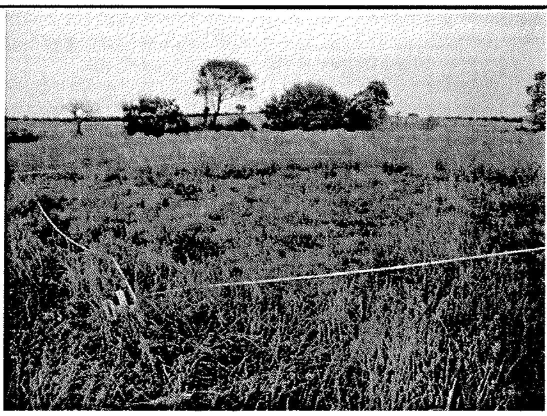


Bodeilio Farm Spring pond

Cors Bodeilio - M13 below Fly Orchid Spring



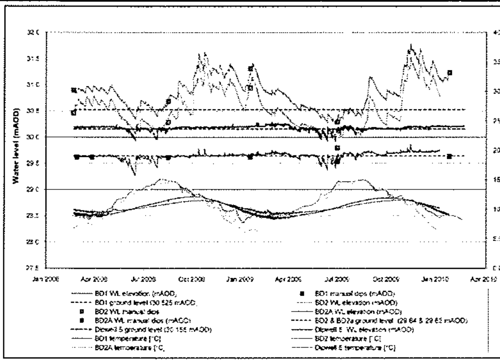
Location of targeted ecological survey quadrats – Cors Bodeilio



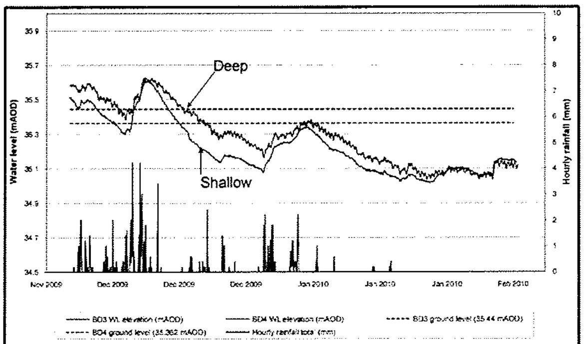
Targeted Ecological Survey – Cors Bodeilio

Receptor

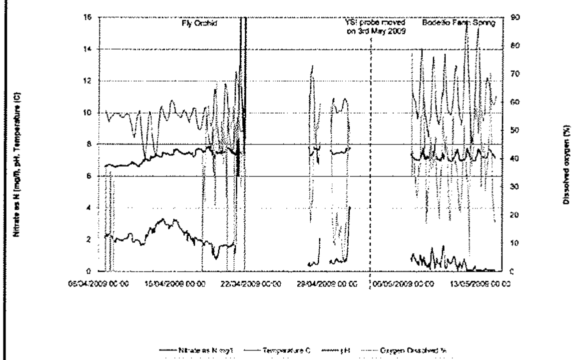
- Key data:
  - Standard NVC mapping
  - Targeted ecological quadrat vegetation surveys.
- At Cors Bodeilio there is some evidence, in the ecological quadrat vegetation surveys (Plot 3 located in the north-west sector of the site), to suggest damage of key features (M13 communities) from eutrophication.
- This can be associated with the main focus of high nitrate influxes to the site from Fly Orchid and Bodeilio Farm Pond springs plus general seeps in the same vicinity.
- Here, a key question will be whether this extent of damage is considered significant?



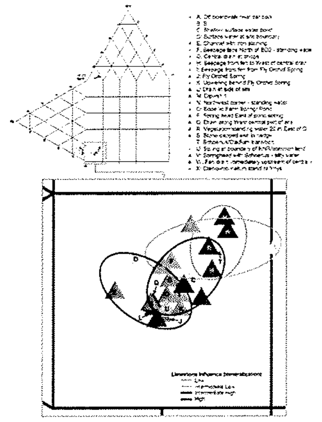
Site specific
groundwater level hydrographs plus temperature plots



Detailed hydrographs for the new Stone Science Park piezometers plus rainfall hydrograph



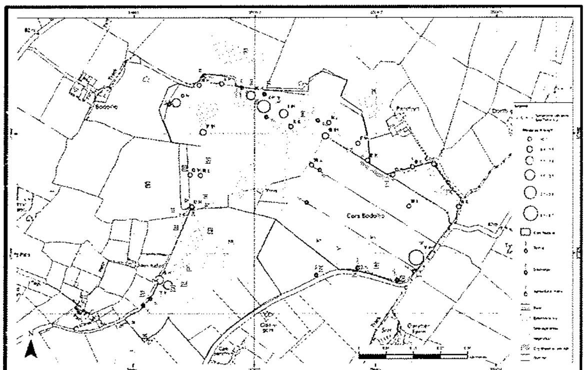
High-frequency water quality data from the YSI Sensor
Fly Orchid Spring and Bodeilio Farm Pond



Zoomed version of Durov Diagram for April 2009 Survey Locations showing suggested groupings associated with "limestone influence"

Source term - groundwater

- Groundwater variably enriched in nitrate is found around the margins of the site
- Carboniferous Limestone and drift sands & gravels aquifers.
- Highest groundwater nitrate concentrations found in springs and sands & gravels aquifer
- lower levels of nitrate enrichment found in the Carboniferous Limestone aquifer



Nitrate concentrations and 'limestone influence' overlain on the hydroecological map

Atmospheric nitrogen deposition

Table A.5 Estimated fluxes of atmospheric nitrogen at Cors Erddreiniog

Component	Estimated flux	Potential sources
Atmospheric NO_2	0.55 kg N/ha/yr ($5.07\ \mu g\ m^{-3}$)	Relatively low pollution load reflecting low industrial/traffic effects
Atmospheric NH_3	10.57 kg N/ha/yr ($1.85\ \mu g\ m^{-3}$)	High pollution load probably related to surrounding agriculture & in particular chicken farming
Wet deposition	11.77 kg N/ha/yr	These data comprise NO_3 & NH_4 (but not DON). The value is relatively high with a significant (~60% contribution from NH_4) probably again reflecting agricultural (chicken farm & stock rearing) influence.
Total N input	22.89 kg N/ha/yr	

Age dating – springs and boreholes

		pmol/L	pmol/L	fmol/L	Modern Fraction			Year of Recharge		
	Date	CFC-12	CFC-11	SF6	CFC-12	CFC-11	SF6	CFC-12	CFC-11	SF6
Sample										
Pentraeth EA borehole 27m	2008	1.23	1.13	0.51	0.42	0.21	0.18	1975	1969	1983
Stone Science EA borehole 70m	2008	0.44	0.77	21.42	0.15	0.15	7.61	1966	1967	>modern
Fly Orchid Spring	16/01/2009	3.4	5.1	2.1	1.17	1	0.8	>modern	1987	2002
Bodeilio Farm Pond	16/01/2009	2.9	4.4	2.2	0.98	0.8	0.8	1993	1984	2002

Stable isotope data – Cors Bodeilio

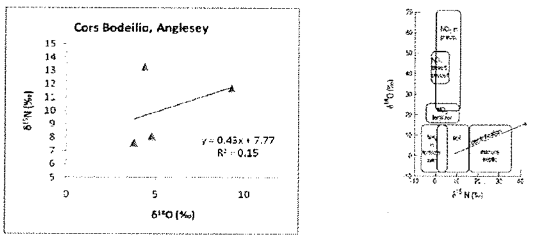
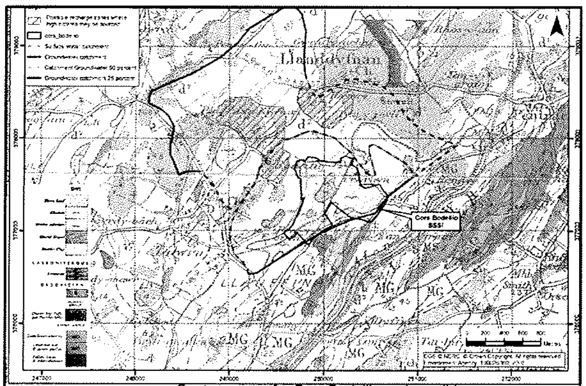


Fig. 2 Cross-plot of $\delta^{15}N_{NO3}$ versus $\delta^{18}O_{NO3}$ for groundwater samples collected from Cors Bodeilio, Anglesey in February 2010.



Capture areas for Cors Bodeilio and possible recharge zones where high nitrates to site could be sourced

Interpretation

- the most significant activities generating nitrates are agricultural diffuse sources
  - Fertiliser application to improved pasture.
  - Stock rearing (cattle & sheep).
  - Chicken farming (though this may be regarded as a point source).
  - Organic waste spreading to land

Where have we got to?...and what would we do differently next time?

- The hydro-ecological conceptual model is very important
- assessing local source-pathway-receptor linkages based on conceptual understanding
- investigations are expensive, need to be smarter next time around. We are still on the journey…

Cost effective techniques

Cheaper

√ Soil Augering
√ Hydro-ecological walkover survey
√ Dipwells (with dataloggers)
√ Chemical sampling
√ Ecological quadrats
? Nitrogen Isotopes/age dating
? Deep piezometers
? Geophysics (resistivity, GPR....)

More expensive

Conclusions

Local knowledge is key to risk screening

- **vital** in initial appraisal process (risk screening alone based on GW conveyed P values would not have identified these sites as being at risk).

Targeted ecological surveys can indicate impacts

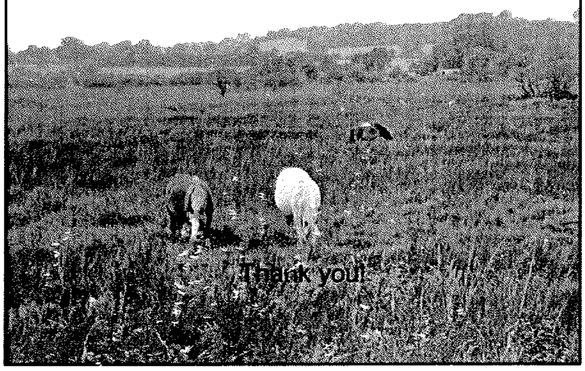
- do indicate impacts from eutrophication *(though there is a question-mark over significance).*

Can't rely on low P preventing damage

- eutrophication damage can occur to these oligotrophic sites in the presence of enriched nitrates and low phosphates in GW. Some of the existing guidance on the limitation to eutrophication in such wetland sites where phosphate values are low and nitrate values elevated may be misleading?
- Alternatively, are there other pathways/processes for significant P (atmospheric?, bio/soil element of P cycle?).

Recommendations

- Incorporate consideration of nitrate in initial risk screening (at least for oligotrophic sites). Then place more emphasis on local knowledge eliminating rather than including sites.
- Develop clearer guidance on evaluating significant damage from eutrophication.
- Further investigate link between eutrophication & nutrient limitation (e.g. Wetland triggers project)
  - EU Groundwater Working Group C October 6th 2010

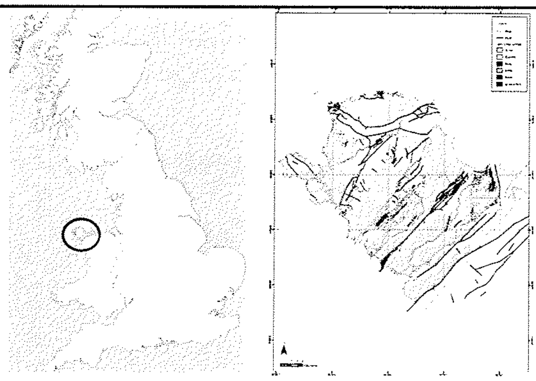


Groundwater surveys in Anglesey;

To implement WFD monitoring, improve conceptual understanding and provide baseline data for GWDTE investigations

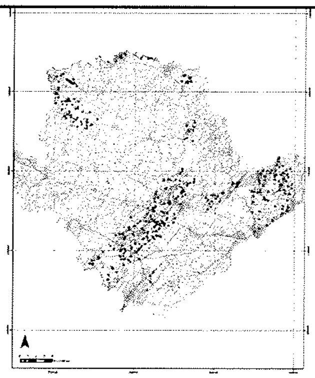
Gareth Farr	Environment Agency Wales
Paul Inman	Schlumberger Water Services (formerly WMC)
Amanda Coffey	Schlumberger Water Services (formerly WMC)
Rob Low	Rigare Ltd (formerly WMC)
Dave Banks	HolyMoor Consultancy

Schlumberger WATER SERVICES HolyMoor Environment Agency



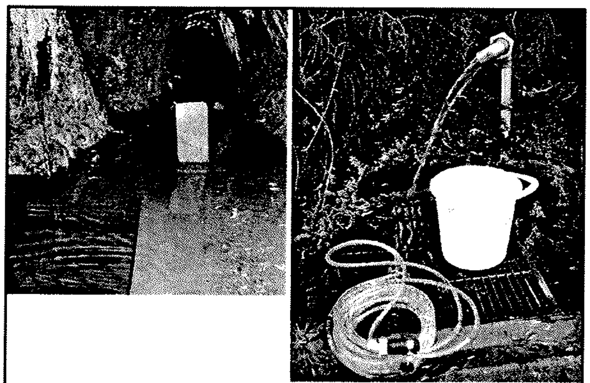
Study area

Greenly, 1919
Robins & McKenzie, 2005
EAW, 2007
EAW, 2008

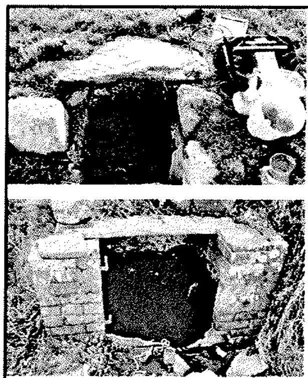


314 Sites
33 Samples
22 Wells
9 springs
1 borehole
1 audit

Case Study 1 – Pre-Cambrian Gwna Group

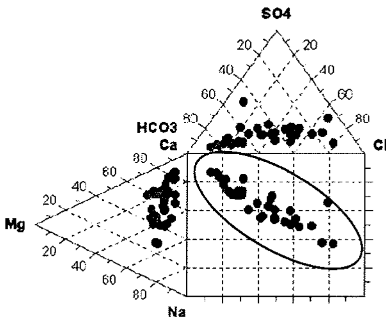


Case Study 1 – Pre-Cambrian Gwna Group

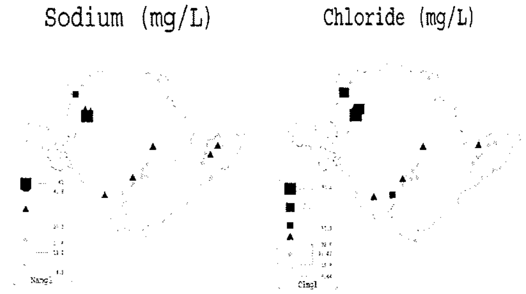


- Field parameters
- Water Levels
- Site description
- Construction details
- Abstraction / Flow
- CFC/SF6
- Radon
- Land Use
- Possible contamination

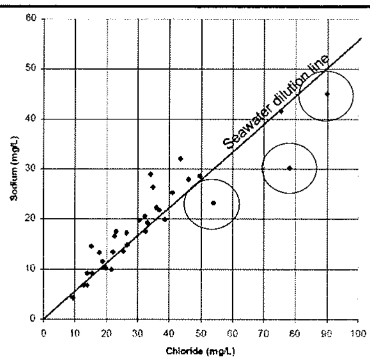
Case Study 1 – Pre-Cambrian Gwna Group



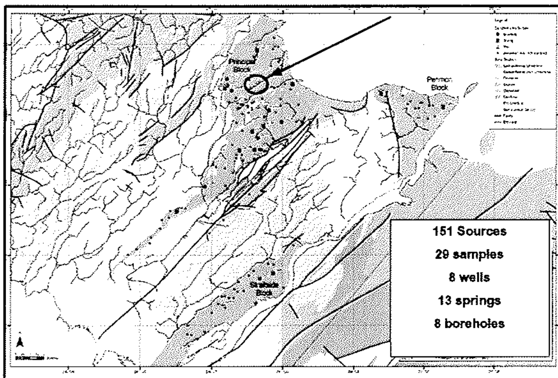
Case Study 1 – Pre-Cambrian Gwna Group



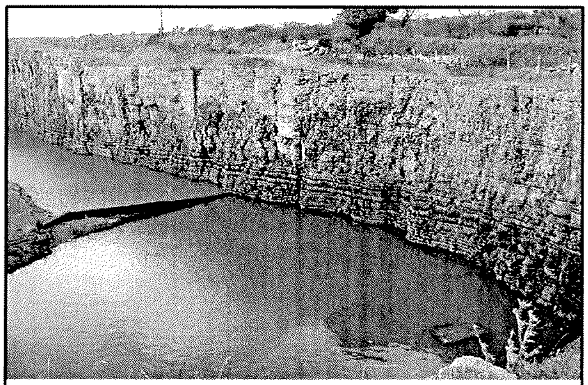
Case Study 1 – Pre-Cambrian Gwna Group



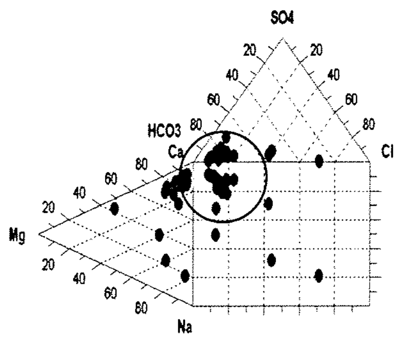
Case Study 1 – Pre-Cambrian Gwna Group



Case Study 2 – Carboniferous Limestone



Case Study 2 – Carboniferous Limestone



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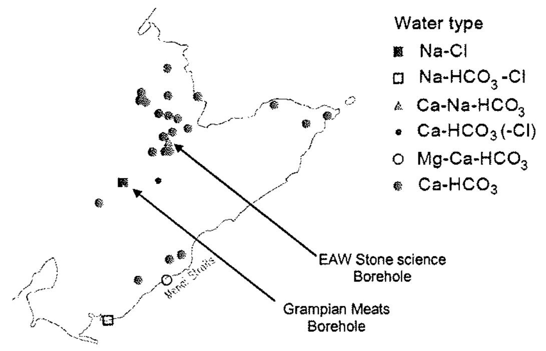
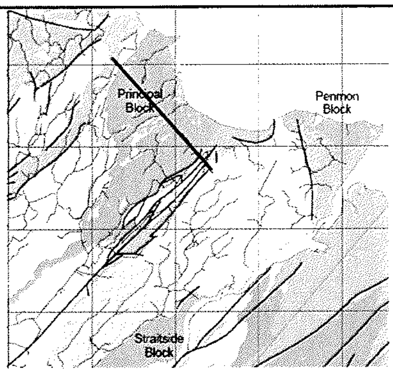
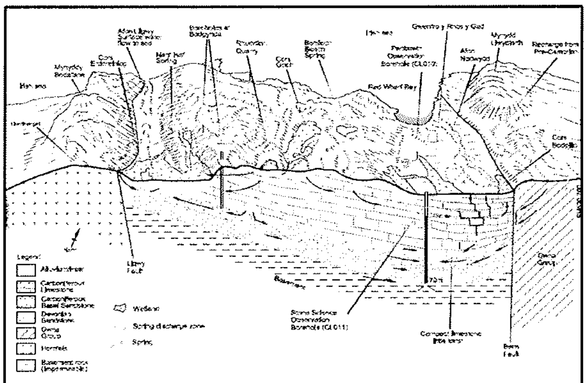


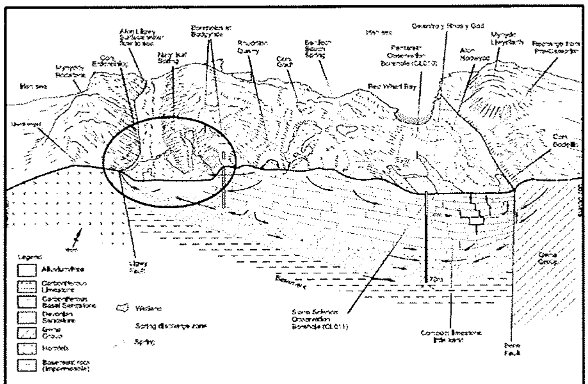
Case Study 2 – Carboniferous Limestone



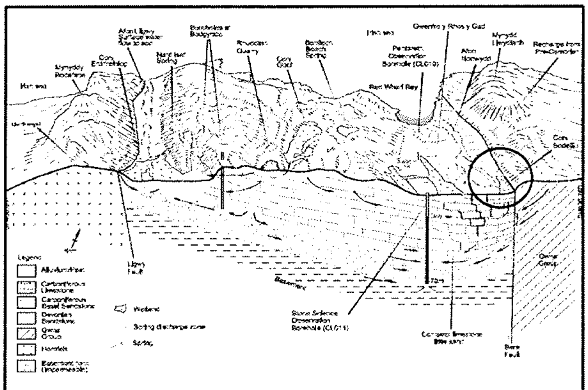
Case Study 2 – Carboniferous Limestone



Schlumberger Case Study 2 – Carboniferous Limestone



⊃ Cors Erddereiniog



⊃ Cors Bodeilio

Banks, Farr, Inman and Low, 2007*. A Groundwater quality and Supply survey for the Pre-Cambrian Gwna Group, Anglesey Wales. Poster at the Geological Society of London 200yr celebration at the QEII Centre London.

Greenly, E. 1919. The Geology of Anglesey.

Robins & McKenzie. 2005. Groundwater occurrence and the distribution of wells and springs in pre-Cambrian and Palaeozoic rocks, NW Anglesey. QJEH, 28, 83-88.

WMC, 2007* *. Groundwater Quality and Supply Survey for the Pre-Cambrian Gwna Group, Anglesey. For Environment Agency Wales.

WMC, 2008* *. Groundwater Quality and Supply Survey for the Carboniferous Limestone, Anglesey. For Environment Agency Wales.

*Download reports free at http://publications.environment-agency.gov.uk

* Request a free PDF copy from Gareth Farr

gareth.farr@environment-agency.gov.uk

Thank you

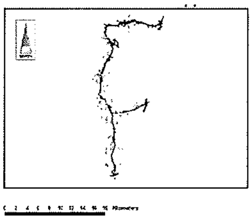
Private Groundwater Supplies in the Archean Aquifers of Aberdeen

JACOBS — Aberdeen Western Peripheral Route

Structure

1. Background information
2. Field investigations
3. Interpretation: geology, GI and pump-test data
4. Conceptualisation: construction of CSMs
5. Modelling
6. Conclusions and findings

1 - Project overview - AWPR



3 sections: Northern Leg, Southern Leg and Fastlink

Dual carriageway of 46 km around city of Aberdeen with 25 road cuts adding to a total of ~21 km in cutting, and most cuttings intercept groundwater

Identification of potential impacts:
- private water supplies (PWS)
- burns and ecological receptors
- altered polluted groundwater flows.

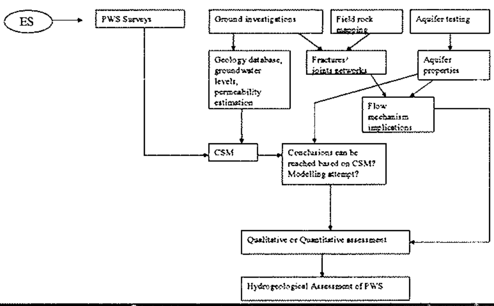
1 - Geology settings - Bedrock

Drift
- Highly variable in nature, generally comprising glacio-fluvial sands and gravels interlayered with clayey glacial till.

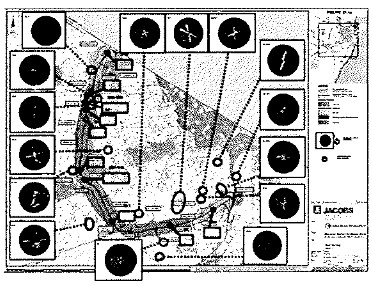
Bedrock
- Predominantly heavily folded and faulted Archean metamorphic strata (particularly gneiss and schists)
- Frequently intruded by igneous materials which have been subsequently foliated by tectonic movements
- Four phases of regional deformation have produced complex folding and composite structures
- Dominant folilation directions are NE-SW trending features associated with D1 – D3 phases and NNE-SSW to N - S trending features associated with D4 deformation (BGS 1995)

1 - Assessment methodology

Phased assessment Process: Environmental Statement > Surveys > Detailed GI & Interpretation



2 - Field Investigations : fracture mapping



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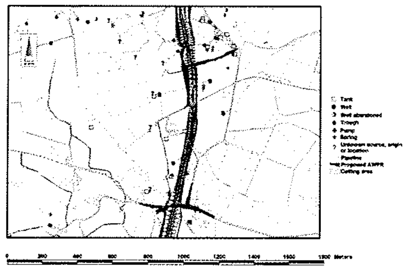
2 - Field Investigations : PWS surveys



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2 - Field Investigations : ground investigations

- Four phases of ground investigations (GI)
- Step tests in selected locations (5 pumping rate tests of 60 minutes each)
- Constant rate tests in selected locations (24 hours duration)
- Slug tests performed occasionally to complete data set, particularly to help characterise drift deposits.

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3 – Interpretation: Permeability from geology

Secondary permeability of the rock classified using system developed by the International Society for Rock Mechanics (F.G. Bell, 1987) which relates the spacing of the discontinuities to the secondary permeability

Rock mass description	Fracture Index	Estimated Secondary Permeability	
		Description	K (m/s)
Very closely to extremely closely spaced	≥16	Highly Permeable	10^{-2} to 1
Closely to moderately widely spaced discontinuities	3 to 15	Moderately Permeable	10^{-5} to 10^{-2}
Widely to very widely spaced discontinuities	0 to 2	Slightly Permeable	10^{-9} to 10^{-5}

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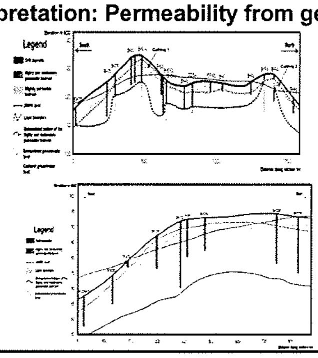
3 – Interpretation: Permeability from geology



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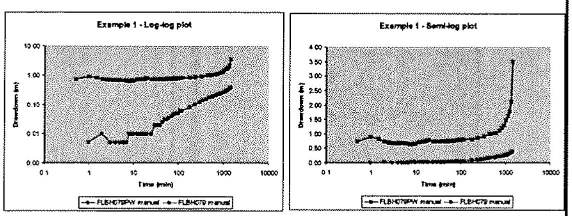
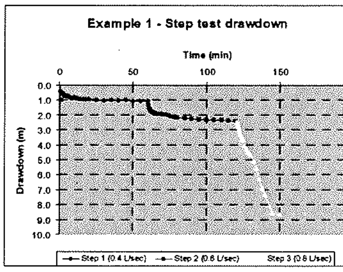
3 – Interpretation: Permeability from pumping tests



1. Example response of fracture driven flow

JACOBS

3 – Interpretation: Permeability from pumping tests



2. Example response of fracture driven flow

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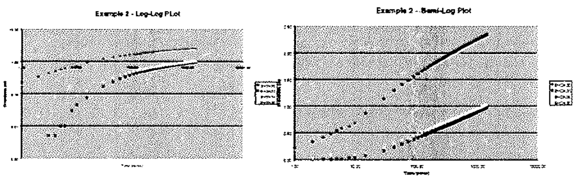
3 – Interpretation: Permeability from pumping tests



3. Example response of granular-type flow

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3 – Interpretation: Permeability from pumping tests

Pumping test curves were found to group into four main "families":

- F1 – granular-like (unconfined) or double porosity (confined) flow mechanism
- F2 – granular-like (confined) flow mechanism
- F3 – fractured zone/single vertical fracture (confined) flow mechanism
- F4 – variable – pumping well generally displaying a fractured flow behaviour, but one or more observation boreholes generally indicating a granular type flow behaviour.

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3 – Interpretation: Permeability from pumping tests

T and S values were derived from the step and constant rate tests using AquiferWin32

Step test interpretations based on Eden-Hazel method

Constant test interpretations mostly derived from Theis equation, but also from other alternatives depending on the conditions encountered such as Neuman (unconfined with partial penetration), Moench (double porosity), etc.

The fit with theoretical curves was of variable quality, and the confidence in interpretation was included in the overall assessment.

- Calculated T values fluctuate between 0.1 and 150 m^2/d
- Calculated storage coefficient range between 4E-2 and 2E-5

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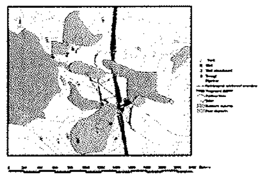
4 – Conceptualisation: Catchment balancing

Example 1



PWS	No. Livestock	No. Farms	No. Cottages	Total Volume of water abstracted for PWS in m^3 per annum	Hydrological catchment area m^2	Derived minimum groundwater recharge required to sustain PWS demand (mm per annum)
1	Number unknown but measured average discharge is 2.0 l/s			65225	141795	467
2	200	1	1	4745	6468	733
3	100	1	6	4745	5795	818
4	500	3	2	11680	33110	352

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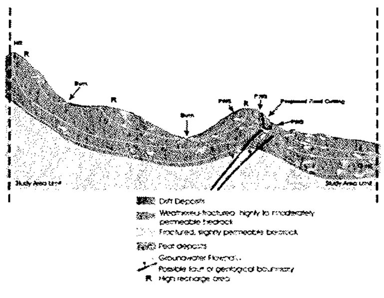
4 – Conceptualisation: Groundwater flow mechanisms

Example 1 (cont)



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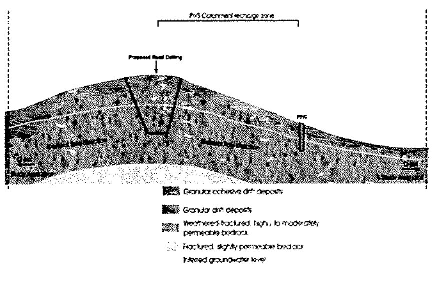
4 – Conceptualisation: Groundwater flow mechanisms

Example 2



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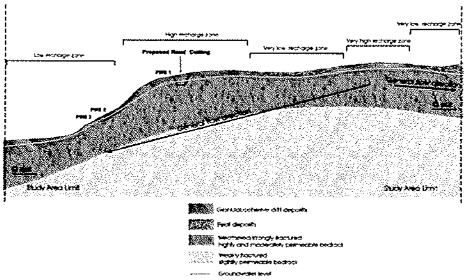
4 – Conceptualisation: Groundwater flow mechanisms

Example 3



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5 - Modelling groundwater behaviour in Archean Terrane

Modelling of fractured rock: "equivalent porous media" approach chosen based on geological evidence to support it. ModFlow therefore considered suitable for use.

Modelling limitations

- Standard limitations of the software used to reflect reality (discretisation, model boundaries...)
- Data uncertainties (distribution of boreholes along the proposed scheme, groundwater data set, aquifer tests..)

Site specific models developed using common elements:

- Models are catchment focussed
- Two layers typically modelled
- Simulation of cutting using drainage package in ModFlow.
- Model calibration in three phases:
  - steady-state current conditions (calibration on recharge, layer 2 thickness and K values)
  - 24 hour transient mode simulating constant rate test to calibrate storage coefficient values and adjust model if required
  - transient mode of cutting simulation (time steps 1 month, 6 months, 1 year...)

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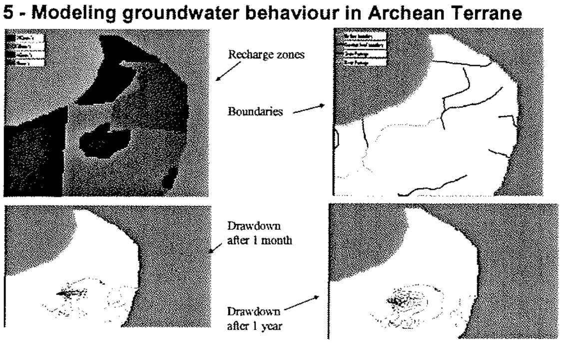
5 - Modeling groundwater behaviour in Archean Terrane



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Conclusions

Key findings

- *Low productivity aquifers are used extensively in Aberdeenshire for decentralised water supply. A number of these private water supplies were likely to be affected by dewatering from nearby cuttings for the AWPR.*
- *Detailed conceptualisation and modelling of the complex hydrogeological regime successfully enabled identification of the PWSs most likely to be affected by proposed road cuttings.*
- *The results of the PWS modelling are now also being used to prepare CAR licensing applications to account for the dewatering produced by the cuttings.*

The Assessment of Groundwater 'Future Resource Value' and the Allocation of Groundwater Receptor Status.

Alex Pritchard

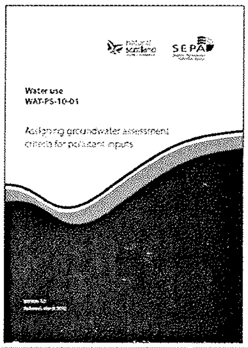
Principal Policy Officer

SEPA

What I am going to talk about

- Legislative context
- Key principles of groundwater pollution assessment
- What groundwater has future resource potential?
- How do you determine this?
- How do you assess pollution of groundwater with resource potential?

Where to find information



Legislative Context

Repealed in 2013

➢Prevent entry of List I substances
➢Prevent pollution by List II substances

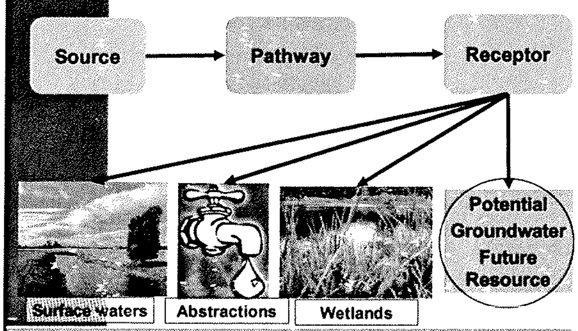
➢Water Environment Controlled Activities (Scotland) Regulations 2005 (CAR)
➢Water Environment and Water Services (Scotland) Act 2003 (WEWS)

Water Framework Directive

2006 Groundwater Daughter Directive

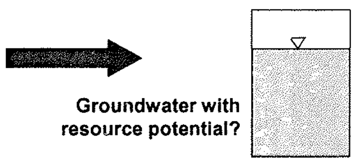
➢Prevent inputs of Hazardous substance
➢Limit inputs of Non-Hazardous substances to avoid pollution

Assessing Pollution



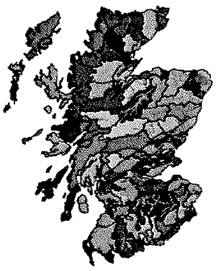
What is groundwater?

➢ Groundwater: all water which is below the surface of the ground in the saturated zone and in direct contact with the ground or subsoil. (WFD definition)



Groundwater with resource potential?

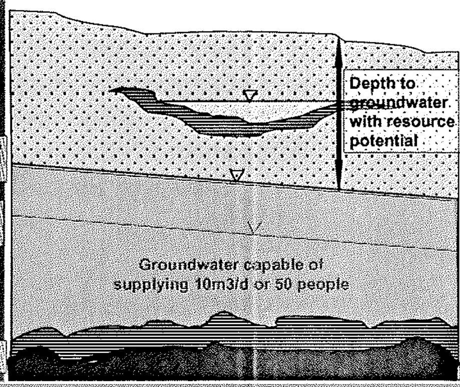
What groundwater has future resource potential?



Defined Groundwater Bodies – bedrock and Superficial deposits (capable of supplying 10 m3/day or 50 people)

Other groundwater not in a groundwater body which is capable of supplying 10 m3/day or 50 people (not mapped due to inherent variablity and lack of information)

www.sepa.org.uk



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How to determine the depth to groundwater with future resource potential

Question: Do the superficial deposits above the groundwater body fulfil the UKTAG criteria for a groundwater body?

Methodology in Annex 2 of WAT-PS-10-01

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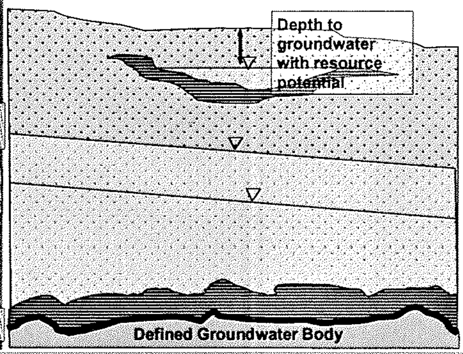
Tier 1 - **Assume all saturated materials have a future resource value**



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Tier 2 - **Use available info to infer productivity linked to areal extent and thickness of stratum**

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Tier 2- determination of sand and gravel

Sand and Gravel =

- Principal soil type should be sand or coarser, with the martial having no apparent plasticity/cohesion or being dominantly cobbles or boulders. (Field description in accordance with British Standard)
- Less than 8% fines in all samples (Partial size analysis)

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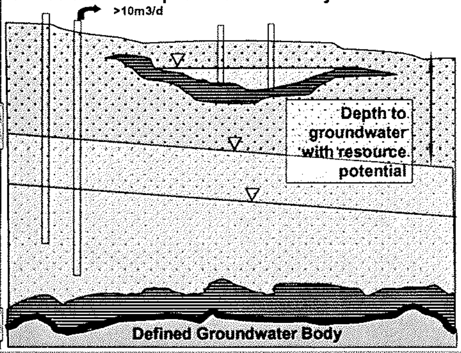
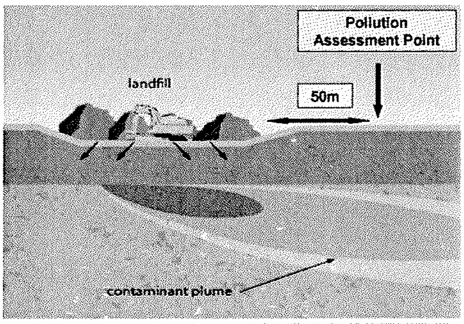
Tier 3 - Productivity testing to demonstrate if the stratum can provide >10m³/day



Key Points for Tiered Assessment

- Anticipated types with no future resource value include silt and clay soils/ mixtures.
- Not intended to rule out layered sediments with laterally persistent granular layers of either 'significant' thickness or demonstrable hydrogeologic function.
- **All** bedrock units constitute groundwater receptors

Assessing if there is pollution of groundwater with resource potential



Assessing if there is pollution of groundwater with resource potential

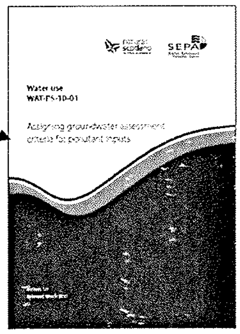
Pollution assessment point can be up to 250m where:

- Land use limits exploitation e.g. urban areas
- Steep slopes
- Where concentration of substances naturally exceed appropriate quality standard

Key Points

- All bedrock aquifers have groundwater resource potential.
- Unless otherwise demonstrated by tiered assessment set out in WAT-PS-10-01 other groundwater is also considered to have resource potential.
- Pollution should be assessed in groundwater with resource potential at 50m unless there are specific circumstances.

Further Information



Questions?