INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS - Irish Group

Celebrating our 40th Anniversary

Sustaining Ireland's Water Future: The Role of Groundwater

Proceedings of the 36th Annual Groundwater Conference
Tullamore, Co. Offaly, Ireland

12th and 13th April 2016

www.iah-ireland.org

INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS
(IRISH GROUP)

Presents

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Tullamore Court Hotel
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INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS (IRISH GROUP)

Founded in January 1976, the IAH-Irish Group membership has grown from 10 to over 130, and draws individuals from professional backgrounds ranging from academic to state agencies to private consultancies. The committee consists of a council of: President, Secretary, Treasurer, Burdon Secretary, Northern Region Secretary, Fieldtrip Secretary, Education & Publicity Secretary, Conference Secretary, plus a conference sub-committee.

Regular activities of the Irish Group consist of an annual two-day conference (currently held in Tullamore), an annual weekend fieldtrip, and a series of monthly lectures/ technical meetings. Funding for the association is derived from membership fees and the annual conference. We welcome the participation of non-members in all our activities. Other activities of the IAH (Irish Group) include submissions to the Irish Government on groundwater, the environment and matters of concern to members, organising the cataloguing of the Burdon library and papers, which are now housed in the Geological Survey of Ireland Library, invitation of a guest speaker (often from outside Ireland) to give the David Burdon Memorial Lecture on a topic of current interest, and contributing to the Geological Survey of Ireland's Groundwater Newsletter.

The Irish Group provides small bursaries to students doing post-graduate degrees in hydrogeology and pays the annual subscriptions of a few members in other countries as part of the IAH's Sponsored Membership Scheme. If you would like to apply for a student bursary, details can be found on the IAH (Irish Group) website shown below. IAH are encouraging members to highlight their local IAH Group to their colleagues/ students and to invite anyone they feel may be interested to join.

The IAH (Irish Group) is also a sponsoring body of the Institute of Geologists of Ireland (IGI).

For more information please refer to:	http://www.iah-ireland.org
Future events:	http://www.iah-ireland.org/upcoming-events/
IAH Membership (new or renewal):	http://www.iah.org/join_iah.asp
	http://www.iah.org/payonline

2016 Conference Objective

The Irish Branch of the International Association of Hydrogeologists was formed in 1976 by a small group of hydrogeologists with a clear ethos of openness and inclusivity. From the opening lecture by C.R. Aldwell in Trinity College Dublin, 23rd March 1976, the organisation has grown through the strength, dedication and enthusiasm of its members and continues to make a positive contribution to society and the environment today.

This year sees the 40th anniversary of the Irish Group of the IAH and in recognition we have included in the proceedings a transcription of Bob Aldwell's inaugural paper, wherein he outlined the wide canvas that was groundwater in Ireland. We are also delighted to be able to celebrate this event with addresses from two longstanding members of our group. David Ball will take us through the history of groundwater in Irish society with his inimitable style, elucidating the 40 years of the IAH Irish Group and 45 years of modern hydrogeology. Bruce Misstear (Trinity College Dublin) will then look to the future, highlighting the opportunities and challenges in hydrogeology education and training.

In addition to the anniversary celebrations the theme of this year's conference is "Sustaining Ireland's Water Future: the Role of Groundwater". IAH (Irish Group) President Henning Moe will start proceedings with an introduction and welcome address. Following this we are honoured to host three keynote speakers who are leaders of international hydrogeological research on specific subject matters that have direct relevance to the hydrogeological context of, and water resources management in, Ireland.

Dr. John M. Sharp is Professor of Geology at The University of Texas. His hydrogeological research covers groundwater flow in fractured rocks, regional groundwater flow in carbonate rocks, and effects of urbanization on water resources protection and management. Prof. Sharp will lend his experiences to speak on “Sustainability of groundwater resources: conceptual evolution, opportunities & challenges”.

Dr. Beth Parker is Professor at the School of Engineering at University of Guelph, Ontario. Her research is focused on developing improved field and laboratory methods for characterisations and monitoring of industrial contaminants in sedimentary rocks, clayey deposits and heterogeneous aquifers. Prof. Parker will share her latest research findings on “Field Studies of Chlorinated Plume Behaviour in Sedimentary Rock: from Source to Discharge Zones”.

Dr. Kevin Hiscock is Professor of Environmental Sciences at the University of East Anglia. His interdisciplinary research interests are in hydrochemistry, environmental isotopes and the impacts of land use and climate change on groundwater resources at regional and global scales. Prof. Hiscock will speak on “Changes in groundwater storage under future climate change”.

The topics of the keynote speakers will undoubtedly serve to both guide and challenge hydrogeological practitioners and researchers in Ireland. Moreover, the topics were selected to enhance the technical perspectives on subject matters that are close to home, and which are covered by main conference sessions on groundwater for decision makers, groundwater resources and groundwater research. Specifically we will see talks addressing topical issues such as EU Water Framework Directive implementation, resource and risk assessment, communications and wastewater and groundwater research.

We are pleased to once again host an Early Career Hydrogeologists’ Network session, which provides a valuable forum for young researchers and professionals to interact with the wider hydrogeological community. The conference will also host an exhibitors area, social evening and technical workshop for delegates which provides a unique opportunity for networking and upgrading scientific and technological awareness.

We hope the conference will be a useful forum for delegates to keep abreast of trends and the range of hydrogeological and environmental work shaping water supply and environmental protection initiatives in both Ireland and abroad in the coming years. We would also like to extend our appreciation to you all, the members, colleagues and friends of IAH Irish Group, for your support over the last 40 years and we are confident we can face the challenges facing Ireland’s water future with the same spirit of openness and collaboration that has served our community well.

Owen Naughton
IAH (Irish Group) Conference Secretary

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For more information and contact details please refer to: *www.iah-ireland.org*

Sources of photographic imagery on the proceedings cover courtesy of Orla O'Connell.

The proceedings for the 36th Annual Groundwater Conference 2016 will also be made available digitally on the IAH-Irish Group website within the next six months.

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The IAH (Irish Group) would also like to acknowledge the support of the following members and organisations whose staff have worked on the committee of the IAH-Irish Group throughout the year and helped to organise the conference:

CDM Smith

Katie Tedd

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‘Sustaining Ireland’s Water Future: The Role of Groundwater’

International Association of Hydrogeologists – Irish Group
Tullamore Court Hotel, Tullamore, Co. Offaly: Tuesday 12th & Wednesday 13th April 2016

Programme Day 1, Tuesday 12th April

08:30 - 09:30 *Conference Registration; Tea, Coffee, & Exhibits*

INTRODUCTION

09:30 – 09:40 Welcome and Introduction
Henning Moe – *President IAH Irish Group*

SESSION 1: KEYNOTE

09:40 – 10:20 ‘Sustainability of groundwater resources: conceptual evolution, opportunities and challenges – John M. Sharp (The University of Texas)

10:20 – 11:00 ‘Field Studies of Chlorinated Plume Behaviour in Sedimentary Rock: from Source to Discharge Zones’ – Beth Parker (University of Guelph)

11:00 – 11:15 Q & A

11:15 – 11:45 *Tea and coffee*

SESSION 2: CELEBRATING 40 YEARS OF IAH IRISH GROUP

11:45 – 12:20 ‘Groundwater in Irish society: 40 years of IAH Irish Group and 45 years of modern hydrogeology’ – David M. Ball (Hydrogeologist)

12:20 – 12:45 ‘Looking to the future: opportunities and challenges in hydrogeology education and training’ – Bruce Misstear (University of Dublin Trinity College and Vice President of IAH)

12:45 – 13:00 Q & A

13:00 – 14:00 *Buffet lunch in Tullamore Court Hotel*

SESSION 3: GROUNDWATER FOR DECISION MAKERS

14:00 – 14:25 ‘Progress in implementation of the Water Framework Directive in Ireland’ – Donal Daly (Environmental Protection Agency)

14:25 – 14:50 ‘Water Framework and Groundwater Directive implementation: A UK perspective’ – Rob Ward (British Geological Survey)

14:50 – 15:15 ‘SEVESO III and assessing risk to the water environment’ – Teri Hayes (AWN Consulting)

15:15 – 15:40 ‘Hydrogeological Characterisation and Catchment Managemet at Fardrum and Roosky Turlough SAC. County Fermanagh, Northern Ireland’ – Les Brown (Arup)

15:40 – 15:55	Q & A
15:55 – 16:15	*Tea and coffee*
SESSION 4:	**EARLY CAREER HYDROGEOLOGY NETWORK**
16:15 – 16:30	'Natural attenuation of chlorinated solvents in the hyporheic zone: Insights from a multi-scale field investigation on a gaining lowland river in the UK' – John Weatherill (Geosyntec Consulting)
16:30 – 16:45	'Provenance, pathways and geothermal potential of Irish thermal springs: a multi-disciplinary investigation' – Sarah Blake (Dublin Institute for Advanced Studies)
16:45 – 17:00	'The impact of domestic wastewater effluent on private wells: An evaluation of contamination fingerprinting techniques' – Christopher Fennell (University of Dublin Trinity College)
17:00	*Wine Reception*
18:30	*Social event, including light evening meal, sponsored by IAH (Irish Group).*

‘Sustaining Ireland’s Water Future: The Role of Groundwater’

International Association of Hydrogeologists – Irish Group
Tullamore Court Hotel, Tullamore, Co. Offaly: Tuesday 12th & Wednesday 13th April 2016

Programme Day 2, Wednesday 13th April

9:00 – 9:15 *Tea, Coffee & Exhibits*

SESSION 5: KEYNOTE

09:15 – 09:55 ‘Changes in groundwater storage under future climate change’ – Kevin Hiscock (University of East Anglia)

SESSION 6: GROUNDWATER RESOURCES

09:55 – 10:20 ‘Making the red one green – renewable heat from abandoned flooded mines’ – David Banks (Holymoor Consulting Ltd. and University of Glasgow)

10:20 – 10:45 ‘Zooming in with Groundwater 3D: Focused GSI investigations in priority areas’ – Sophie O’Connor (Geological Survey of Ireland)

10:45 – 11:00 Q & A

11:00 – 11:20 *Tea & Coffee*

SESSION 7: GROUNDWATER RESEARCH

11:20 – 11:45 ‘Getting the buggers to listen – some observations of the trials, tribulations and success in delivering (and using) relevant scientific research’ – Bob Harris (University of Sheffield)

11:45 – 12:10 “It may be excreta to you, but it’s my bread and butter” – research into onsite wastewater treatment’ – Laurence Gill (University of Dublin Trinity College)

12:10 – 12:35 ‘Groundwater research in coastal catchments: new results, new challenges’ – Colin Brown (National University of Ireland, Galway)

12:35 – 12:50 Q & A

12:50 Conference closing address: Owen Naughton (*Conference Secretary* – IAH Irish Group)

13:00 *Buffet lunch in Tullamore Court Hotel*

TECHNICAL WORKSHOP

14:00 Environmental sensing technology for groundwater applications – Fiona Regan (DCU)

14:40 Logging fluorometer demonstration for tracer study applications – Les Brown (Arup)

15:00 End of Workshop

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Lecture by C. R. Aldwell at the opening meeting of the Irish Branch of the International Association of Hydrogeologists, in Trinity College Dublin, March 23rd, 1976.

GROUNDWATER IN IRELAND

It is a great pleasure and honour for me to be given the task of presenting the first paper of what I hope will be a long and varied series by our newly formed Association. As perhaps befits an opening paper it is on a very wide canvas, namely Groundwater in Ireland. I propose to interpret this as the hydrogeology of Ireland, North and South. As a person from the Republic, albeit with strong Northern connections, I hesitated slightly whether to include the North but Peter Bennett assured me to go ahead and I have done. In fact I have been in all parts of Northern Ireland except Rathlin Island. Regrettably not so often in recent times, but much of what I will say is based on Peter Mannings paper "The development of the groundwater resources of Northern Ireland."

The way I plan to go is to run through the stratigraphic column of sedimentary and metamorphic rocks and then after them our igneous rocks.

PRE-CAMBRIAN

These ancient metamorphic rocks occur most widely in the Northwest in a spread extending across Cos. Donegal, Londonderry, and Tyrone. We also have them in Counties Galway and Mayo with small amounts in Cos. Antrim, Leitrim and Sligo. In most oases water is confined to the small fissures in the weathered zone. In many of the Mountainous areas of the far West the heavy rainfall and acid environment result in high iron and manganese in the groundwater. However these rocks like those of every age vary both in their composition and subsequent history. Schists, slates, hornfelses and other clay rocks are particularly poor waterbearers. Quartzites, gneisses and rocks of strong and rigid physical qualities are most likely to develop tension fissures and thus some secondary permeability. Finally one has the marbles which as carbonate rocks are liable to chemical solution. In summary, for boreholes of 50 - 150 ft in areas of:

(a) schist etc. yields of 10 to 300 gallons per hour (gph)
(b) of quartzite 200- 500 gph
(c) of marble several hundred to perhaps a couple of thousand gph,

but these latter are usually small in areal extent.

THE LOWER PALAEOZOICS

I see no valid reason to sub divide these "sedimetamorphic" rocks, except to mention in passing the volcanic rocks of the South East which I shall deal with in more detail later. These rocks occur most notably in the Longford-Down Massif and the South East and rather locally elsewhere. Normal yields are of the order of 50- 300 gph in boreholes of 50- 150 ft. Some areas are however better than others and the odd fluke does turn up. The biggest yield of a few thousand gph was recorded at Lough Egish in Co. Monaghan, over 1000 gph near Ballylanders Co. Limerick and isolated yields of 500-1000 gph are on record for Cos. Down and Louth.

Significantly all the ones of which I know that produce such yields in these two counties were from boreholes of less than 100 ft. On the other hand a borehole a t Killinchy Co. Down was reported dry at 400 ft, while at 700 ft a boring at Inch Co. Wexford also failed. The Cambrian quartzites around Wexford Town on the other hand are much faulted and yields of 500- 2000 gph are on record. An especially bad area is just south of Wicklow Town, where the rocks ore mica schists and slates and there are sizeable areas of the Longford-Down region where yields of 10- 100 gph are the order of the day.

THE DEVONIAN

The Old Red occurs extensively at the surface in the South in Cos. Cork, Kerry and Waterford, its outcrop becomes more intermittent in the midlands being overlain on low ground by the Carb Limestone. Northwards of the Slieve Bloom and Slieve Aughty Mountains it peeps up as small isolated outcrops until we get a sizable extent again in Cos. Fermanagh and Tyrone. It comprises slates, ortho quartzites and conglomerates. One naturally does not expect too much from the slates, but from the quartzites and conglomerate one should hope for better things. Yet to date I have heard of but a few good results, some not well documented , for example in Cork and 1,400 gph from a 100ft boring at Irvinestown Creamery Co. Fermanagh. Part of the trouble may be that the stronger more aranaceous facies form high relief which is not well suited for allowing recharge to take place. None the less I feel some of these rocks do have possibilities for groundwater where the right combination of facies, topography and tectonics coincide.

LOWER CARBONIFEROUS SLATES AND SANDSTONES

These occur in-two main areas, the South of Co. Cork and in patches in the North West, including Cos. Donegal, Fermanagh, Londonderry, Leitrim, Longford, Mayo, Sligo and Roscommon. Elsewhere they intermittently flank the Old Red and Silurian inliers.

Where argillaceous members predominate yields are often poor, e.g. Clonavaddy, Co. Londonderry and Brinny, Co. Cork. However yields of 6,000 gph at Brinny from a sandstone and 5,000 gph at Killala, Co. Mayo, 3,696 gph at Ballykelly Co. Londonderry a couple of thousand gph at Roosky Co. Roscommon and from several wells in Co. Cork, show that we have now come at last to our first somewhat encouraging aquifer.

THE CARBONIFEROUS LIMESTONE

The Carboniferous Limestone ls our most extensively outcropping rock, covering nearly all the central plain of Ireland and present in 31 of the 32 counties. From the point of view of hydrogeology it varies tremendously in its waterbearing and water yielding properties. These depend of course on its degree of karstification which in turn relates to its initial purity and its geological formation and subsequent history. The chemical solution required for well-developed karst needs limestone of a high carbonate content. Besides bedding planes, joints, faults, etc. are needed to enable the water to get to work and finally the limestone must be exposed to weathering over a reasonable period of time and of course their topographic position is important. One can divide the limestones into large numbers of groups depending on which criteria appears most important to you. To me there are four major types. (1) Well bedded pure limestones (2) Pure massive limestones (reef) (3) Dolomites (4) Argillaceous. These of course at times overlap but most of our limestone rocks fall into one of these groups. This however is only one part of the story as the factors of geological environment tectonic and stratigraphic history together with topography must then be taken into account.

A couple of examples may perhaps help to illustrate the point. Much of the Southern Syncline Limestone is reef. In these favourable topographical conditions for advanced karst well developed solution has taken place resulting in high yielding aquifers. Much of the area around Askeaton Co.

Limerick is also reef limestone and some good yields are on record. The number of such openings is however much less than in Cork and failures and very deep wells (300 ft) are not uncommon there. Isolated reef knolls are found in the Midlands locally forming high ground, and reef limestones may even form Mountains in parts of the North. These usually are quite poor water prospects.

Then there are the limestones of the Gort lowlands, the Burren and the Aran Islands. These in many ways are petrologically at least superficially quite similar. However their post depositional history has been very different. The Gort lowlands have been very well karstified having been exposed to chemical solution for vast periods of time. Huge quantities of water are present in these limestones.

The Burren on the other hand was protected by an impervious cover until quite recently and solution has only worked down a couple of hundred feet which taking into account its high topography results in quite limited water except for isolated often flash springs and some water held near the base of the zone of solution.

From what we have seen so far on the Arans it would appear that they are rather similar to the Burren except they lack the topography and mass to encourage solution for more than a few tens of feet. In summary yields of 10,000 gph have been obtained from the limestones of most of the Cork and Waterford synclines, South Wexford and at favourable spots in all the limestone counties south of a line Galway to Dublin with the possible exception of Offaly, and totalling about 40 to date. The largest yield has been 120,000 gph at Dungarvan with 50,000 gph at Mitchellstown and 30,000 gph at Carlow.

In the Northern half of the country there are rather fewer in number, but to me this seems partly due to lesser requirements of water in many of the Northern counties with large areas of limestones, especially Fermanagh, Longford, Mayo and Roscommon.

The largest yield I have details for is 29,000 gph at Cabragh near Dungannon Co. Tyrone. Yields of about 20,000 gph have been reported from Armagh, Killeshandra (7) Co. Cavan, Carrickmacross and Emyvale Co. Monaghan, at Athenry Co. Galway, again at Cabragh Co. Tyrone and Clogher Co. Tyrone. Boreholes with yields of at least several thousand gph have been sank in most of the remaining counties.

Beside boreholes we must also remember springs which are groundwater and are a common feature of most limestone districts. Springs with measured flows of the order of 4 M gph are reported near Castlemartyr Co. Cork, near Dunmore in Co. Galway and Taughmaconnell Co. Roscommon. While one near Timahoe Co. Laois is credited with over 1 M gph. There are many lesser ones and undoubtedly some not yet measured. I do not have any spring data for the Northern Ireland Carboniferous limestone.

THE NAMURIAN

These rocks, shales and sandstones, outcrop in 21 counties but are much more local than the underlying limestone. They remain capping the limestone often at an elevation of. 500 - 1,000 ft. around the periphery of the Central Plain. Their most extensive spread is from Lisdoonvarna to Killarney and Mallow by the Tipperary - Laois – Kilkenny - Carlow coalfield area in the South East and the Fermanagh, Sligo, Leitrim, Roscommon belt in the North West. 1he important aquifers in the Namurian are the sandstones, which in favourable conditions can be strongly artesian. The area which up to now has caught the most attention and which may be unique from the others in some vital respects is the Castlecomer Plateau. During exploration for coal water sometimes shot 20 - 30 ft. into the air in quantities estimated at the time to be of the order of 1 Mgph. Some of these boreholes are still flowing after 36 years. The rock traditionally credited as the aquifer has been the relatively thin

Claygall Sandstone. Recent work by Eugene Daly however, suggests there are probably several artesian sandstones in the Leinster Coalfield.

Elsewhere yields of close to 10,000 gph were obtained at Kilrush Co. Clare and also at Charleville Co. Cork. Where shales predominate, however, yields are low and iron is an endemic if local problem with groundwater in this formation.

THE PERMO-TRIASSIC

The Permian strata seldom outcrop but their top member, the Upper Permian Marl forms an important impervious base to the overlying permeable Bunter Sandstone of Triassic Age. These rocks are generally relatively small in areal extent and occur with one exception around the edges of the Antrim - Derry Basalt Plateau. The most important stretch is the Lagan Valley - Newtownards - Comber. It also occurs Southeast of Dungannon, east of Dungiven to Limavaddy and Lough Foyle. Finally there is the small Kingscourt occurrence straddling the Co. boundaries of Cavan, Meath and Monaghan.

At Derriaghy between Belfast and Lisburn a 300 ft borehole sunk in 1975 has been tested at 25,000 gph and at Kennel Bridge near Comber a 270 ft boring got 21 ,000 gph. According to the Geological survey of Northern Ireland 35,000 gph represents the highest yield achieved in this sector while 12,000 gph was all that was obtained last year in a borehole at Englishtown which is interpreted as an indication of the generally tighter and finer nature of the Bunter Sandstone as one proceeds S.W. up the Lagan Valley. *A* yield of 10,000 gph has been obtained near Limavaddy and 6,000 gph near Dungiven. The only deep borehole at Kingscourt for which a flow has been measured is said to have yielded 6,000 gph. It is believed that fissure flow plays an important role in the permeability of the Bunter in Ireland and is at least partly the cause for somewhat variable results in some areas.

THE JURASSIC

The Rhaetic-Lias Shales occur beneath the chalk here and there around the edges of the Basalt Plateau and are not water bearing. Their hydrogeological significance is that they provide an underseal to the water in the overlying Cretaceous.

THE CRETACEOUS

The chalk and the basal Hibernian Greensands, both are water bearing. For those who have not seen the Irish Chalk, I should explain it has neither primary porosity nor permeability. In fact it is quite difficult to credit that the unconsolidated Cretaceous I saw in Alabama and the chalk of the South of England or the North of France and these Irish Cretaceous rocks are all of the one age. As a consequence of the importance of fissure flow, strong springs discharge much of its groundwater. Near Larne, the Four Springs are reputed to yield 2 M gph and smaller ones occur elsewhere. A boring yielded 14,000 gph near Larne and 8,000 gph at White Mountain near Belfast.

THE TERTIARY

The Lough Neagh clays are practically impermeable and well yields are poor.

IGNEOUS ROCK

(A) ORDOVICIAN OF WEXFORD AND WATERFORD

These rocks are mainly rhyolites and tuffs and occur most extensively in East Waterford and more irregularly up through Wexford. We do not fully understand as yet all the tectonic and related factors that have resulted in these rocks being quite good aquifers. Their pivotal position close to the hinge joint between the lines of the Hercynian and Caledonian trends may have helped to provide that extra tension needed to encourage good physical fissuring. Whatever be the cause some two dozen boreholes have yields of 1,500 to 6,000 gph which in the case of Waterford has been most fortuitious in a county with considerable water supply problems.

(B) CARBONIFEROUS OF LIMERICK

In east County Limerick occur quite extensive volcanic rocks of Carboniferous age. They are rather more widespread than the Survey maps suggest and range from basalts to rhyolites with extensive beds of pyroclastic deposits often with carbonate cement.

As water bearers they are very variable and a great deal depends on their individual structure and topographic situation. In favourable conditions yields of up to a few thousand gph are certainly possible, but in cases where they form isolated lava ridges they can be very poor water bearers.

(C) TERTIARY LAVAS OF ANTRIM AND LONDONDERRY

These rocks cover 25% of the land area of Northern Ireland. Their hydrogeology, like so many of our Irish rocks is still but little known. At Mossley a 400 ft boring yields 9,000 gph. Yields of up to 6,000 gph have been reported from near Glengormley, while near Ahoghill a 150 ft well yielded 4,000 gph. Like the two previous groups of volcanic rocks results thus tend to be erratic, but can be good.

THE GRANITES

Four major occurrences of granite are present in Ireland. Donegal, Galway, Wicklow and the Mournes.

(i) The Donegal Granite has three main divisions and has usually but little overburden. It forms rugged wild country, often covered by bog and dotted with lakes. Few boring have been sunk in it and my expectation would be limited water in the weathered zone.

(ii) That of Galway is rather similar. In this case we have had some borings mostly for domestic supplies. One well of 300 ft. at Spiddal has yielded over 4,000 gph, perhaps due to local felstone dykes.

(iii) The Wicklow granite shows weathering for tens or even hundreds of feet, it also often has overburden, sometimes thick. There are lots of fissures in the weathered zone and borings of 40 - 100 ft almost invariably yield a few hundred gph. I cannot however recall a case of over 1,000 gph and I have seen hundreds of borings in this Leinster Granite.

(iv) The Mourne Granite is said by my Northern Colleagues to contain water in rare joints.

THE QUATERNARY

So we come to the last, but by no means the least of our geological deposits, the Quaternary. I reminded you earlier that the Carb Limestone was present in 31 of the 32 counties, well now we have come to the one present in them all. Of course its importance as an aquifer is by no means uniform, although we should also remember that even where it is impervious it may well perform the useful task of protecting the groundwater in the aquifer below, from pollution. Our main interest are the fluvio glacial sands and gravels. These are very wide spread and even quite a small deposit can act as a valuable water source. For example two borings at Ballyragget Co. Kilkenny and Brinny Co. Cork have yielded over 20,000 gph. There seems little doubt that accurate mapping of these deposits combined with the development of the techniques and technology of abstracting water from them will be one of the main jobs to be undertaken in the field of Irish water re source utilisation in the next couple of decades.

You will I hope see that we do know a little about the hydrogeology of Ireland, do not know a great deal and hopefully together we can as a profession help to start putting that position to rights in the years to come.

SESSION I

SUSTAINABILITY OF GROUNDWATER RESOURCES: CONCEPTUAL EVOLUTION, OPPORTUNITIES, & CHALLENGES

John M. Sharp, Jr.
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ABSTRACT

Sustainability requires rates and methods of water resource utilization that can support a reasonable human population indefinitely at an acceptable standard of living and maintain an acceptable environment. BUT what is a reasonable population; what is an acceptable standard of living and an acceptable environment? Have we already passed reasonable population levels both domestically and globally (>7 billion globally already)? How much environmental degradation can we tolerate and achieve sustainability? Finally, what environment are we to preserve and for whom or what? Hydrogeologists understand the variability of Earth properties and the difficulty of "remediating" past mistakes; that the Earth is not static, but is continually evolving; that the environment that we observe is a "snapshot" at a moving target; and that we cannot maintain the natural environment of today or of a century past, even if human activities cease. We understand that all water resources are to some extent limited and their development itself affects the safe yield, which was one of the initial concepts espoused in water management. The safe yield concept has evolved since first promulgated nearly 100 years ago, but safe yield is not sustainable.

To achieve sustainability, we need to match the stakeholders' needs/desires (the consensus yield) with the ability to produce and deliver water (the effective yield). This means that the stakeholders must define mutually acceptable goals. Narrative elicitation is one technique that can assist in this often difficult endeavor. In addition, scientists must make known to the public both our uncertainties and our evolving and growing knowledge of water resources. Major challenges are: 1) to focus hydrogeologic knowledge to the temporal and spatial scales of human development; and 2) to develop adequate bases to assess and communicate the effects of human activities. Groundwater decision support systems can help evaluate how these human demands and potential future changes in climate, technology, and management strategies affect our ability to provide water as sustainably. Especially challenging are the changes to the hydrologic cycle from climate change and from human factors (e.g., urbanization, sea level changes, irrigation practices, population shifts, etc.). In addition, future technological advances in, for instance, desalination of brackish or saline waters could have dramatic effects on the sustainable use of our groundwater resources. The challenges are daunting, but good science and management can address them.

INTRODUCTION

Theodor Roosevelt stated that “The nation behaves well if it treats its natural resources as assets which it must turn over to the next generation increased, and not impaired, in value.”

Sustainable use of groundwater resources requires the consideration of a mutual dependence between the natural environment and the human economy. Thus, geologic, hydrologic, and ecological factors must somehow be combined with the economic, social, and political issues in order to determine rates, times, and places of groundwater extraction as well as the actual uses of the groundwater. The Brundtland Report (1987) defined sustainable development as that which “meets the needs of the present without compromising the ability of future generations to meet their own needs." Sustainable use of a natural resource can be defined as the rates and methods of resource allocation that can support a reasonable human population indefinitely at an acceptable standard of living and maintain an acceptable natural environment.

This immediately raises several questions. What is a reasonable population (now >7 billion globally); have we already surpassed it; or will we surpass it in the next 100 years? Projections indicate at least 10 billion by 2100 with most of the growth to be in urban areas. What is an acceptable standard living? Finally, what is the environment that we are to maintain? The environment is in a continual state of change, much the result of human activities and we cannot maintain the natural environment of today or 100 years ago, given population growth, migration, urbanization, changing technology, and socioeconomic and political factors.

Sustainable use of groundwater begins with the concept of safe yield, which has evolved since defined a century ago. Below the evolution of this concept, the consequences of groundwater over-exploitation, and the development of the concept of sustainable yield are reviewed. The need to consider human economy, water policy, and environmental issues consequences of groundwater is a great challenge as is the need to consider future changes in technology and climate in determining sustainable groundwater yields. In addition, our understanding of the natural hydrogeologic systems is continually evolving. To meet the changing and rising demand for groundwater, the options are to increase supplies, decrease demands, or become more efficient in groundwater usage in the context of these challenges.

SAFE YIELD

The term "safe yield" or "net safe yield" as applied to groundwater, although often credited to Meinzer, may actually have been by Lee (1915). Meinzer used the term in a 1920 paper but did not publish a definition until 1923. However, in 1915 Lee was working in San Diego County, California, under the direction of Meinzer. It might be inferred, therefore, that the adaptation of the safe yield concept to groundwater was a joint effort. The concept of safe yield has been widely debated, but remains a controversial topic (e.g., Conkling, 1946; Mann, 1963; Sophocleous, 1997, 2000; Kalf and Woolley, 2005; Zhou, 2009; Pierce et al., 2013).

Lee (1915) defined safe annual yield as "...the limit to the quantity of water which can be withdrawn regularly and permanently without dangerous depletion of the storage reserve." He considered quantities directly, but listed no other limitations. Meinzer's first published definition (1923) was "The rate at which water can be withdrawn from an aquifer for human use without depleting the supply to such an extent that withdrawal at this rate is harmful to the aquifer itself, or to the quality of the water, or is no longer economically feasible." This definition recognizes that the calculated quantity may have to be reduced under certain circumstances.

Conkling’s (1946) definition is widely-cited - safe yield is the annual extraction from the ground-water unit that will not or does not: 1) exceed the average annual recharge; 2) so lower the water table that permissible cost of pumping is exceeded; or 3) so lower the water table as to permit the intrusion of water of undesirable quality. Not exceeding the average annual recharge, is commonly misinterpreted to mean average annual recharge of new water, but this is not necessarily correct. If any of the water extracted is delivered locally, then the return to groundwater storage from those deliveries must be included in the average annual recharge. Because of this circumstance, safe yield (expressed as withdrawals or pumpage) commonly exceeds what is usually understood as average annual replenishment. Conkling addressed questions and problems that still confront us today. Banks (1953) modified Conkling's definition by including legal limitation by adding that safe yield will not interfere with prior rights of others in adjacent groundwater basins.

Todd (1959) generalized the definition of safe yield of a groundwater basin as the amount of water which can be withdrawn from it annually without producing an undesired result. He discusses four categories of undesired results - water supply availability; economics of pumpage; water quality; and water rights. In the 1962 California Los Angeles vs San Fernando case, the Report of the Referee defined safe yield as the "maximum quantity of water which can be withdrawn annually from a ground -water supply under a given set of conditions without causing an undesirable result.” This definition also raises several questions: how is maximum defined; what is the significance of a “given set of conditions”; what is the base period for which such conditions are to be defined; and how does one quantify an undesirable result? Additional modifications to the safe yield concept include: 1) pumping limits to prevent subsidence (e.g., in the Houston, Texas); 2) legal constraints requiring beneficial groundwater use and that pumping cannot be done to maliciously harm another’s water rights or water use; and 3) protection of groundwater dependent ecosystems and aquatic endangered species (e.g., pumping at safe yields, as defined, could diminish discharge to ecosystems that depend on groundwater. A prime example is Comanche Springs, Texas, where pumping dropped spring flows to zero).

The calculation of safe yield can be generalized by the classic Hill, Harding, and zero water-level change methods (Figure 1). Today, we commonly use numerical models that follow the same basic principles (e.g., the Texas Water Development Board, 2016). The Hill method (Conkling, 1946) plots annual pumpage versus average annual changes in the potentiometric surface. The pumpage at which this change is zero is the safe yield. The Harding (1927) method was developed for shallow alluvial aquifers. It quantifies aquifer inflows (e.g., recharge, leakage from streams, irrigation return flows) minus outflows (e.g., pumping, spring discharge, base flow to steams). The pumpage where inflows-minus outflows corresponds to zero water level change is safe yield. The zero water-level change method simply takes two times where the water level is the same; the average pumpage between these times is the safe yield. These methods demonstrate the inherent uncertainties in safe yield calculations. First, what method do we use to quantify aquifer system water levels (e.g., specific wells, a cell by cell average of a numerical model, etc.). How do we evaluate drawdown effects necessitated by pumping and how equivalent drawdowns in one part of the aquifer might be critical (e.g., drawdowns close to a saline-water source may be more critical than drawdowns at a distance from the source)? The quantification of inflows versus outflows is also not always straight forward considering increasing data on climate variability, natural discharge, recharge, and aquifer properties. Finally, over what time period do we make our safe yield predictions. This is clear on the zero water-level change methods as there are many different time periods over which we could specify that water levels are the same.

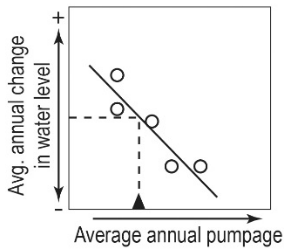
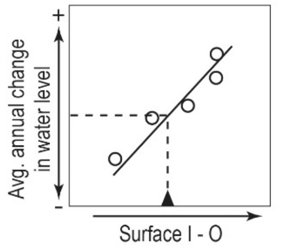
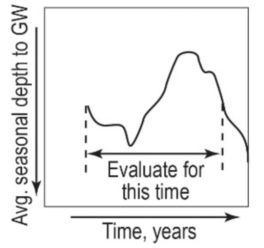
Hill Method	Plots annual pumping versus Average water-level change	
Harding Method	Inflows - outflows in an unconfined aquifer versus Average water level change	
Zero Water-Level Change Method	Maintains a constant groundwater storage elevation at the beginning and end of pumping (average pumping rates over time period = safe yield)	

Figure 1. Safe yield estimation methods.

The discussions of appropriate aquifer yields and the effects of over-exploitation have focused and still focus on: 1) What is the effective long-term recharge and discharge to the aquifers, both natural and anthropogenic; 2) what are the economic effects whether short-term, long-term, or episodic; 3) are there negative water quality repercussions; 4) are there other side effects such as subsidence; and 5) what are the environmental effects? Because there may be other water resources, such as surface water reservoirs, other aquifers, desalination, or dual distribution systems, the effects of over-exploitation have to be compared with the economic and social consequences. Other yield definitions have been promulgated and are included in the Appendix.

Thomas (1951) and Kazmann (1956) suggested that safe yield should be abandoned because it is too indefinite. Clearly, in areas where there is considerable opportunity for induced infiltration from large rivers, safe yield may have no clear upper limit. Another suggestion (Mann, 1963) is that the term is legally misleading. As used in litigation, the connotation that extractions beyond a certain annual rate will result in a condition that is unsafe unduly dramatizes the situation. A term without a semantic impact, such as "sustained yield" or "perennial yield" is considered preferable. The trend is towards using sustained or sustainable yield.

SUSTAINABLE OR SUSTAINED YIELD

The concept of sustainable yield also continues to be a topic of discussion (e.g., Committee on Ground Water, 1961, Hiscock et al., 2002; Kinzelbach et al., 2003; Alley and Leake, 2004; Sophocleous, 2012; Walton and McLane, 2013; Pierce et al., 2013). What is sustainable? Is using a resource sustainably always the best use of the resources? Figure 2 shows the possible range of sustainable yield. The available yield covers the range from no pumping (no use at all) to the maximum mining yield (i.e., pumping the entire aquifer dry or taking the average annual recharge plus all the water in storage). Of course, this is not a fixed number as technological evolution may allow us to be able to extract more in

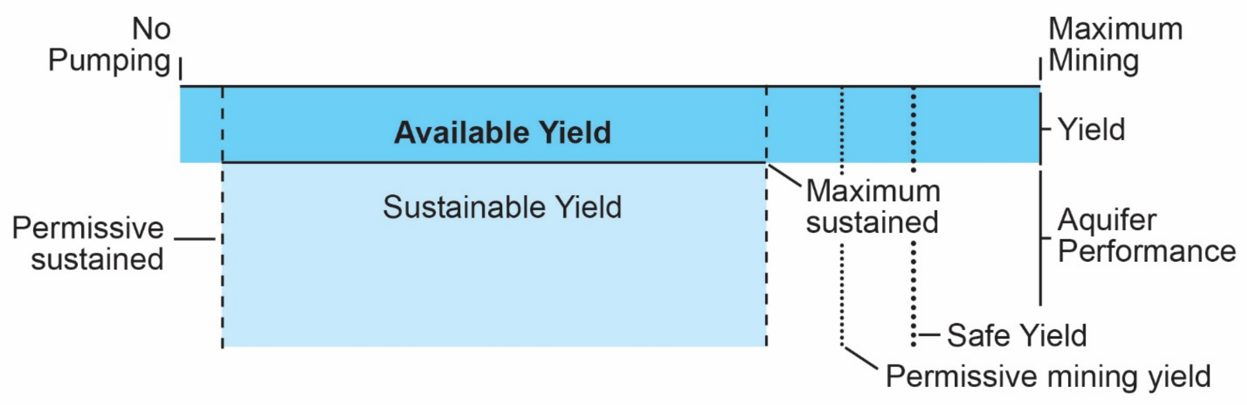


Figure 2. Sustainable yield.

the future. At the low end of the possible range of sustainable yield is the permissive sustained yield, which is a rate of extraction with no impacts of concern. In other words, this pumping rate is such that there are no discernable environmental side effects. As noted above, safe yield may have environmental impacts. As pointed out by Sophocleous (1997, 2000), safe yield is not always sustainable, which is demonstrated by the loss of perennial streams in Kansas (Fig. 3).

The maximum sustained yield is defined the amount of pumping at which other factors (e.g., environmental flows to springs or streams, subsidence, loss of wetlands, etc.) are affected, but the level of these effects in acceptable to society. This is by definition less than the safe yield. The permissive mining yield is extraction in excess of the long-term annual recharge to the aquifer, but the effects of this mining are tolerable to society. This may be a short term mining and it could be either greater or less than the safe yield. In addition, there can be times of overdraft, where more water is being extracted from an aquifer than is entering or recharging that resource over a given period of time.

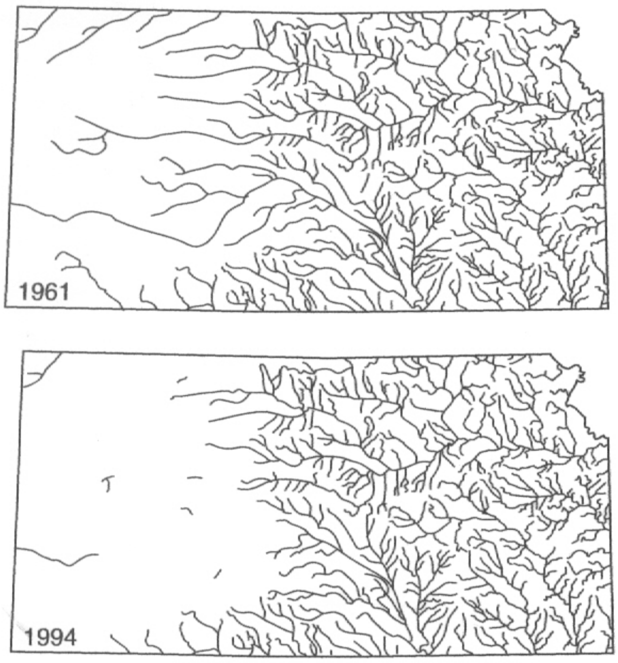


Figure 2. Loss of perennial streams in Kansas, USA, between 1961 and 1994 caused by groundwater pumpage (Sophocleous, 2000).

Permissive sustained yield, maximum sustained yield, permissive mining yield, and safe yield are all ranges that will vary with climate change, technology, our knowledge of the aquifer systems, and societal needs and concerns. Two other yields, consensus yield and effective yield, are needed in the discussion of sustainability.

CONSENSUS AND EFFECTIVE YIELD

The above discussion focusses on scientific, technical, and to a certain extent economic factors. However, another factor must be considered – the desires, needs, and expectations of the water users, the stakeholders. Groundwater, like oil, is a common pool resources and the desires of the municipal, agricultural, industrial, recreational, and environmental stakeholders commonly clash. Similar clashes can occur with trans-boundary aquifers. The consensus yield is the acceptable extraction volume from an aquifer system as determined by the inter-related elements of both local and regional hydrologic regimes within the context of the specific preference sets held by affected stakeholders. The process involves stakeholders identifying different management goals; scientists, and engineers calculating the amount of groundwater available for use for each of management goals, and the stakeholders reaching consensus (however consensus is defined) on the final amounts of groundwater for use. In some societies, this is an important or deciding factor in groundwater management. Consensus yield requires dialogue with stakeholders with widely varied interests and can thus be a range or a consensus space). This can be a challenge to scientists and engineers dealing with water resources issues. There is considerable research in how these dialogues can operate effectively (e.g., Stoll-Kleeman and Welp, 2006; Pierce, 2006; Dulay, 2011; Pierce et al.,2006, 2013). Kinzelback et al. (2003, citing Negri, 1989) state that a collective stakeholder decision to a common pool problem, if it can be achieved, is preferable to the sum of all the independent, individual stakeholder decisions. The consensus yield will also be a range spatially and temporally as stakeholder interests and knowledge evolve. At The University of Texas, we have used narrative elicitation as tool to reach consensus between stakeholders with varied and, initially, conflicting positions (Pierce, 2006; Sharp et al., 2008; Dulay, 2011).

The effective yield is the amount of water that can be extracted from an aquifer under a given set of operating conditions while meeting community-defined performance metrics or consensus yield constraints over a planning horizon. The effective yield will also evolve in response to changing policy goals, increased understanding of the resource, and technology. As shown on Figure 4, where the stakeholder consensus space (somewhere between permissive sustained yield and safe yield) intersect with our ability to provide that water (effective yield) delineates the desired sustainable rate of groundwater extraction.

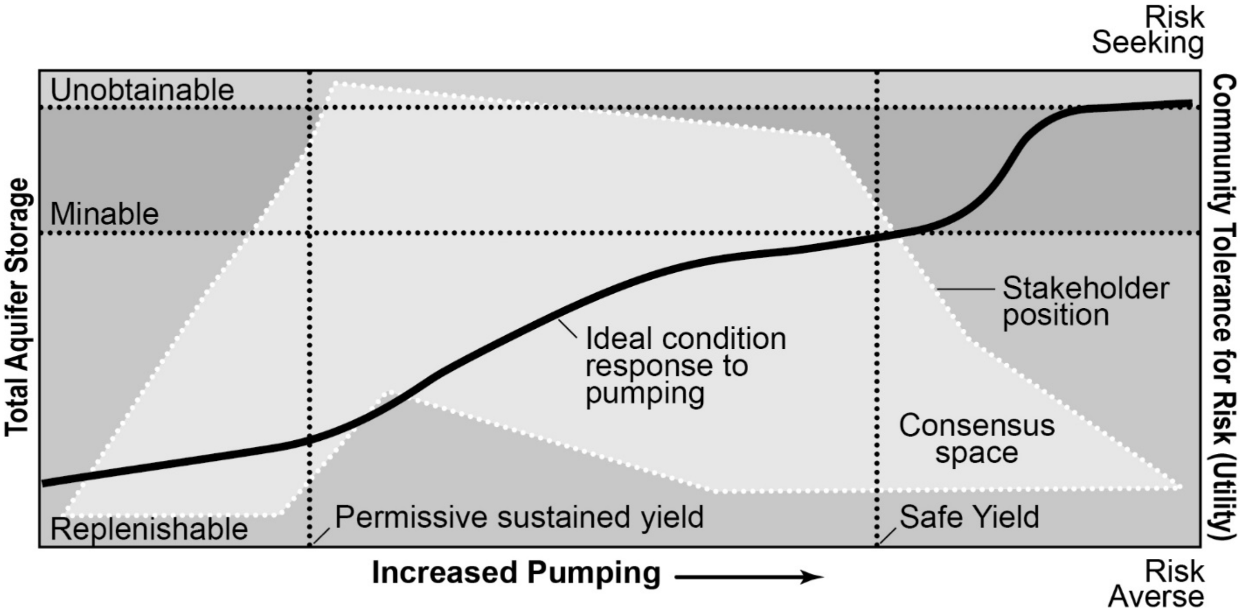


Figure 4. The intersection of stakeholder position (the consensus space) and effective yield (solid line) provides the possible range for sustainable yield.

MEETING FUTURE WATER NEEDS

To meet the water needs for our growing populations, given the many hydrogeological, technological, social, economic, and climatic complexities, there are only 3 inter-related options: increase supplies, decease demands, or become more efficient. The traditional method in developed countries to meet increased demand has been to use new water sources, such as developing a previously untapped aquifer or constructing a new reservoir. Sometimes, these "new" waters are transported for considerable distances. Where feasible, this is the first resort, but in many areas, the feasible aquifers are already being pumped and the prime dam sites already utilized. On a small local scale, harvesting of rainwater or fog can be implemented. However, it is in the future use of unpotable waters that increased supplies is most promising. First, dual distribution systems – one for drinking, cooking, and perhaps bathing and a second for all other uses (e.g., sanitation, irrigation, industry, etc.). This would be a capital-intensive option in much of the world, but brackish waters do represent a major potential water source. Second, when or if desalination technology becomes economically and environmentally feasible, there would be essentially unlimited sources near our coasts. The distribution range of these new waters would be determined by the costs of distribution.

Decreasing demands for water is the second and complimentary course. Conservation is commonly the easiest and most cost effective measure, but it has limits. Demand can be decreased to some extent by raising the cost of supplied water, fines or penalties for excessive water use, rationing, or public appeals to reduce water use. All these courses of action can have political, medical, and social consequences. Limiting population growth is the obvious, ultimate solution to decreasing water demands, but controlling birth rates and immigration (legal or illegal) is indeed a challenge.

Finally, increasing the efficiency of water production, use, and distributions is the third, complementary course of action. As technology advances we can expect more water efficient technological infrastructure (e.g., leak-minimizing water mains, new waste water treatment systems, etc.) and techniques (e.g., drip irrigation, waterless toilets, etc.). Artificial recharge and aquifer storage and recovery (ASR) can extend aquifer resources. Conjunctive use of surface water, groundwater, and possibly desalinated water offers the potential of efficient and economical use of the suite of water resources available to a community.

CONCLUDING STATEMENT

In many place across the globe, water is in short supply. Famine, crop failures, disease, and damage of the natural environmental follow the water shortages and over-exploitation of groundwater. Given the historic and projected population growth, increasing urbanization, and the predicted effects of climate change, the situation may look dire. Our inability to account for possible future technological advances, future climate, and the political, social, and economic factors that control water management policies make long-term planning a challenge. We need *a priori* collection of necessary data and sound predictions of the effects of future climate change and normal climate variability, ecological patters, urbanization, new technologies, and water policies.

However, the future is not necessarily bleak. We recognize the need for the sustainable water resources development, the importance of maintaining the natural environments, and the need to integrate stakeholder input into water planning. The development of brackish or saline water resources holds immense promise. If desalination ever becomes widely economical, the water supply situation will be dramatically altered. However, even without this development, our continued hydrogeological research is constantly adding to our understanding of aquifer systems; this coupled with improved models of groundwater flow and transport, including neural network models, will increase our ability to make accurate predictions of future water yields and how our actions will affect them.

Hydrogeologists are uniquely qualified to address problems of water resource sustainability because we have quantitative backgrounds. In addition, we recognize past and possible future changes in hydrology, geology, and climate and that we must interact with other areas of science, engineering, law, and policy.

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Appendix 1. Some yield definitions (Pierce et al., 2013; Sharp, 2015).

available yield – the volume of water that is considered acceptable for permitted extraction from an aquifer because it is: a) scientifically feasible; b) within the bounds of effective yield quantification; and c) acceptable to the community of stakeholders.

consensus yield - the acceptable extraction volume from an aquifer or aquifer systems as determined by the inter-related elements of both local and regional hydrologic regimes within the context of the specific preference sets held by affected stakeholders. The process involves stakeholders identifying different management goals, scientists, and engineers calculating the amount of groundwater available for use for each of management goals, and the stakeholders reaching consensus (however consensus is defined) on the final amount of groundwater available for use.

dynamic or effective yield - the amount of groundwater available for use that is allowed to change over time in response to changing policy goals and an increased understanding of the resource.

effective yield – (1) the amount of water that can be extracted from an aquifer under a given set of operating conditions while meeting community-defined performance metrics or consensus yield constraints over a planning horizon; or (2) an implementable and quantifiable volume of water that can be allocated from an aquifer or aquifer system.

mining yield - the appropriate rate of pumping from an aquifer that is receiving no or little recharge.

permissive mining yield - extraction in excess of the long-term annual recharge to the aquifer, but at rates so the effects of this mining are tolerable to society.

optimal yield - the rate of extraction of groundwater from an aquifer, aquifer system, or groundwater basin for various uses that maximizes the time discounted rate of return.

safe yield - the volume of water that can be annually withdrawn from an aquifer (or groundwater basin or system) without: 1) exceeding average annual recharge; 2) violating existing water rights; 3) creating uneconomic conditions for water use; or 4) creating other undesirable side effects (e.g., subsidence or saline water intrusion).

sustained or sustainable yield - the volume of water that can be extracted annually from an aquifer or a groundwater basin that can, in conjunction with other available water resources, sustain a reasonable human population indefinitely at an acceptable standard of living and maintain critical natural habitats indefinitely.

maximum sustained yield – the rate at which water cab be drawn continuously from and aquifer system without dewatering the most productive water-yielding formation.

permissive sustained yield – the yield at which there is no perceptible damage or predicted damage to ecosystems, recreational uses, or other non-market uses.

FIELD STUDIES OF CHLORINATED SOLVENT PLUME BEHAVIOUR IN SEDIMENTARY ROCK: FROM SOURCE TO DISCHARGE ZONES

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Director, G360 Centre for Applied Groundwater Research

ABSTRACT

Chlorinated solvent source zones and plumes in fractured sedimentary rock have been investigated intensely at several industrial sites in Canada, USA and elsewhere. A comprehensive methodology, referred to as the Discrete Fracture Network (DFN) Field Approach has been developed providing a toolkit for characterizing these sites. The sites show many common features providing the basis for a general conceptual model for source zone and plume behavior. Contamination was initiated by DNAPL releases decades ago; however the source zones have evolved or "aged" over decades due to dissolution and diffusion processes, such that nearly all mass now occurs as dissolved and sorbed phase in the matrix, causing reduction in source strength such that mass input to the plume may be controlled more by back diffusion. While nearly all groundwater flow and downgradient transport occurs in the interconnected fracture network, diffusion in the plume also causes mass transfer from groundwater flowing in fractures to the rock matrix, causing strong retardation of rates of plume front migration and strong attenuation of mass discharge within the plume. In many cases, the combined effects of declining source strength and diffusion causes the plume to be essentially stationary at present time or possibly even retreating if even slow rates of contaminant degradation are also occurring. This presentation will provide an overview of the DFN Approach, insights from its application at several sites, and implications for understanding long term plume behavior, risk assessment and remedial efficacy.

BIOGRAPHY

Beth L. Parker has a Bachelor degree in Environmental Science and Economics, Masters in Environmental Engineering and PhD in Hydrogeology. She is Professor in the School of Engineering and Director of G360 - The Centre for Applied Groundwater Research at the University of Guelph. She has more than 25 years of experience as a groundwater professional investigating subsurface contamination issues at industrial sites around the world. Her current research activities emphasize field and laboratory studies of DNAPLs in sedimentary rocks, clayey deposits, and heterogeneous sandy aquifers, and focus on the effects of diffusion into and out of low permeability zones and on DNAPL fate, plume attenuation, and controls on remediation. She is currently involved in research and technology demonstration projects at Superfund and RCRA facilities in the United States and similar sites in Canada, Europe and Brazil. In July 2007, she was awarded an NSERC Canada Industrial Research Chair in Fractured Rock Contaminant Hydrology. In December 2009, she received the John Hem Award from the Association of Groundwater Scientists and Engineers of the United States National Groundwater Association. http://g360.uoguelph.ca/our-people

SESSION II

GROUNDWATER IN IRISH SOCIETY: 40 YEARS OF THE IAH IRISH GROUP AND 45 YEARS OF MODERN HYDROGEOLOGY

David M. Ball Hydrogeologist

ABSTRACT

The modern story of hydrogeology goes back into ancient history. Modern hydrogeology started in Ireland in the 1970s with the arrival of hydrogeologists trained on Masters degree programmes. The IAH Irish Group was formed in 1976 by this small group with a clear ethos of openness and collaboration. It has thrived on the strength and commitment of unpaid efforts by its members. It has had many successes, and made a positive contribution to society and the environment, but hydrogeologists are still a small pioneering community in the context of the importance of the resource and the potential role that the profession should fulfil in modern Ireland

1. INTRODUCTION

This paper is written for people attending the IAH (Irish Group) Conference in Tullamore on the 12th April 2016, most of whom will be familiar with the people, places and institutions referred to in this paper. Therefore, the paper does not give formal titles to people, or full descriptions of places or institutions. The paper is an informal opinion piece.

The history of the early development of hydrogeology and the IAH in Ireland is being written by Bob Aldwell, who retired from the Geological Survey about ten years ago. His article will be published in the Groundwater Newsletter later this year. I will touch upon his history lightly, but as I was working abroad from 1972 to 1984, Bob's account will be the authoritative document. There are also histories of the IAH on the International website that are soon to be revised, and Nicholas Howden and John Mather in 2014 produced a large book on the History of Hydrogeology. Others before have also produced histories of hydrogeology as introductions to their textbooks. I will draw upon this material for context in so far as it is relevant to the development of hydrogeology in Ireland.

2. HYDROGEOLOGY – WHAT'S IN A NAME AND THE EARLY DEVELOPMENT OF THE SCIENCE

Hydrogeology is regarded as a new science in Ireland, by many outside our discipline. The name of our science and our profession is still unfamiliar to most people including the press and decision makers. I, and I am sure many of us, have often corrected engineers, and members of other disciplines, when they refer to us simply as 'Hydrologists' or 'Geologists'. Perhaps the name 'Hydrogeology' is an awkward mouthful, but perhaps the lack of recognition also reflects a hesitancy to recognise a profession and science, that they feel ill equipped to understand, or for which they do not see the relevance. It is not the same in other countries, particularly those that have less rainfall and fewer surface water resources. By contrast even Touareg nomads are happy to refer to me as a 'Hydrogeologue' in Franco-phone Africa. While most people in Ireland have not heard of hydrogeology and do not know what we do, some people are aware of us, but have pigeonholed us as 'Specialists'. This label implies that they do not regard us as an essential, or mainstream profession.

Concern Worldwide carries out numerous rural water development programmes involving water well drilling, yet from my experience, they regard this as work for young engineers who in turn usually regard the work as a civil's contract. Concern will employ a trained hydrogeologist usually when their programme is not going well, and their borehole 'failure rate' has become a problem for themselves or their donors.

I expected a lack of recognition for our science in the 1970s, but it is interesting to reflect that 45 years on, we are still trying to help people pronounce our name, and explain what we do. There is probably a cultural reason for this, which I touch on below.

Hydrogeology, or the understanding of underground water resources and flow, has been a part of human history from the beginning. It wasn't called hydrogeology, but the presence of water underground (as found in wells and caves) and the flow of water out of the ground in springs has been a subject of much thought, argument and conjecture throughout history. It is easy to imagine early humans being mystified by water emerging from rock with no obvious river or stream feeding the rock. The reason for this conjecture is that people need water daily, and there will always have been an intimate connection between people and perennial water supplies.

The mysteries of water and in particular groundwater became an obsession of early Greek and Roman philosophers. Myths, stories, worship and magic were all associated with explaining the occurrence and movement of water; in particular groundwater. The evidence in some names in Ireland suggests that pre-Christian Ireland ascribed mythical associations with springs and wells. Later, Christianity gave Saint's names to springs and wells. The myths stories and conjecture are understandable because underground water is hidden from view and its origins and the processes by which it emerges are not evident from the surface.

For much of human history, most people's perception of their world was limited by their own local observations and the teachings of their leaders. Up until the 1500s, the general understanding was that the terrestrial parts of the earth were surrounded by water and that the dry land floated on water. There was a deep sense of insecurity about digging down through the dry earth and finding water because, as with a boat floating on a river or the sea, a hole in the bottom, means that water will rise up and the boat will sink.

From St Jerome (340-420 AD), interpreters of the Holy Scriptures taught that springs have their origins in the sea. Water escapes from the sea through holes in the sea floor, and flows through subterranean channels, and thence is elevated to the springs on land. Why it does not remain salty was a subject of heated debate. However, for much of early Christian history it was heresy to question this seawater subterranean feed to land springs theory. This is an example of a second issue with which hydrogeologists in Ireland have to cope; the legacy of religious perspectives and teaching. There are people in Wexford who believe their well is fed by water from Wales; people in Antrim who swear their water comes under the St George's channel from the Mull of Kintyre, and hoteliers in the Aran Islands who believe their borehole is supplied by rain falling on the Burren.

These perspectives may seem weird to us, but they are still relevant, because most people don't understand, or need to understand, groundwater. Hydrogeology in modern times is still dealing daily with myths and misconceptions that have remained unchallenged up until the point when a hydrogeologist appears. It is a part of our work, in modern Ireland; to pull away the veil, and reveal that common sense and gravity still apply below the surface.

The illogicality began to be dispelled in Europe through North America and the Middle East to China with the advent of the Enlightenment when society started to question whether God or Gods controlled the order of the natural world and natural events.

By the early 19th century in Europe engineers and geologists in parallel started to make observations and deductions about groundwater. They started logging wells and bored holes and measuring groundwater levels. They published information. Water underground was becoming important for water supplies, but also for engineering and mining during the industrial revolution, and also in relation to pollution, effluent disposal and public health particularly in cities.

He term ‘Hydrogeology’ was first used in Britain France and the USA from the 1880’s, though up to the present day, some in the USA prefer to refer to us as ‘Geo-hydrologists’. Hydrogeology became a recognisable applied science by the end of the 19th century, but it was still being practiced from two perspectives; engineering and geology. It is as if they ran in parallel and met in the middle. This appears to have continued in all parts of the world during the early 20th century. There were a band of polymaths particularly working in the USA and France approaching hydrogeology from different core disciplines. The challenge for hydrogeology was sharpened during the first and second world wars, when water supplies were required for large armies, particularly mobile armies in North Africa and Europe in the second war. There was no formal training specifically in hydrogeology as a subject until after the Second World War.

The foundation of modern hydrogeology, as a specific taught discipline, started in the 1960’s with taught Masters programmes in, for example, the UK, Holland, Israel and North America. These Masters programmes were set up in response to changes in perspective, legislation and regulation regarding the assessment and management of water resources and an obvious and pressing need for the development of new water supplies as the post war population increased rapidly, and many former colonies tried to develop agriculture and improve living standards in rural areas towns and cities.

Our discipline may have been a part of human consciousness since the birth of mankind, but it only became fully recognised as a unique, stand-alone science in the second half of the last century.

3. THE START OF MODERN HYDROGEOLOGY IN IRELAND

Bob Aldwell will explain this in detail in his forthcoming article, and I don’t want to ‘steal his thunder’.

I didn’t realise it fully at the time but I was present at the beginning. I was the first graduate from an Irish University to obtain a taught Masters training in Hydrogeology. I did Natural Sciences in Trinity in 1971 and went straight on to London University to do the Masters course set up in 1965 by Glyn Jones at University College. I came back in the summer of 1972 to do my summer project on the King’s River catchment in Co. Kilkenny. Glyn Jones did not know of any hydrogeology institution or research work in Ireland. Therefore, he urged me to contact the Geological Survey before he allowed me to do my project in Ireland. His final words to me were that he hoped there was some data to process and analyse, and I should only spend 2-3 weeks collecting new data in the field.

My initial contact in the GSI was Bob Aldwell. He was most welcoming and excited that a student was returning to carry out the first hydrogeology project. Bob’s enthusiasm in part arose because he had recruited Eugene Daly about six months before, after Eugene had completed his Masters in Hydrology and Water Resources in North Carolina State University. I arrived in the GSI’s offices in Hume Street, and I was welcomed by Bob and then interviewed by the new expert Eugene. Eugene appointed me as his Temporary Field Assistant, and got me to sign the official secret’s act. A 24 year old employed a 23 year old as his assistant to work on a part of the Nore Basin. My fieldwork lasted for 12 weeks and not three.

Therefore for me, the beginning of ‘modern hydrogeology in Ireland starts with Bob Aldwell and Eugene Daly in the GSI. They are the fathers of our modern profession.

Bob joined the Survey in 1960 and soon found himself handling the well enquiries routinely received by the survey from farmers and householders across the country. There were grants for rural water supplies, and with the extension of rural electrification, power was available for borehole pumps. The survey was short staffed and this obligation on the survey to provide advice on where to site a borehole or well, was not relished by other more senior geologists. Bob had no formal training in hydrogeology, but he learned on the job with enthusiasm. Bob also was a member of the Irish National Committee for the UNESCO International Hydrological Decade started in 1964. This IHD committee contained two of the foremost international hydrologists of the era; Professors James Dooge and Eamon Nash. Through this committee Bob started to make international links that he developed further throughout his career for both the benefit of the GSI but very much for the benefit of the IAH.

The young but soon to be eminent karst hydrologist Paul Williams was a member of staff in Trinity. He preceded David Drew. Paul was enthusiastic about hydrogeology, but in 1971 he wrote a paper entitled

"The Management of Groundwater Resources in the Republic of Ireland.

In it he said that: -

"The general state of hydrology in Ireland has recently been reported on by the National Committee for the International Hydrological Decade.

They pointed out that there are many deficiencies in our knowledge of surface and ground water resources and that the important problem of water supply management has been entirely neglected.
No organization has any kind of general hydrological responsibility in Ireland.
With virtually no funds or statutory authority the enlightened IHD Committee appears condemned to frustration, being able to achieve little beyond recommendations.
Its present role is at best advisory, and there are doubts as to how seriously its suggestions are taken.
...No systematic observations have been made of ground water in Ireland and no one has been charged with the responsibility of collecting and processing data, despite the recommendations of the IHD Committee that a Ground Water Division should be established within the Geological Survey.
In fact, the Survey has for many years operated a valuable skeleton advisory service on ground water, receiving and distributing information on underground water supplies; but it has never been instructed to do so…."

This was one academic's view of the stark and bleak situation at the start of the modern era of hydrogeology in Ireland. Eugene Daly's arrival changed this. Eugene sought advice, and through Bob managed to get money for water level 'sounding lines' (electric dippers as some call them), down-the-hole borehole geophysical logging equipment, a Landrover station wagon, autographic chart recorders to measure water levels in boreholes and eventually a drilling rig.

There was no job opportunity in the survey after my MSc, and I joined Hunting Technical Services in the UK and went immediately to Mauritius then Madagascar, Greece and Abu Dhabi, but I kept in contact with Eugene and Bob.

In the summer of 1975, an unusual gathering took place on the quay in Spiddal to board an ancient landing craft to travel to Inishmaan in the Aran Islands. It did not seem unusual at the time. The group consisted of Eugene Daly and his wife, Bob Aldwell, my wife and two year old daughter, and I and two recent graduates Bruce Misstear and his future wife, and Donal Daly. Five hydrogeologists embarked to spend a week carrying out geophysical logging on unproductive boreholes on the island, and ultimately try to improve the yield by detonating explosives next to the shale "weyboards". We were all keen to learn together and from each other.

Hydrogeology developed quickly in the mid 1970's. Bob Aldwell met David Burdon for the first time and managed to arrange for David to provide three months consultancy to the new Groundwater Section of the Survey. Donal and Bruce did their Masters in Birmingham under John Lloyd, and Geoff Wright and David Ede joined the Section. Curiously, I had taken over the job in Abu Dhabi from Geoff Wright in 1974 and as he was leaving I mentioned to him that the long awaited new post in the GSI was about to be advertised. I said that, as I was about to be stuck finishing off his job in the Gulf, then why did he not think of applying when he got back to Europe.

David Ede left the survey within two years and Donal Daly was selected to fill the open position. Meanwhile Kevin Cullen who had been working in mineral exploration under David Burdon's influence went back to college did the Masters in Birmingham and shortly after set up K.T.Cullen and Co.

Bob, Eugene, Peter Bennett from Northern Ireland, Paddy Nicholson from Johnson Wellscreens European headquarters and manufacturing plant in Leixlip and others set up the Irish Group of the IAH in 1976. David Burdon was the first President.

The GSI and the IAH were the building blocks that made up the beginnings of modern hydrogeology in Ireland.

4. THE IAH IRISH GROUP

The ethos of the IAH Irish Group that we experience now in 2016 was set up in the early meetings in 1976. The realisation then, as now, is that hydrogeology is bigger than any of us. None of us know everything. All of us can learn from each other.

The small core group realised that to get stronger and survive, it was necessary to be open and not restrictive about membership. One of the reasons for us calling ourselves the "Irish Group", and eschewing the more formal North American term 'National Chapter', was to suggest openness, informality and non-exclusivity. The idea was to welcome anyone with an interest in groundwater, who was willing to contribute their knowledge and enthusiasm.

The first meeting of the Irish Group made a clear decision that the Irish Group would be an all-island association and involve the academics consultants and members of the British Geological Survey in Northern Ireland.

The IAH is a scientific association. It is not a professional body. Therefore, the Irish Group has welcomed members from engineering, planning inspectors, geographers, hydrologists, pump suppliers, water chemistry laboratories, equipment manufacturers, lawyers and drilling contractors. The latter are important members of the IAH, and for a while the Irish Drillers Association used to hold their AGM at the IAH Annual Seminar.

Our annual meeting used to be called a Seminar; again to make our meeting seem less pompous and formal. We changed the name to Annual Conference in 2005 when we realised that it had been going for 25 years and non-members were regularly referring to it as the IAH Annual Conference. We held the first Annual Seminar in Portlaoise in 1980. The early Seminars were true to the name, and involved field demonstrations as well as papers.

The IAH Committee up until the early 1990s consisted of a formal President, Secretary and Treasurer with a Seminar Secretary. Each January this four-person team held a meeting, principally to decide whether we could take the financial risk of running a Seminar again in the spring. The early seminars had an attendance of 15-30. Kevin Cullen sponsored a golf outing at the Heath Golf Club on the afternoon of the second day. We suspected that some regular attendees actually came for the golf and the prizes. We would do anything to interest, in particular, engineers from the engineering consultancies and the local authorities. The seminar would now be called an 'outreach event'. Every year without fail, this small band decided with trepidation to run the seminar. Then, we had to decide the theme, find speakers and get people to attend. I remember as Secretary in 1993, finding that only four people had signed up 10 days before the Seminar was due to begin. We had the hotel booked and international speakers flying in from the US and UK. We, the committee, decided to just phone everyone that we knew who might be interested. I think over 50 attended in the end.

The seminar has since gone from strength to strength. Though we have kept prices comparatively low, we have made a profit each year. This is because it has become more and more professional, but it is still run by volunteers. The strain felt by the conference secretary between January and April is difficult to imagine. Conference Secretaries from the private sector often found that their professional paid work took second place to the conference. The profits built up by the IAH have been at the expense of the institutions, companies or sole trader consultants who have put the conference together. The big changes took place when Donal Daly was the Seminar Secretary in the mid 1990s. Donal re-vamped and established high standards for the conferences and proceedings that we have enjoyed since. The load of Seminar/Conference Secretary was lightened slightly in 2003 when we decided to appoint a formal conference sub-committee.

A successful feature of the IAH Irish Group are the monthly Technical Discussion Meetings in the GSI. Donal Daly and the Groundwater Section and Kevin Cullen and latterly Taly Hunter-Williams and Gerry Baker kept these going with good and topical speakers month after month from the autumn to spring.

A third success has been the Groundwater Newsletter, again sustained by the voluntary efforts of principally Donal Daly aided by others. Many important long and short papers have been published in the Newsletter, and on Donal's initiative these are accessible on-line.

The IAH has organised excellent annual field trips throughout Ireland for over 30 years. They have been excellent events for learning from people working in different areas of the island and also exchanging ideas with other members of the Association in an informal setting.

The IAH Burdon Secretary (Morgan Burke) also organises an annual Burdon Lecture usually on a topic that relates to overseas hydrogeology and in memory of David Burdon's contribution to both Irish and World hydrogeology. Morgan also travelled to Nigeria to take part in a BGS training programme.

The IAH in Ireland is collaborative and supportive. Many overseas visitors, who see us in operation on field trips, technical discussion meetings and the annual conference, often comment that there seems to be little flag-waving, one-upmanship or point scoring between members or institutions. I think this is because we have fostered a sense that we belong to one community, and we all have had different experiences that are equally valid. Sharing rather than competing helps us all.

The IAH has been involved internationally largely through Bob Aldwell's overseas contacts developed during his time as a senior geologist in the GSI. Bob does not see a new language as a barrier, and was often co-opted onto international committees and commissions. This lead to many contacts, and visits from overseas hydrogeologists. It also lead to a link between the University of St Petersburg and Ireland. There followed a 10-day field trip of 15 hydrogeologists from Ireland to Russia in 1995 followed by a reciprocal field trip by Russian students and researchers. Bruce Misstear and I were invited to St Petersburg to give lectures to undergraduates and postgraduates for a week during winter.

David Drew has been an international commissioner and played a very significant role in Karst in the IAH. The Karst Commission has visited Ireland. Many others such as Morgan Burke, Bruce Misstear, Paul Johnston, Catherine Coxon, Donal Daly, Bob Kalin, Ray Flynn, and Kevin Cullen have also developed and used their contacts for the benefit of the IAH Irish Group.

A final positive contribution from the IAH was the work done by Eugene and the IAH committees since 1995 to foster, form and financially support the Institute of Geologists in Ireland.

The IAH Irish Group has been successful on many fronts but there have been problems and missed opportunities.

Ireland is known around the World for the important *Dublin Statement on Water and Sustainable Development,* also known as the **"Dublin Principles"**. There are four Dublin Principles. There was a meeting of experts on water related problems that took place in the Burlington Hotel in Dublin on the 31st of January 1992 during the International Conference on Water and the Environment (ICWE) organised by Ireland and the WMO, the Department of the Environment and An Foras Forbartha between the 26 and 31 January. Every country in the UN was asked to provide delegates, and a report that described and assessed their water resources and the health and vitality of water science and the water sector in their countries.

A glossy book entitled "Water in Ireland - A Review of Water Resources, Water Supplies and Sewerage Services" was produced for the host nation by Bill McCumiskey and the Environmental Research Unit in An Foras Forbartha in December 1991.

Neither the IAH Irish Group nor, more critically, the GSI Groundwater Section were informed in advance that the conference was taking place, or involved in the preparation of documents or organization of the conference. We heard about it from a visitor on the day before it started. We went to the Burlington, but as we were not on the list of 32 Irish delegates, we could not enter. In frustration we stole in via Anabel's, the nightclub, entrance round the side of the hotel and then through the kitchens.

The book contained only 12 lines of text on Groundwater in Ireland within its 59 A4 pages. Groundwater was not mentioned in the context of water quality or water services.

Many of the delegates were people that we knew and had worked alongside in their home countries, and several asked us, innocently, whether we would be chairing the influential sessions on groundwater development.

It was not to be.

A second opportunity was the organization of an International IAH Conference in Dublin in 2011. Another country dropped out in 2008 and Ireland was asked to take its place. The World and Ireland's financial system started to collapse two weeks later. A lot of thought and discussion took place within the committee. Eventually, the Irish Group decided not to try to host the conference. The process taught us a lot. We might be good at organizing our national conference using our volunteer efforts, but we would have to pay up front for professional conference organizers and a venue for a 600-800 delegate International Conference. It made us recognise that most members of the Irish Group are in the private sector in small firms or as sole consultants, and that few, relative to other countries, are in big state institutions or universities. We were not able to find institutional support that was able to underpin the organization of a large conference, particularly given the precarious outlook for the national economy at that time. The opportunity came at probably the worst possible moment, but the disappointment in the international community probably affected the reputation of the Irish Group.

5. HYDROGEOLOGY ISSUES

The primary efforts in the 1970s were to try to compile existing information and gather new information on groundwater resources and water supplies. This effort was not unique to Ireland. Many developed and developing countries had similar programmes. An issue that pervaded the early years was to try to establish the boundary between hydrology and hydrogeology. In the 1960's 1970s hydrologists held sway. I understand that there were over 80 staff in the hydrology and drainage section in the OPW and the ESB and there were strong hydrology departments in UCD, Galway and eventually Cork. Hydrologists carrying out catchment studies and calculating rainfall-runoff relationships and water balances frequently found that groundwater was a convenient unknown. In short if they could not account for a certain quantity of water they tended to put it in a sack called groundwater. Groundwater was 'the bit that they couldn't account for'. When we started to claim and demonstrate that we were competent to carry out our own water balance studies from a groundwater perspective, the hydrologists, from my experience, invented another sack for their errors or uncertainties called 'interflow'; something that in their mind didn't belong to groundwater or surface water, but was something that they could leave as an unknown in their calculations. It took about five years for hydrogeologists to reclaim all water below the land surface as groundwater, and remove the hybrid term 'interflow' from the discourse.

Modern hydrogeologists receive training from lectures and textbooks that explain the basics of groundwater flow, storage, recharge and contamination using a porous media conceptual model. The principles are straight forward, but for example the equations for the analysis of pumping test data under different conditions and borehole construction and aquifer penetration can seem daunting to absorb in an intense training. Many students have just managed to understand the basics on leaving a Masters programme. They often enter the work place expecting Nature to conform to the conditions and assumptions explained in their training.

Looking back on my first job, trying to develop new irrigation water supplies from basalt lavas in Mauritius, I realise now, with hindsight, that I was subconsciously trying to make them conform to a porous media conceptual model. Even though the evidence was staring me in the face during every borehole that I drilled and tested in mountainous volcanic lavas, I kept on using standard methods and techniques that were appropriate to 'homogeneous, isotropic aquifers of infinite extent'. Maybe, I was following a path of awareness called 'hydrogeology for slow learners', but I think it took me about three to five years to throw off my early indoctrination and have the confidence to recognise that most rock as rock is not an aquifer. There maybe a good flow of groundwater, but the water is not flowing through or stored in the actual fresh rock. Instead, it is flowing through the gaps in the rock or the zones of alteration. Eventually, real porous media became something rare to relish, and I got to a state where I would hang a flag belonging to the Madagascan Navy from a nearby tree, whenever I started to get pumping test data in the field that fitted with a type curve from a textbook. All bedrock within this jurisdiction on the island is over 300 million years old, with the exception of the Trias around Kingscourt. There is no primary porosity in these old rocks, and at a borehole or wellfield scale. They do not conform to either a porous media model or an equivalent porous media model.

Therefore, one of the issues faced by hydrogeology in Ireland, is providing space, time and opportunity for recent graduate hydrogeologists to put aside the straight jacket of a bedrock porous media and absorb the concept of a groundwater flow system in a subsurface with extreme heterogeneity. I can tell when a hydrogeologist is still hanging on to porous media when I see a water well drilling borehole design specification that requires a well screen and gravel pack in, for example, a limestone bedrock with a karst conduit groundwater system. Another sign of residual porous media thinking is a design specification that recommends a wide diameter borehole in order to obtain a high yield.

The desire for a porous media bedrock is particularly prevalent in hydrogeologists who believe that mathematical modelling is the ultimate aim of hydrogeology.

There are post Carboniferous rocks in the north that have the desired porosity and homogeneity.

Water diviners: The most predictable questions from a layperson when they meet a hydrogeologist for the first time is “Well, what do you think of water divining?” or “Do you believe in water divining?”. Sometimes, you can sense the agitation and anticipation as people try to steer the conversation around so that they can get the opportunity to slip in this ‘burning issue’ question.

Answering the question about water divining, perhaps two or three a day, during the course of a well inventory in the field, can become tedious. It is tempting to not engage with the question and provide a short flippant answer.

The issue for hydrogeologists in Ireland and also many other countries where the culture contains a strong religious element, is to recognise that most people want to believe in water divining. It is a part of the human condition to want to believe in magic.

It is important for hydrogeologists to recognise that water divining is a belief, just like a belief in Father Christmas or the ‘Tooth Fairy’ when we were young. The belief in water divining cannot be easily dispelled by logic and science because it is a deeply held belief with a long socio-cultural history with powerful associations for the holder. Many people were first told about water divining at an impressionable age by a grandparent. Therefore, trying to explain hydrogeology can be taken by some people to be an implied insinuation that their grandmother lied to them when they were five.

The issue is for us is to recognise that the belief is personal and genuine, and at the outset of a first meeting assume that it is probably held by everyone present. They may not recognise it, but don’t be surprised if it emerges.

We have had 4,000 years of Judaeo-Christian teaching that the ‘netherworld’ or the ‘underworld’ is a place to be feared and a mystery, and that mere mortals should not try to imagine or understand it.

I have found from my experience that County Managers, Ministers for the Environment or Natural Resources, An Bord Pleanala Inspectors, engineers in charge of water services, lawyers and judges in the High Court, medical doctors, poets, environment correspondents for newspapers and television, and even geologists believe overtly or covertly in water divining.

A deep-set belief cannot be dispelled. I worked for over 15 years with an area engineer in charge of water services, on numerous successful groundwater development projects for village water supplies. I found out that he regularly allowed a water diviner to check my recommended borehole sites the evening or the day after, and gave him a gratuity for his confirmation that I was right. It became a joke, but it kept on happening.

A current issue is an apparent trend to constrain the scope of a hydrogeologists work.

I visited Eugene Daly in hospital about 10 days before he died. We did not dwell on his condition, but he talked passionately about hydrogeology and the work of hydrogeologists in Ireland and Britain. The first issue that he raised was the way that the role of a modern hydrogeologist was being limited or circumscribed by outside and internal misconceptions. He used the awkward, and easily mis-heard or misinterpreted, term the ‘femalisation’ of hydrogeology. I was a bit taken aback when I first heard him say this, but my concerns disappeared as he explained further.

He and I think our profession is content that in Ireland there is a near gender balance amongst hydrogeologists. Gender is not an issue for us or amongst us. What Eugene was talking about is that employers appear to be taking on women hydrogeologists, and then presuming that they are best suited to an office-based role in GIS, analysis, compliance with regulation, application of protocols, mathematical modelling, writing hydrogeology EIS statements and writing proposals. These employers are not assuming that, as many women are showing in Ireland, that a woman hydrogeologist is equally good, if not better than her male peers, standing next to a big rig, directing drilling, on a cold afternoon in February. There have been several examples of drilling programmes where a woman hydrogeologist is nominally supervising borehole drilling or a site investigation, but in fact is held in the office, either by the contract or by expectations, or by other commitments, and instead, an un-trained junior civil engineer has been sent out, to keep an eye on the drillers, and provide a running commentary by mobile phone back to the office. The hydrogeologist is held back from learning first hand and the drillers do not get the support they need to cope with the conditions underground as they are encountering them.

Groundwater Masters training at the beginning of modern hydrogeology was lead by people like John Lloyd or Glyn Jones who had learned their ‘trade’ by experience in the field and reading. They stressed the importance of fieldwork and subsurface exploration. In more recent times there have been trainers or research supervisors who have developed their career mostly in academia, and have not spent ten or twenty years carrying out a wide variety of roles.

Both Eugene and I have noticed that some recent graduates have absorbed a perception from their training programme or their research that a hydrogeologist does not need to go out into the field to collect original data and use their knowledge to investigate and explore the many uncertainties and anomalies in existing data. Instead some seem to believe that existing data now on web sites and databases, or in models and GIS systems, is sufficient.

I wish to make it clear that we live on the water planet, and there is no limit to the scope of a hydrogeologist’s interest or work to do with water supplies or the environment on above or below the surface of our water planet. We must resist any pressure to constrain our breadth of interest and extension of our competency, or any trend to prescribe us as uni-dimensional token ‘specialists’. Like engineers we have many applied competencies based on our understanding of water above and below the surface. We can erect tap stands, use a stillson wrench, lay pipe-lines, erect an Oxfam water tank, and site and construct pit latrines in refugee camps, as well as support health education programmes.

6 FUTURE DEVELOPMENTS AND CHALLENGES

We used to think that the ‘Sky was the limit’ for boundaries of our science and profession, but this has changed. The discovery of clear evidence of subsurface water, whether liquid, bound into hygroscopic crystals or in the form of ice, on Mars means that hydrogeologists are becoming extra-terrestrial. The success and sustainability of the future colonies on Mars and perhaps other planets will depend on the rapid development of water supplies from below the Martian surface. There could be a future role in space exploration and settlement for hydrogeologists from Ireland with expertise in heterogeneous groundwater systems.

One of the advantages of experience is that I am beginning to realise how little I know. It is exciting to begin to realise how much is still to be discovered and understood. One of my frustrations is my inability, except in my mind's eye, to see how and where water moves underground. I am anticipating that soon there will be developments in genetics and microbiology and robotics that will have a big impact in understanding our groundwater systems. At the moment we have essentially dumb tracers. We can put them into the ground and we can try and find them in the ground, or where they re-emerge from the ground. I anticipate that soon we will have tracers that that can tell us where they have been, how fast they have travelled in different sections of their journey and how pressure, temperature and chemistry changed. Submersible robotic nano-particles are one possible development but they could be expensive to create in vast numbers. Another line of development may be to change the genetic code inside simple micro-organisms so that they acquire a 'GPS type' memory that can be downloaded at the end of their journey. It could be a lot cheaper to create millions of GPS bacteria, to 'seed' a recharge area, by biological reproduction, than it would be to build millions of nano-robots or nano-particles with memory. I foresee that developments such as these will mean that we can really begin to understand and predict and protect our groundwater flow systems.

Again in the field of micro-biology and biochemistry; we will probably carry out more research on the larger animals and fungi bacteria and viruses existing or living in the groundwater systems in Ireland. So far I feel that we have barely started to understand the eco-systems, biofilms, predators and grazers and the growth or digestion and dissolution of encrustation in the fractures, and conduits in the bedrock and the pores in the overburden.

We will be required for on-shore and offshore assessments of 'reservoirs' for storing heat and energy.

Education and training is big challenge for us, but I will leave this issue to Bruce Misstear.

A minor current challenge is to break away from the top down, plan view, GIS way of looking at our groundwater systems and instead look in vertical section or 3D section. The subsurface is not made up of sharp boundaries that extend vertically from the black boundary lines depicted on our geology and soils maps. The limestones in particular, laid down often synchronously in different depositional environments, exhibit subtle, changes in lithology and response to structural deformation and weathering. A vertical section or 3D view will greatly assist us in our understanding of, for example, groundwater supply source protection zones.

A future area of research will be to tie our shallow, mid depth and deep karst conduit systems particularly buried under the Midlands with the palaeo-geomorpholoy and drainage before the last ice ages, in particular in relation to base level or sea level changes.

Another area of investigation will be to understand the geochemistry of deep karst development without the input of carbonic acid in water with a meteoric origin. The role of acids generated by the biochemical decomposition of organic compounds or sulphides within shales may be an area of research for Ireland.

The final and immediate challenge is the strengthening and support necessary for a national water supply and sanitation utility in Ireland. At the time of writing this paper, it is called Irish Water, but whether it continues with this name, or in this form currently is politically uncertain. I, personally, hope it continues, but I am conscious that it does not yet contain a centre of applied scientific excellence regarding groundwater resources and sources. I see this as an essential foundation for the day-to-day management, operation, maintenance and protection of existing sources, and also to lead the development of capital and low operating cost high quality new sources.

Hydrogeology has become diverse over the last 40 years. There are many new sub-branches of our expertise. I think that an immediate issue or challenge is to find a way of explaining that all hydrogeologists are not the same. There is no hierarchy, but there are 'horses for courses'. Some of us are very experienced on modelling, contaminated land, planning, regulation, integrated catchment studies, water chemistry, karst hydrology, water resources and water supply sources. I think we have got to a stage of development where we can be confident to explain clearly to decision makers that need different types of hydrogeologists for different roles.

LOOKING TO THE FUTURE: OPPORTUNITIES AND CHALLENGES IN HYDROGEOLOGY EDUCATION AND TRAINING

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ABSTRACT

Whilst it is essential that hydrogeologists understand the fundamental principles of their science, they must also be aware of the interactions between hydrogeology and other disciplines. The author presents his views on the roles of universities and the International Association of Hydrogeologists (IAH) in hydrogeology education, training and mentoring, including some current and future challenges. The paper ends with a brief discussion of the dangers associated with following a "recipe book" approach to tackling hydrogeological problems – a problem that will increase if courses that currently provide students with a well-rounded hydrogeology education disappear in the future.

INTRODUCTION

As this is an opinion piece rather than a technical paper, I shall depart from convention and write in the first person. The importance of groundwater may be obvious to this audience in Tullamore, but unfortunately it is not obvious to many water resources policy makers across the world, nor to some of the funders of hydrogeology education in universities. Because groundwater is a 'hidden resource' it is often misunderstood or ignored by policy makers, and therefore one of the tasks of an organisation like IAH is to promote greater awareness of groundwater among policy makers and the public at large. It is especially important that we highlight the future challenges we face in managing this resource under pressures from climatic and land use changes and the water demands of an expanding global population.

Therefore, it should be clear that the need for well-educated hydrogeologists will continue into the future – and probably increase. As a profession, hydrogeology is less susceptible to the vagaries of market forces than e.g. the oil industry. Coontz (2008) notes that 'While geologists in the energy and mineral industries face roller-coaster hiring-and-firing cycles, those who study the movement and chemistry of water seeping through rocks and sediment find demand for their expertise almost as steady as the flow of groundwater itself'. Whilst hydrogeology was not fully "recession-proof" (a phrase quoted in Coontz) in Ireland during the economic downturn that followed the Celtic Tiger years, hydrogeology jobs were probably less impacted than jobs in many other branches of geology and engineering.

In this paper I will examine some of the core knowledge necessary for hydrogeology students and identify some of the challenges we face in balancing the need for instruction in the fundamentals of groundwater science versus the need for greater awareness of the linkages between hydrogeology and other disciplines. I will also talk about the taught masters programmes in UK that have been the traditional means by which Irish hydrogeologists have received their hydrogeology education. In a 2013 article in *Geoscientist* 2013 I wrote 'The loss of funded studentships for taught masters means that even the long-established and highly-regarded Birmingham course could be vulnerable in the future'. Sadly, this prediction almost came to pass with the threatened closure of the Birmingham course last year.

I shall also comment on the role of the IAH in education and training, including the mentoring of early career professionals by some of our more experienced members.

Finally, I shall revisit some comments I made in a 2003 presentation to this conference about the pitfalls of applying a recipe-book approach to solving hydrogeology problems.

CORE KNOWEDGE

A useful review of current practice in hydrogeology teaching is given by Gleeson *et al*. (2012). A survey of academic hydrogeologists identified around 15 topics that are considered essential by most hydrogeologists (Table 1). The focus here was on undergraduate education, but it is interesting that all of the top 15 topics relate to groundwater occurrence, aquifer properties and groundwater flow, and none covers e.g. groundwater quality. Gleeson *et al*. found that the topics highlighted in the survey were broadly consistent with the topics identified as being most important in literature on hydrogeology education.

Table 1 The top 15 most important hydrogeology topics for an undergraduate hydrogeology course, as identified in a survey of 68 academic hydrogeologists (from Gleeson *et al*., 2008)

Topic
Hydraulic conductivity/intrinsic permeability
Darcy's law and its applicability
Aquifers and confining units
Water table and mapping
Gradient and head
Water table
Hydraulic head
Specific yield and storativity
Wells and piezometers
Transmissivity
Specific discharge and average linear velocity
Primary and secondary porosity
Homogeneity and isotropy
Recharge and discharge areas
Steady flow in aquifers

One of the more entertaining - as well as instructive – articles cited in Gleeson *et al*. is by Siegel (2008), who identifies ten fundamental principles of what students (and practitioners) should know about hydrogeology:

1. Don't push the data farther than they can be pushed and be honest with respect to what can be done (referred to as the "Hydrogeologist's Credo")
2. Darcy's law needs to be understood at the 'gut' level
3. Potentiometric surfaces are different from the water table
4. Surface water is an 'outcrop' of the water table
5. Groundwater occurs in nested flow systems, separated by hydraulic boundaries
6. Groundwater chemistry is predictable from first principles
7. Chemical oxidation and reduction control many important groundwater and contaminant chemical compositions

8. As a working approximation, contaminant plumes should be considered narrow and no wider than a few times the width of the source at their heads
9. Contour using your head, and not your computer
10. Explore simple bivariate plots as an analysis tool.

These points are all elaborated upon by Siegel in his paper – and there is much wise advice to be had therein. Nevertheless, many of us have found over the years that not all hydrogeologists have a good grasp of the fundamentals. In a recent paper, Unterbruner *et al*. (2015) commented that 'international studies with students of different ages have shown that the basic hydrogeological concept of groundwater defined as water within porous and permeable rocks is not an established everyday notion'. They go on to describe an interactive multi-media approach that helps to convey a better appreciation of the basic concepts (they applied this approach to both school children and university undergraduates).

The review by Gleeson *et al*. (2012) also highlights the growing importance of field and laboratory instruction to reinforce classroom learning. Whilst university courses are mainly concerned with education, field and lab exercises can provide an element of training – albeit that hydrogeologists will receive their main training in the workplace.

Looking to the future: what knowledge and skills will be needed by the next generation of hydrogeologists? As well as the fundamentals of hydrogeological science, hydrogeologists will increasingly need education in topics that link hydrogeology with other disciplines that are key to sustainable water management e.g. climate change, integrated catchment management, and the sociological aspects of water development. Taking the last point as an example, the hydrogeologist who is working on rural water supply projects in sub-Saharan Africa must have a good understanding of social and gender issues surrounding the collection, distribution and governance of water. Otherwise, his/her efforts to install new well schemes are unlikely to be successful.

ROLE OF UNIVERSITIES

There is relatively little hydrogeology taught in geology, earth science or civil engineering undergraduate programmes in Ireland. The most that an undergraduate student may be exposed to is one or two introductory modules. If an Irish graduate wishes to pursue a career in hydrogeology, then the usual educational route has been to study a taught masters programme in hydrogeology at a British university (as there are no hydrogeology masters courses in Ireland – albeit some of the Irish environmental science and environmental engineering masters courses include significant elements of hydrogeology).

The taught hydrogeology masters programmes in UK have been in a state of flux in the last 25 years, with several courses starting up and closing during this period (Table 2). The first hydrogeology masters course in Britain was at UCL, but sadly this well-respected course closed in 2001. The longest standing MSc is the Birmingham course, but this was threatened with closure by the university last year. Although the course has had a reprieve, it is not clear (to this writer at least) whether the delivery of this course will continue in its present format.

Table 2 Taught hydrogeology masters courses in UK, 1965 to present

Date	*University*	*Title of Masters course*
1965 – 2001	University College London	Hydrogeology
1972 – present	Birmingham	Hydrogeology
1987 – 1999	Newcastle upon Tyne	Groundwater Engineering

? – present	Newcastle upon Tyne	Hydrogeology and Water Management[1]
1992 – c.2003	Reading	Hydrogeology and Groundwater Quality[2]
1992 – 1999	East Anglia	Hydrogeology
? – 2012	Leeds	Hydrogeology
? – 2012	Cardiff	Environmental Hydrogeology
? – present	Sheffield	Contaminant Hydrogeology
? – present	Strathclyde	Hydrogeology

[1]Formerly ‘Applied Hydrogeology’
[2]Formerly ‘Hydrogeology and Groundwater Chemistry’

In view of the strong demand for hydrogeologists amongst employers - plus the considerable contribution that hydrogeologists will make in meeting future challenges in water and environmental sustainability - it may seem strange that hydrogeology degree programmes have been closed down and that the future of other hydrogeology masters programmes such as that at Birmingham has been under threat. The main reasons for this situation are:

- the priority given by funding organisations like the Natural Environment Research Council (NERC) in UK to supporting doctoral researchers rather than taught masters students
- the introduction of masters-level (MSci or MEng) primary degree programmes in line with recommendations of the Bologna Declaration of European education ministers back in 1989.

In relation to the first point, a course like that at Birmingham (and previously those at UCL and Reading) formerly received a limited number of student support grants from NERC, but these have all ceased. The implications of the introduction of the MSci and MEng degrees for the specialist one-year masters courses is not fully clear, since many universities continue to offer a range of one-year masters programmes. In some of these, students select from a range of module options which are shared between different MSc courses; this “pick and mix” approach presumably makes the delivery of these programmes more cost-effective than an integrated specialised masters. In Ireland, the traditional civil engineering primary degree programmes at universities such as Trinity College Dublin, University College Dublin and NUI Galway have all moved recently to a 5-year masters-level programme, in line with the chartership requirements of Engineers Ireland. To date, the geology, earth and environmental science primary degrees have not followed suit.

There are, of course, options outside of UK or Ireland where aspiring hydrogeologists can pursue a taught masters programme in hydrogeology (or at least a closely related discipline). The late Eugene Daly was a pioneer in this respect, when he travelled to North Carolina in 1969 to do his masters there. The masters courses in USA and Canada are often 2-year programmes in hydrology, with substantial groundwater hydrology options. American masters courses include those at Arizona, California (Davis), Nevada, Ohio, Penn State, Stanford, Texas and Wisconsin, whilst Canadian courses include those offered by British Columbia, Toronto and Waterloo universities.

Nowadays, there are an increasing number of postgraduate hydrogeology courses in continental Europe which are taught through English, many of which are of 2-year duration. Examples include those at Tübingen in Germany (Applied Environmental Geoscience), Utrecht, Netherlands (Environmental Hydrogeology) and Stockholm University, Sweden (Hydrology, Hydrogeology and Water Resources).

Undertaking a taught masters programme has become increasingly expensive. In UK, there have been substantial fee rises in recent years. It is likely to also prove expensive for an Irish student who travels further afield for their masters, especially as many masters in USA and continental Europe are 2-year programmes.

Another option is to pursue hydrogeology education through a 3 or 4-year funded doctoral project. This may be attractive financially and a doctorate is obviously valuable for students wishing to pursue an academic career. However, doctoral research is inevitably very specialized and therefore may not provide the same all-round hydrogeological knowledge and skillset as a taught masters programme. (Although it should be acknowledged that PhD programmes in some countries do include substantial taught-course components).

ROLE OF IAH

Enhancing the role of IAH in education was identified as one of the priority actions during a strategic planning meeting held in Reading in 2010. This meeting led to the preparation of the so-called *Forward Look Action Plan* (IAH, 2011).

EDUCATION WORKING GROUP

A working group on education was established in 2013 in response to the Forward Look Action Plan. The remit of the WG was to identify options for short courses and for producing educational materials – see https://iah.org/knowledge/education-plans. A report of the Working Group on Education was prepared during 2014 and was approved by Council at its meeting in Marrakech in September 2014. The recommendations of the report included:

a) Developing a separate *Education and Training* banner on the IAH website home page;
b) Preparing a list of hydrogeology degree courses available internationally, with links to course information from the IAH Education web pages;
c) Listing short-courses, field courses and webinars organized by national chapters on the IAH Education webpages;
d) Developing an IAH YouTube channel. The channel could then show recordings of e.g. keynote talks from IAH congresses as well as, in time, dedicated educational lectures and films on groundwater topics;
e) Linking in with existing webinar providers to provide IAH-branded talks.
f) Compiling an international panel of experts who would potentially be willing to contribute to short courses organized and run by national chapters. The panel members' expertise and contact details would be made available on the IAH Education web page;
g) Preparing IAH-branded educational materials (lectures, illustrations, etc) and making these available for download from the website;
h) Developing short thematic papers on key strategic topics to help IAH increase the awareness of groundwater issues amongst policy makers and water managers, and the wider public.

Many of these recommendations centre around making improvements to our website, so this has been the focus of much of the effort since the production of that report. Training pages have now been added to the home page and, in future, these will be split into separate pages that distinguish between short courses/webinars and hydrogeology degree programmes. More substantial development of education webpages is underway. It is proposed to organise the information according to whether the web browser is a member of the public or a specialist hydrogeologist. So, for example, members of the public would follow links to: About groundwater; What hydrogeologists do; Information on groundwater for schools; Videos; whereas hydrogeologists would follow links to Learning resources (publications, strategic overview papers (see below); IAH's plans for enhancing education and academic development; Mentoring; and Commissions, Networks and Working Groups. Regarding an IAH YouTube channel (or equivalent using another platform such as Vimeo), work is underway reviewing the videos already out there, in order to avoid unnecessary duplication and identify where the gaps are that IAH may attempt to fill.

STRATEGIC OVERVIEW PAPERS

One of the WG report recommendations was to develop a series of thematic papers to inform professionals in other sectors about key interactions with groundwater resources and hydrogeological science. Five papers, referred to as Strategic Overviews, have now been completed:

- Food Security & Groundwater
- The Energy Sector & Groundwater
- Resilient Cities & Groundwater
- Ecosystem Conservation & Groundwater
- Human Health & Groundwater

These are being made available on the IAH website – currently at https://iah.org/news/iah-strategic-overview-series, but there will be links from the education webpages when these become live. A sixth paper, Global Change & Groundwater, is currently being written.

HYDROGEOLOGY JOURNAL

The main purpose of Hydrogeology Journal is to publish research articles. However, in 2013 the journal introduced a new type of review paper called Foundations. The aim here is to allow authors to review some of the basic principles of hydrogeological science in a depth that is beyond that possible in most textbooks (Post, 2013). These articles have a useful educational role. Excellent recent examples include the two papers on the hydraulics of water wells published by Houben in 2015.

MENTORING

Again in response to the *Forward Look Action Plan*, IAH has introduced a mentoring scheme: https://iah.org/knowledge/mentoring. This is something that some of our early career members were especially keen to see established.

To quote from the IAH website, the scheme can potentially help members in three areas:

- the scientific – providing advice and technical knowledge on various topics within the many strands of hydrogeological science;
- career options and pathways – providing guidance on job types and locations, CVs, interviews, networking, courses and training openings;
- practical experience – case studies, local hydrogeological knowledge of specific regions or aquifer types, volunteering to undertake short assignments.

A mentoring scheme does raise some complex issues regarding responsibilities and liabilities. Therefore, the Association sought the advice of a career development/mentoring expert during the planning stage. The scheme was initially trialled with a small number of volunteer mentors and mentees, and feedback from these has been taken account in the implementation of the full scheme. Since November 2015, the website has included a call for mentors and mentees.

THE DANGERS OF FOLOWING A RECIPE BOOK APPROACH

In my 2003 paper to this annual seminar, I cited a number of authors in the USA who were increasingly concerned about a recipe book approach being used to tackle hydrogeological problems. This trend had developed partly in response to the very large amount of work being carried out in connection with the investigation and remediation of contaminated sites, activities that are subject to a large degree of regulation and hence susceptible to a very prescriptive approach. Possin (2002) commented “I further fear that the too often mindless nature of their work has caused them to lose a significant portion of their own self-awareness of professionalism", whilst Nyer *et al*. (2002) suggested: "We have created a generation of hydrogeologists that have a very limited variety of experiences". These authors gave examples of the kind of problems that can result from a recipe book approach:

- Incorrect screen setting (in clay below aquifer)
- Pumping test interpretations to five significant figures
- Computer-generated groundwater level contours.

It is pertinent to compare the last bullet point with Siegel's fundamental principle number 9 (described earlier): 'Contour using your head, and not your computer'!

In an article in the *GSI Groundwater Newsletter* in 2012, I wrote 'I feel it [i.e. the "recipe book approach"] is still an issue, especially, perhaps, with the continued expansion of the role of groundwater modelling within hydrogeology, and professionals who regard themselves as modellers first and hydrogeologists second. Alas, many modelling studies are underpinned by a poor understanding - and hence poor conceptualisation - of the hydrogeology, and are overly-complex for the problem at hand'. By way of support, I would like to quote from an internationally-respected groundwater modeller, Cliff Voss (2011), who is also Executive Editor of *Hydrogeology Journal*: 'the best way to go forward with practical management [of water resources] is to rise above groundwater models as final products, and instead, empower hydrologists to provide advice by using groundwater models in simple ways, that are intended to elucidate understanding. Pursuit of complexity in groundwater models intended for practical management is a diversion from the real work at hand.'

CONCLUSIONS

In my view the main role of university hydrogeology courses is to provide the student with a good grasp of the fundamental principles of groundwater science. A secondary role is to cover subjects that cross the boundary between groundwater and other disciplines. Notwithstanding the key role of taught masters programmes in the education of British and Irish hydrogeologists over the last 40+ years, these programmes are under increasing pressure because of the priority many universities and funding agencies give to research. Whilst hydrogeology training occurs mainly in the workplace – especially in employments where there are opportunities for properly supervised fieldwork – organisations like IAH can play an important role in continuing professional development, through e.g. short courses, webinars and mentoring programmes.

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SESSION III

PROGRESS IN IMPLEMENTATION OF THE WATER FRAMEWORK DIRECTIVE IN IRELAND

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ABSTRACT

Successful implementation of the Water Framework Directive is vital to water resources management in Ireland. Based on lessons learned from the 1st cycle of implementation, more effective governance arrangements have been put in place, the EPA has been given additional responsibilities and community engagement has been given a high priority. Integrated catchment management (ICM) has become the accepted philosophy and approach. ICM requires catchments to be the appropriate organising landscape unit for water management, which is undertaken at five scales: site/field; water body (almost 5,000 groundwater, river, lake, transitional and coastal); subcatchment (583); catchment (46) and river basin (one national and two international). A comprehensive characterisation process is being undertaken which allocates all WBs into ***At Risk***, ***Not at Risk*** *and* ***Review*** *categories, whereby* ***At Risk*** *WBs require actions and resources to improve the situation. Geoscientific information and understanding are critical to the characterisation process. Initial subcatchment and catchment characterisation is due for completion in early 2017. Consideration of environmental objectives and mitigation measures has commenced, and will be finalised for the River Basin Management Plan due for publication in December 2017. A new tool, the WFD Application, has been developed to enable ready access to water quality data and the outcomes of the characterisation work. The Application is being made available through the development of a new 'water hub' website called catchments.ie.*

THE CRITICAL ROLE OF THE WFD IN WATER RESOURCES MANAGEMENT

The Water Framework Directive (WFD) (Directive 2000/60/EC, European Parliament and Council) is the main driver for effective water resources management in Ireland for the following reasons:

- It establishes a legal framework to protect, preserve and improve the aquatic environment whilst encouraging the sustainable use of water.
- It encourages integration of all water types – groundwater, rivers, lakes, transitional and coastal waters – and considers both water quantity and quality as the basis for water management, and requires river basins or catchments as the means of connecting all waters with human activities.
- It requires the preparation of river basin management plans by Member States across three river basin planning cycles *viz* 2009-2015, 2016-2021 and 2022-2027 during which management measures must be implemented so as to achieve good ecological status in all waters.
- It is linked to and links together a number of other EU directives (DECLG, 2015) – Groundwater, Nitrates, Habitats, Birds, Drinking Water, Bathing Waters, Urban Waste Water, Industrial Emissions, Environmental Impact Assessment, Floods, Marine Strategy Framework, Sustainable Use of Pesticides and the Sewage Sludge directives.
- It requires engagement with and participation of catchment communities.
- Sanctions via European Court Judgements act as incentive for improved environmental management.

RECENT DEVELOPMENTS

NEW GOVERNANCE ARRANGEMENTS

The OECD (2010) concluded that "*The institutional arrangements for river basin districts may not prove sufficiently robust*" and this conclusion was generally accepted. As a consequence, the European Union (Water Policy) Regulations 2014 (S.I. No. 350 of 2014) brought a new three tier governance arrangement:

1. **National Management & Oversight**: led by the Department of Environment, Community and Local Government and dealing with policy, regulation and resources.
2. **National Technical Implementation & Reporting**: led by EPA and responsible for water monitoring, assessment, characterisation, identification of measures and reporting to the Commission, as well as licensing of discharges and monitoring of enforcement tasks and environmental outcomes. Significant new responsibilities have been assigned to the EPA, together with additional resources, which led to the setting up of the Catchment Science & Management Unit. EPA now has a leadership role in technical implementation and reporting. The EPA is i) undertaking catchment characterisation, ii) reviewing the impact of human activities, iii) preparing template river basin management plan(s), iv) drafting environmental objectives and v) compiling common programmes of measures for further development and input by local authorities at Tier 3, and finalisation and approval by the Minister for Environment, Community and Local Government.
3. **Regional Implementation via Water Networks**: led by the Local Authority Water and Community Office (LAWCO) in co-operation with local authorities and responsible for local authority monitoring, licensing and enforcement actions, implementation of the programme of measures by relevant public bodies, and public awareness and engagement.

As part of the new arrangements, the existing seven River Basin Districts (RBDs) have been merged into one national RBD, together with two international cross-border RBDs.

CHANGES IN WATER QUALITY

There has been a gradual net improvement in water quality since WFD implementation commenced. For instance in the period 2010, there was an improvement of 4% in the length of unpolluted monitored river channel – from 69% to 73% (Bradley, et al., 2015). In 2009 the EPA reported that 116 of 757 groundwater bodies (GWBs) were at poor status, equating to about 14% of the land area. The majority of these poor status GWBs were a result of the estimated phosphate load from groundwater contributing to less than good status rivers. However there were also a small number of GWBs at poor status due to over abstraction, contamination from industrial, waste & historic mining activities and upward trends in nitrate concentrations at drinking water abstraction points. Significant knowledge shortcomings were also identified in relation to groundwater dependent terrestrial ecosystems (GWDTE) and the level of pollution from some industrial and waste facilities.

Further work by the EPA in the interim has included site specific data gathering in relation to GWDTE, an improved process for assessing pollution from industrial and waste facilities (in the context of WFD classification) and greater integration in relation to assessing the contribution from groundwater to surface water. Subsequently a new GWB layer, with 513 GWBs, has been developed[1]. In the 2010-12 Water Quality in Ireland Report the EPA reported that only 13 of the original 757 GWBs were at poor status; however a caveat was added that the status update did not include the updated assessment for GWDTE and industrial and waste facilities. In essence the "improvement" was attributed to a slight reduction in groundwater phosphate concentrations, and a related

[1] With contributions from the GSI, Donal Crean (at the time with OCM), CDM Smith, Geosyntec, RPS, Sarah Kimberley, Shane Regan, Owen Naughton, Melinda Lyons, Pól O'Seasnain, Regina Campbell, Matthew Craig, Anthony Mannix & the EPA Informatics team.

improvement in some of the receiving rivers. Initial characterisation of the 513 GWBs indicates that 61 GWBs (approximately 7% of the land area) are At Risk of failing WFD objectives (mainly due to contamination from industrial & waste facilities), with 280 GWBs still under review (mainly due to diffuse pressures and GWDTE) and the remainder characterised as being Not at Risk of failing WFD objectives. Many of the under review GWBs are a reflection that whilst there has been some improvement in recent years (e.g. slight reductions in groundwater phosphate concentrations), ultimately these GWBs remain close to the tipping point. However, along with the Not at Risk GWBs, it’s likely that the majority of the under Review GWBs will also be classified as being at good status in 2017; indeed a small number of the GWBs that are currently At Risk may also revert from poor to good status due to measures recently taken by licensees to satisfy requirements of the 2010 Groundwater Regulations.

INTEGRATED CATCHMENT MANAGEMENT

Although first proposed for use in Ireland only three years ago (Daly, 2013; Harris, 2013), ICM has become the accepted philosophy and approach for achieving successful management of water resources and implementation of the WFD (DECLG, 2015). This strategic new direction represents a shift away from traditional top-down and one size fits all approaches to a requirement to build partnerships; engage with and involve local communities; take a catchment-based approach; undertake catchment characterisation to a level that enables critical source areas to be delineated and pathways for water and pollutants to be understood; and select both country-wide and targeted measures to achieve objectives.

CATCHMENTS

A CATCHMENT-BASED APPROACH

The catchment (or river basin) is the appropriate organising unit for water resources as it is defined by natural hydrology and hydrogeology, ‘connects’ **all** relevant elements, including pressures, receptors (including all water types and ecosystems) and the people living there. While this has been accepted in principle for decades, the reality is that water management tends to be localised, dealing with specific issues, often discipline-bound and seldom connecting groundwater with surface water. Therefore, it is proposed here that there needs to be a development of the paradigm for water management that requires a clear mental image, converted to a working reality, of catchments as 3-D landscape-based units on which water management decisions should be based. This, to some degree at least, is a challenge to the more traditional discipline-based approaches, including those with an interest and expertise primarily in the underground component of the hydrological cycle. Perhaps now is the time to think a bit more of “looking up from the borehole” while still maintaining, developing and promoting hydrogeological expertise and input!

CATCHMENT SCALES

Catchments exist at multiple scales. In principle, the activities needed to achieve the various water/catchment objectives must be at a scale that is appropriate to achieving these objectives, and, in particular, to enable the problems, solutions and consultations to be targeted effectively. Depending on the scale, different parties may take different roles. For example, for a River Basin District, national state agencies will lead catchment management efforts, while at the local, detailed scale, local authorities and local community groups/stakeholders, will take the lead in developing and implementing solutions. In following the principle outlined above, five scales are used. While these are defined here, linkages across the scales are essential to successful water/catchment management. It is not possible to manage and understand our water resources by focusing on one scale. We cannot “fix” at the national and RBD scale without paying attention to necessary issues and changes at the scales below, and we cannot ensure the future well-being of the water resources we all care about without paying attention to changes and developments at the national scale. Therefore, we need to think ‘multiple scales’ (Daly, et al., 2014).

The scales being used in WFD implementation are outlined in Figure 1 and are as follows:

- **Site/Field scale:** Many water supplies and potential point pollution sources are investigated and dealt with at this detailed scale (e.g., septic tank systems, farmyards, landfills, wells, nutrient and sediment runoff from fields.)
- **Water body (WB) scale:** WBs are the 'units' for monitoring and reporting status and risk characterisation results. Although the WFD probably intends that the WBs are the WFD water management units, in practice they will not fulfil this function as they are bodies of separate water types that are not linked (e.g., groundwater with surface water) or are poorly linked (e.g., rivers with estuaries, coastal waters and lakes). In addition, the sizes vary enormously (e.g., rivers a few kilometres long with small (<10 km^2) catchment areas and groundwater bodies several hundred km^2 in size). Integration of WBs, or their water management issues, is not readily feasible at this scale.
- **Sub-catchment scale**: Waterbodies have been aggregated into subcatchments, varying in area from approximately 70-200 km^2. This is the scale at which the science of characterisation is undertaken. Compliance checking and community engagement are also carried out primarily at this scale.
- **Catchment Scale:** These are the catchments as defined, with some additions in the Shannon catchments, by the nationally-defined hydrometric units, giving 46 catchments in the Republic of Ireland. They are coherent landscape units encompassing and connecting i) water flowing from upland areas to the coast or, in the case of the Shannon catchment, the Shannon itself and ii) all pressures with the potential to impact on all the water types in the catchment. They are at a practical scale for deciding on, planning and coordinating activities; in effect, this is a practical management and 'governance' scale for water.
- **River Basin District (RBD) scale:** The seven RBDs used for the 1st cycle of the WFD have been merged to form one national RBD and two cross-border RBDs. The outputs at this scale are the River Basin Management Plans.

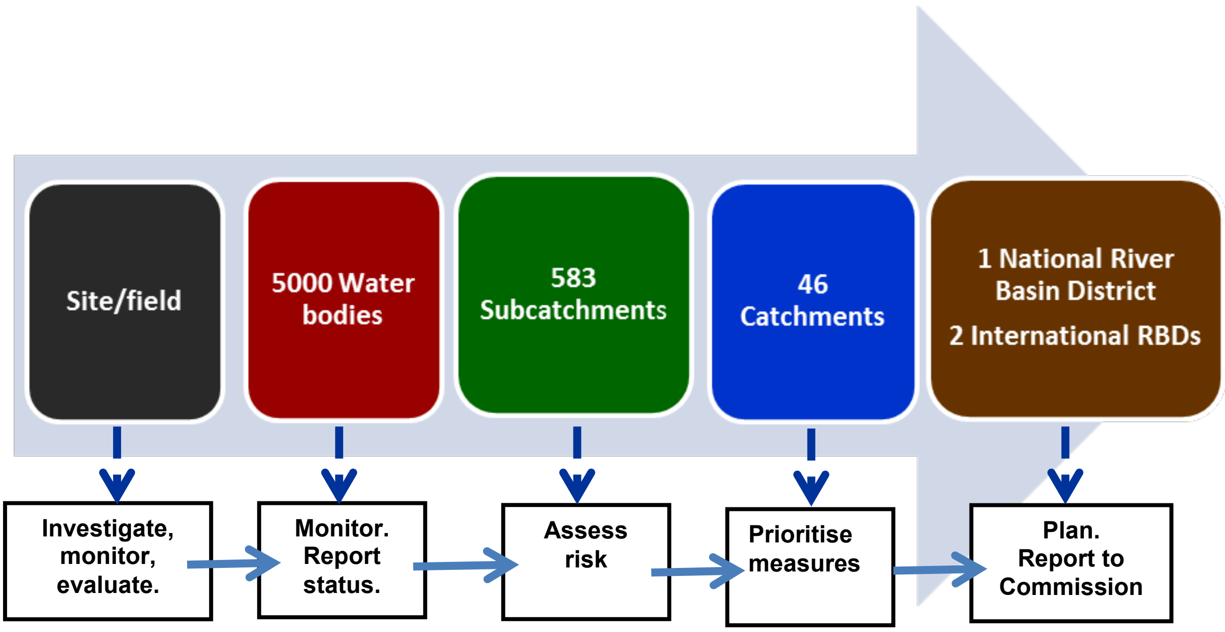

Figure 1: Scales used in catchment management and WFD implementation

CATCHMENT CHARACTERISATION

CHARACTERISATION, ENVIRONMENTAL OBJECTIVES AND RISK

Catchment characterisation is the foundation of integrated catchment management as it provides an understanding of how catchments work. This includes the physical, hydrochemical, and ecological characteristics, impacts, pressures and quantification of pollutant loads and abstraction pressures in the catchment. The aim is to use characterisation to identify the significant pressures so that strategies, measures and resources can be prioritised and targeted to enable effective protection or restoration, as required, of our water resources.

A key component of characterisation is the determination of the 'risk' of not meeting WFD objectives. The environmental objectives are set out in Article 4 of the WFD and are summarised as follows:

- Prevent deterioration in status of all bodies.
- Aim to restore to good status by 2015.
- Aim to reduce pollution to surface water bodies from priority substances and cease or phase out emissions, discharges and losses of priority hazardous substances.
- For groundwater bodies, reverse any significant and sustained upward trends and prevent or limit the input of pollutants.
- For protected areas, such as drinking water protected areas and Natura 2000 sites, achieve compliance with the required standards and objectives.

Alternative objectives may be set, such as:

- *Achieving Good status by 2021.*
- *Achieving High status by 2021 for surface water bodies whose status declined from High to Good.*
- *Achieving Good status by 2027.*
- *Recovering to Good after 2027 (lower stringent objective).*
- *Will not achieve Good, but with no further deterioration happening.*
- *Improving trends in the elements influencing status. (This is not a stated requirement of the WFD.)*

Risk characterisation looks forward towards the targeted environmental objectives for water bodies, and it highlights the areas where monitoring and measures need to be implemented and/or adjusted so that the objectives can be met on time. Three risk categories are used: **Not At Risk**, **At Risk** and **Review**; where Not At Risk water bodies require maintenance of existing measures; At Risk water bodies require new, often more targeted, mitigation measures requiring resources in terms of both finances and staff; and Review water bodies requiring, perhaps, additional monitoring and assessment. The Risk designation is based on: i) consideration of the status of the water bodies (good and poor for groundwater bodies, and high, good, moderate, poor and bad for surface water bodies); ii) the trends in hydrochemistry, particularly of phosphate, nitrate and ammonium; and iii) the distance to thresholds, such as environmental quality standards, as a means of determining whether there is a likelihood of deterioration to a lower water quality status or that a small improvement might ensure a return to a better status.

Three tiers of characterisation are being undertaken so that the level of assessment is commensurate with the level of risk posed:

1. **Preliminary Waterbody Risk Screening (Tier 1)**: An automated screening process to identify waterbodies 'At Risk' based on the national water quality monitoring dataset.
2. **Initial characterisation of subcatchments and catchments (Tier 2)**: Waterbodies are grouped into catchments and subcatchments and prioritised so that integrated catchment science

assessments can be carried out where necessary. Where waterbodies are 'At Risk', potential significant pressures causing the impacts are identified. This is a desk-based stage.

3. **Further characterisation (Tier 3)**: Potential significant pressures will need to be further investigated in many circumstances, such as in rural areas where there are diverse concerns, to confirm that they are significant pressures, i.e. those actually causing the issues. This tier will frequently require fieldwork/investigative assessments and will be undertaken primarily by local authority staff, but in some circumstances will be assisted by specialists such as hydrogeologists and biologists.

THE CRITICAL ROLE OF GEOSCIENTIFIC INFORMATION AND UNDERSTANDING

For significant pressures that are either diffuse (pasture and arable crops, forestry or urban areas) or small point sources (septic tanks systems or farmyards), geoscientific information provided by the Geological Survey of Ireland (bedrock, aquifer, vulnerability, subsoil permeability, karst features) and Teagasc (soils, subsoils) are essential in providing a basis for understanding and modelling the movement of water and pollutants through the landscape, thereby enabling prediction of pollutant attenuation and pollutant loading to water. The EPA-funded Pathways Research Project (Archbold, *et al*., 2015) and subsequent EPA *CatchmentsTools* Project has used the pathway susceptibility concept (Daly, 2004) and produced national (1:25,000 scale) pathway susceptibility maps for both nitrate and phosphate as a means of evaluating the likelihood of these pollutants reaching water. For instance, Archbold, *et al*., (2015) concluded "*Therefore, for mitigation measures and management strategies to be successful, it is essential that these transport pathways are identified and understood at subcatchment scale and that mitigation measures and management strategies are pathway specific*". In addition, by overlaying the loading of phosphate and nitrate from agriculture and forestry on the susceptibility maps, three national pollution impact potential maps for phosphate to surface water, nitrate to groundwater and nitrate to surface water have been created, thereby enabling critical source areas to be determined, and investigative assessments and measures to be targeted to areas where the greatest environmental benefits can be derived.

SOURCE LOAD APPORTIONMENT

A data-driven Source Loading Apportionment Model has been developed by the EPA *CatchmentTools* Project for Irish conditions as a means of predicting the sources of nutrient loads (phosphorus and nitrogen) to surface water from urban wastewater treatment plants, industrial discharges, agriculture, septic tank systems, forestry and urban areas. This enables the identification of the main sources and therefore facilitates the evaluation of the required load reduction and the targeting of mitigation measures.

CHARACTERISATION RESULTS

To-date, the preliminary risk screening is completed. Initial characterisation is being undertaken by the EPA, with the assistance of RPS consultants, and will be completed by December 2016. The approach is being piloted in the Suir catchment and some of the initial results are illustrated by means of the following maps in Figures 2 - 8: water body risk (of not meeting WFD objectives); pathway susceptibility based on geological/hydrogeological information and understanding water and pollutant movement in the landscape (a map indicating the susceptibility of groundwater to impact by nitrate is also available); pollution impact potential, based on overlaying estimated diffuse nutrient loads on the susceptibility maps and modelling impacts on water; significant pressures on surface waters; and estimated load reductions required to reduce nutrient concentrations.

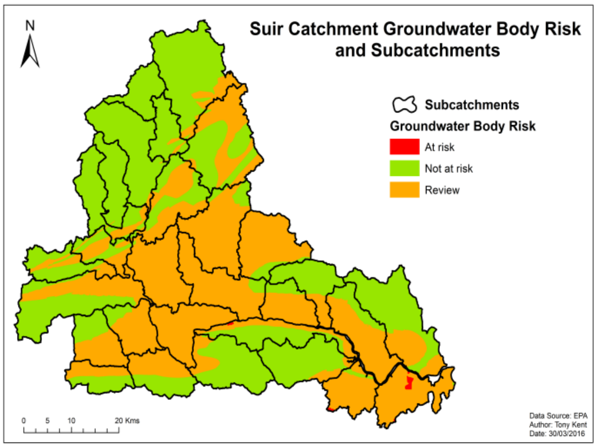

Fig.2: Risk categories for groundwater bodies

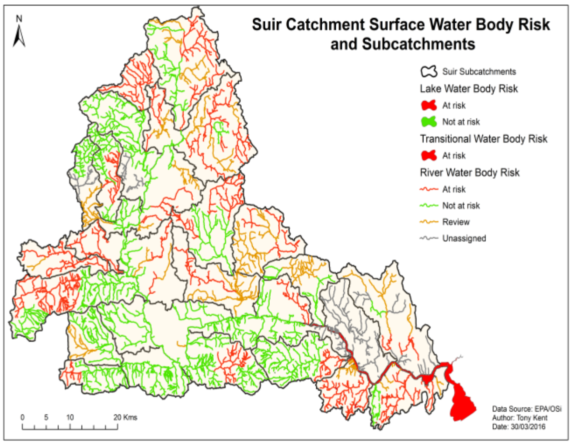

Fig. 3: Risk categories for surface water bodies

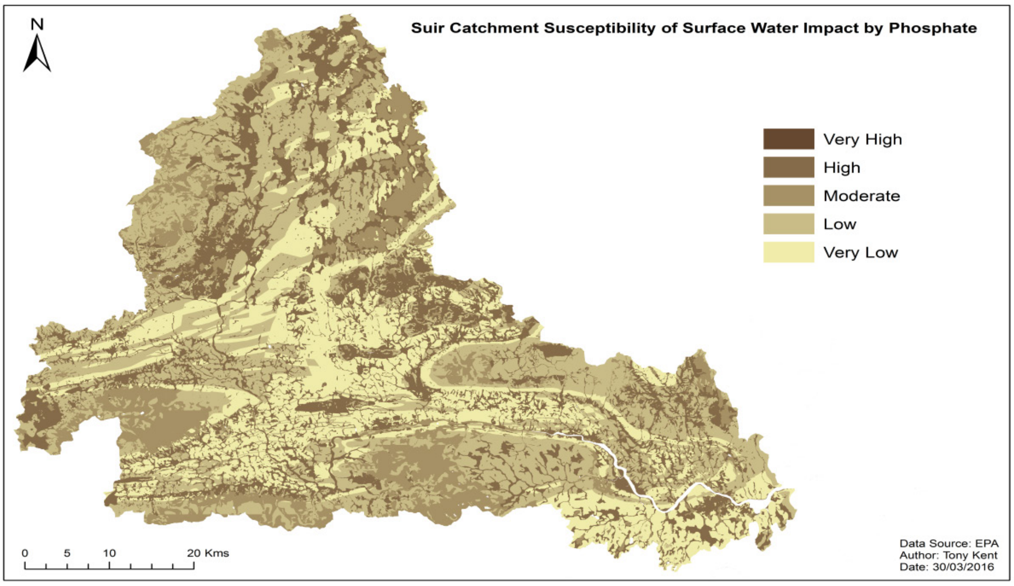

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Figure 4: Map indicating the susceptibility of surface water to impact by phosphate

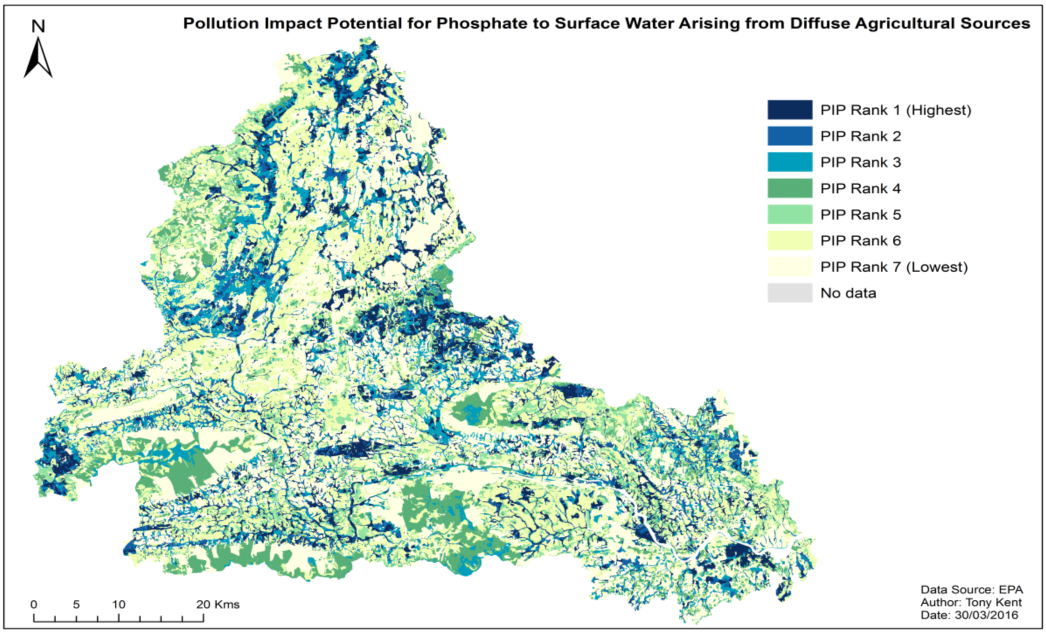

Figure 5: Pollution impact potential (PIP) map for phosphate to surface water arising from diffuse agricultural sources

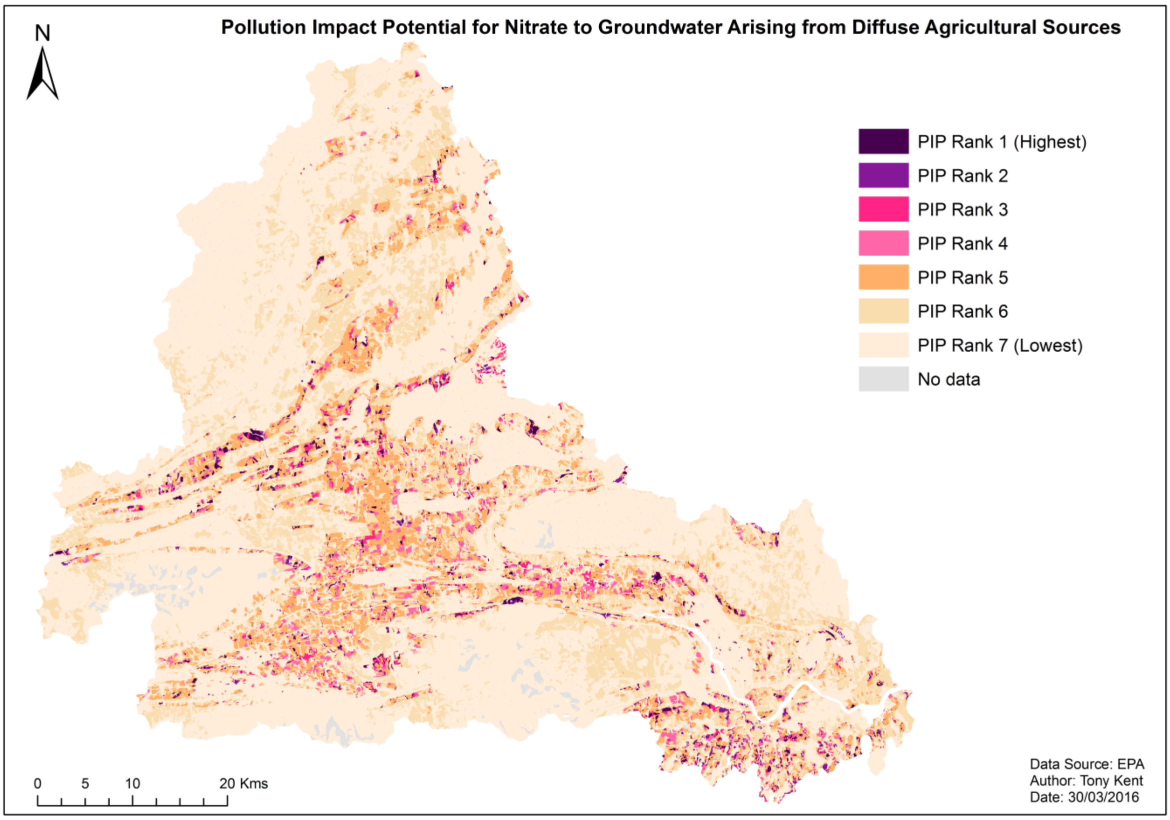

Figure 6: Pollution impact potential (PIP) map for nitrate to groundwater arising from diffuse agricultural sources

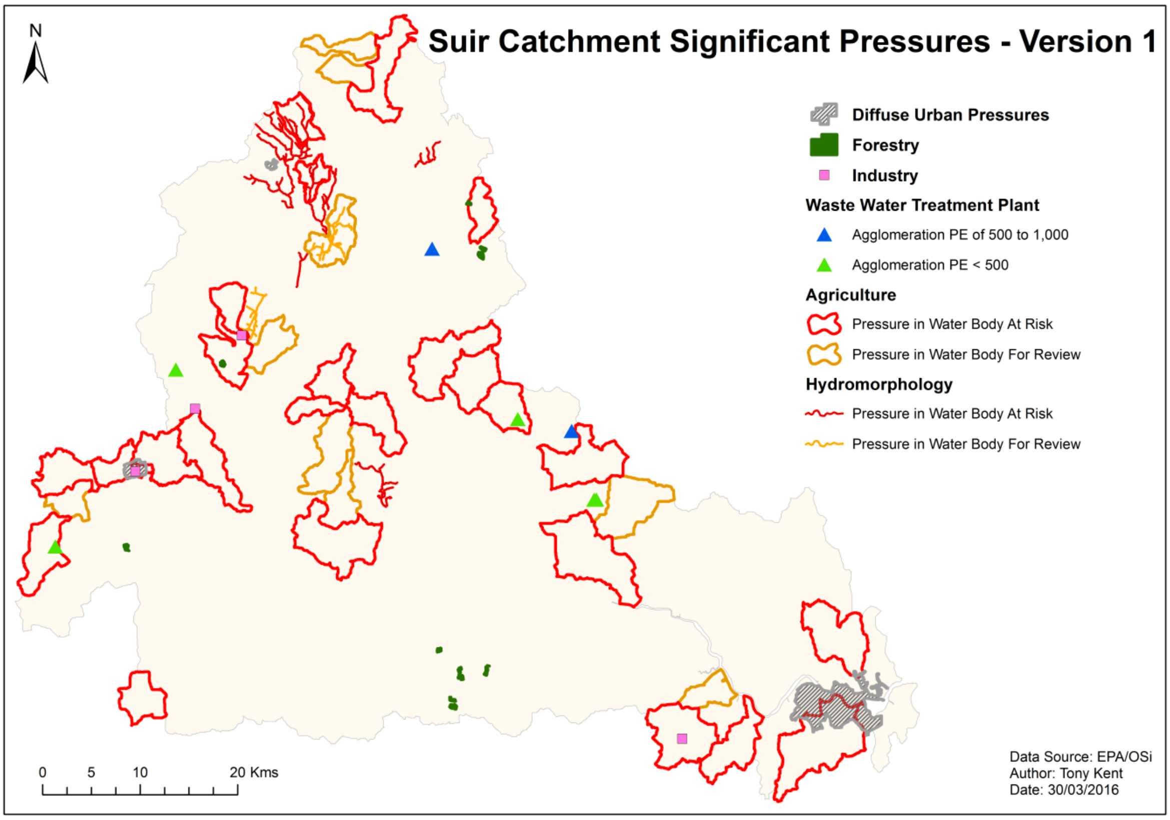

Figure 7: Map of significant pressures

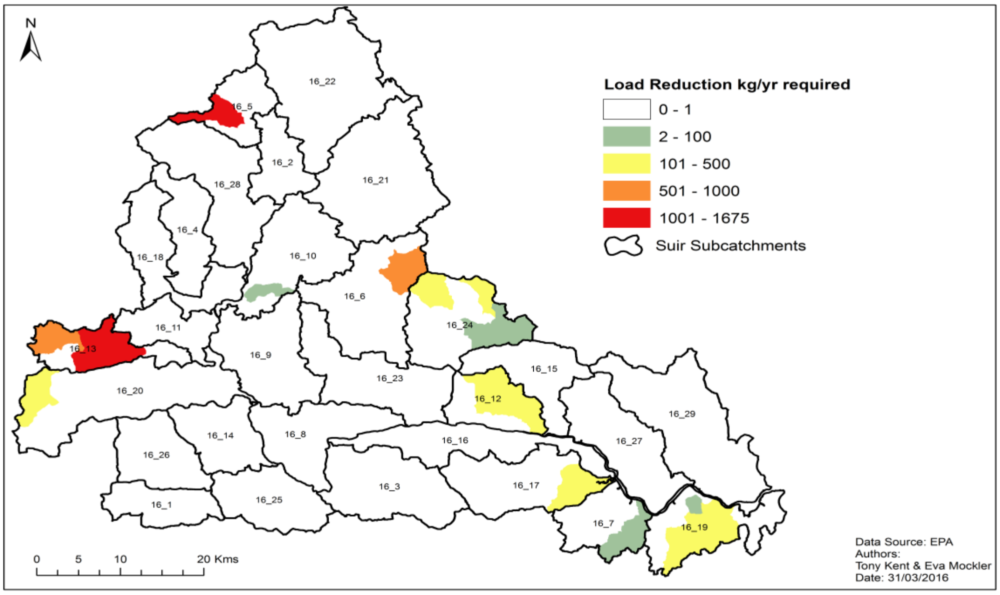

Figure 8: Estimated load reductions in river water bodies required to achieve a phosphate concentration of 0.035 mg/l

PRIORITISING ENVIRONMENTAL OBJECTIVES

As resources are inevitably limited, knowledge of the causes of impact are not always clear-cut and environmental responses are variable even when measures are undertaken. It is necessary to prioritise the objectives for the 2nd cycle River Basin Management Plan and in the process the resulting mitigation measures. As a means of illustrating the process, some of the priorities are given below:

1st Priority: i) protect high status water bodies; ii) prevent deterioration of existing **At Risk** high and good status water bodies (WBs); iii) complete all Investigative Assessments.

2nd Priority: i) "easy wins" – moderate status WBs close to good status boundary, giving consideration to those with an already improving trend; ii) piloting work to improve the situation in a selection (perhaps 10% of the 583 subcatchments) of the **At Risk** WBs with interdisciplinary and multi-organisational involvement; iii) a research and investigation programme to define the environmental supporting conditions for Natura 2000 sites where they don't currently exist; iv) developing a farm advisory service to aid communication of environmental issues with farmers and achieve behavioural change.

3rd Priority: i) improving trends in phosphate concentrations; ii) **i**mproving trends in nitrate concentrations in catchments/subcatchments with **At Risk** TraC WBs and **At Risk** groundwater bodies; iii) maintaining existing **Not at Risk** WBs.

4th Priority: i) achieving good status everywhere; ii) improving trends in nitrate concentrations everywhere.

CATCHMENT MANAGEMENT STRATEGIES

Following the analysis of catchment conditions, quantification of pollutant loads and abstraction pressures, determination of the loading targets or abstraction reductions needed to meet the catchments objectives, identification and evaluation of potential management measures and practices can be undertaken. There is a wide variety of possible management strategies. As a means of adopting a structured approach to their evaluation, they are subdivided into the following categories:

1. Local (site/field-scale) mitigation measures.
    - e.g., buffer zones, increasing the use of clover in grass swards.
2. Engagement & Partnership.
    - e.g., farm advisors, Rivers Trusts.
3. Incentives.
    - e.g., GLAS, funding for Rivers Trusts.

4. Innovation & new technology.
    - e.g., precision farming.
5. Integration of WFD objectives into the planning process.
6. Licensing of discharges to water.
7. Compliance checking & enforcement.

Evaluation of these strategies has commenced; for instance evaluation of local measures will include consideration of costs, effectiveness, potential for benefits for biodiversity, flood mitigation and reduction on greenhouse gas emissions and acceptability.

ENGAGEMENT AND COMMUNICATIONS

The characterisation approach, together with selection and successful implementation of measures and management strategies will involve integration of datasets and knowledge at a national scale. With this in mind, a Catchment Management Network has been established to provide a platform for the EPA, government departments and agencies, local authorities, other public bodies and environmental non-government organisations to work together to avoid duplication of effort while working towards RBMP delivery and achieving integrated catchment management. The Network will also provide a mechanism for knowledge exchange and initiating public participation as community involvement will be essential. Above all, it will enable catchment managers to come together to exchange ideas and assist one another in delivering the 2nd cycle RBMP and taking Ireland further along the path towards achieving integrated catchment management. In addition, the newly initiated Catchments Newsletter (www.catchments.ie) is providing an informal means of facilitating communication and networking on catchment issues.

MAKING THE INFORMATION AVAILABLE

Characterisation is a multi-disciplinary task requiring a variety of datasets, many of which are not currently captured or accessible in a centralised system. The EPA have used IT automation systems to develop a WFD Application that provides a single point of access to catchment data, which will be useful for many catchment science and management purposes, not just those that are specific to the WFD. The Application is accessible currently through EDEN (https://wfd.edenireland.ie/) and is available to EPA staff as well as staff in other public agencies. The information will be made more widely available later in 2016 through a new public website which is in development and will be called www.catchments.ie.

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WATER FRAMEWORK AND GROUNDWATER DIRECTIVE IMPLEMENTATION: A UK PERSPECTIVE

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ABSTRACT

Fifteen years after the Water Framework Directive (WFD) was introduced, followed by the Groundwater Directive (GWD), the UK's second river basin management plans have been published. These set out the objectives for groundwater over the next 6 years, but has anything been achieved so far, and how has the WFD made a difference to management and protection of groundwater in the UK? To get to this stage much work has been done to interpret and understand the requirements of the directives, translate this understanding in to UK guidance (jointly with Ireland through the UK Technical Advisory Group Groundwater Task Team), successfully influence the development of EU guidance, and implement it 'on the ground' to meet the required deadlines. The latter achieved through the dedication of hydrogeologists in the environment agencies.

A difficulty for the UK has been that responsibility rests with the devolved governments. Although each had groundwater protection policies/regulatory tools, none had suitably defined groundwater bodies or adequate monitoring and data and assessment frameworks to meet WFD requirements. Despite this progress has been made. However, this has not been seen in the condition (status) of groundwater. Whilst there has been improvement in some places, there has been a decrease in groundwater bodies at good status. Challenges remain with some proving controversial, such as compliance with the 'prevent' requirements of the GWD. Another is development of an evidence base to justify alternative/less stringent objectives, and a third is how the WFD should apply to new developments such as shale gas.

SEVESO III AND ASSESSING RISK TO THE WATER ENVIRONMENT

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ABSTRACT

Seveso III requires greater emphasis on the protection of the environment from major accident events. This paper presents a best practice approach to assessing the risk to the water environment as part of a Seveso Major Accident Hazard assessment.

AWN Consulting formed part of a consortium in the delivery of a Capacity Building Contract to the Turkish Environment Ministry (2013-2015). The Tüpraş Oil Refinery, located in Kirikkale, Turkey was used as a pilot study for implementing a Seveso assessment and the aspects of the completed Safety Report which relate to environmental risk are presented as a case study in this paper.

INTRODUCTION

The Seveso III Directive came into force in Member States in June 2015. The Directive places a greater emphasis on the protection of the environment from the risks associated with major accidents. The Directive was revised during the period 2008-2012 to take account of a number of major accident events which had occurred, one of which was the Buncefield Fire and Explosion at a bulk oil facility in Hertfordshire.

On 11 December 2005, vapour from a major leak of petrol ignited causing an explosion measuring 2.4 on the Richter Scale and leading to a major fire and explosion involving the release of thousands of tonnes of hydrocarbons. The explosion was the largest peace time explosion in Britain and was audible in France. Contamination of groundwater as a result of the Buncefield explosion and fire was found to extend 2km north, east and south-east of the site and the Three Valleys Water Company Bow Bridge borehole was closed as a precaution, according to the investigation final report. The incident was Britain's most costly industrial disaster.

In order to illustrate the requirement for hydrogeologists to be part of the specialist team undertaking Seveso assessment, a case study completed in Turkey by AWN and partners is outlined.

BACKGROUND AND SITE LOCATION

During a two-year period from 2013 to 2015, AWN Consulting formed part of a consortium (including Turkish (Ekodenge) and Italian (D'Appolonia) partners in the delivery of a Capacity Building Contract to the Turkish Environment Ministry. The project was designed to support the transposition of the Seveso II Directive into Turkish legislation. The Tüpraş oil refinery, located in Kirikkale was used as a pilot study for implementing a Seveso study including the presentation of a Safety Report for the site. Site risk assessments and modelling (including hydrogeological) were undertaken as well as consideration of land use planning, safety management systems and emergency plans. In addition, on-site training for both Ministry and refinery staff was provided. For detailed information see the EuropeAid Turkey website: (http://www.europeaidturkey.risk-technologies.com)

The Tüpraş oil refinery is located approximately 80Km SE of the city of Ankara, approximately 15Km south of Kirikkale and c.500m to the west of the Kizilirmak River which is the main river in the area (see Figure 1). The approximate area of the site is 8,137,025m^2. The oil refinery at Kirikkale was established in 1986 and has the capacity to process five million tonnes of crude oil per annum. The Kirikkale refinery receives crude oil from the BOTAS Ceyhan terminal approximately 400km south of Kirikkale at the Eastern Mediterranean, via the Ceyhan –Kirikkale supply pipeline.

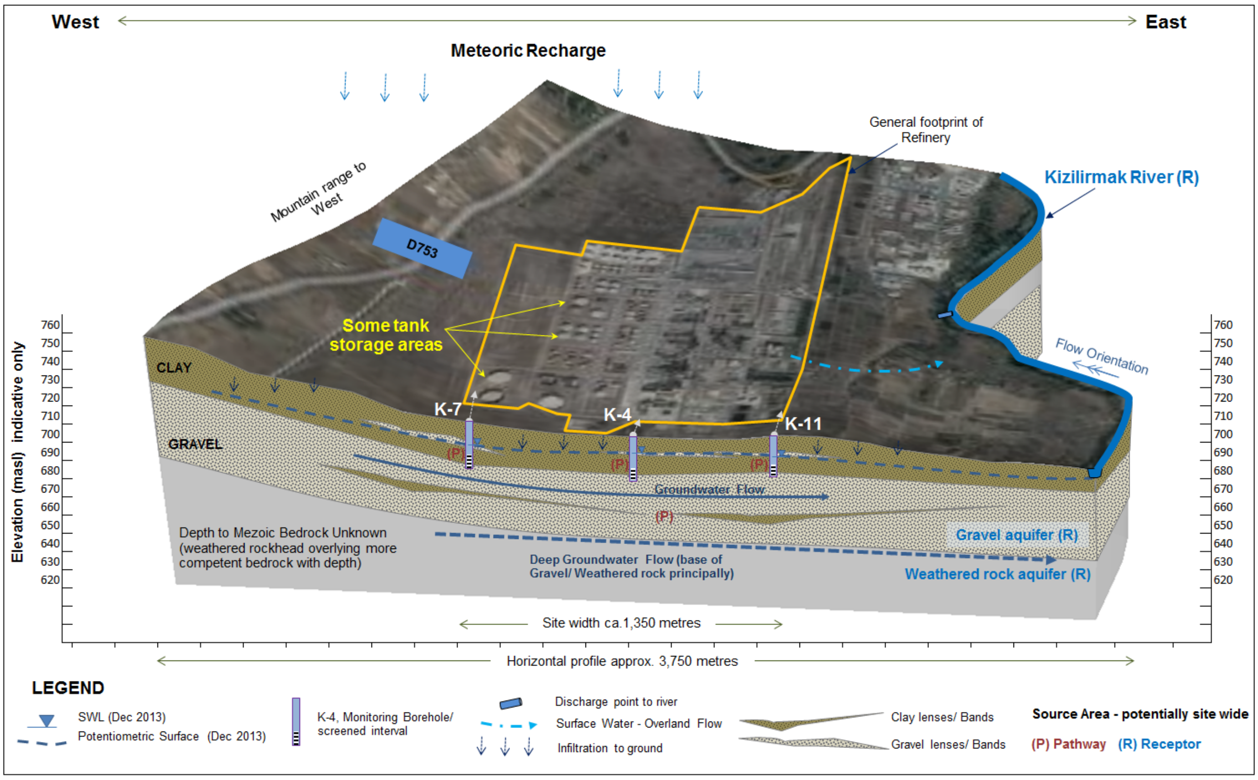


Figure 1 Site Setting & Conceptual Site Model

CONCEPTUAL SITE MODEL APPROACH

Following standard groundwater risk asessment approaches, a conceptual site model (CSM) was developed for the site, and included identification of any pollutant linkages between potentially hazardous sources and receptors (see Figure 1). The hazard assessment, receptor identification and summary of pathways are summarised below.

IDENTIFICATION & QUANTIFICATION OF DANGEROUS SUBSTANCES POTENTIALLY PRESENT AT THE ESTABLISHMENT

The scope of the Seveso Safety Report was confined to three tanks at the tank farm within the Tüpraş Oil Refinery. These tanks are as follows:

- Floating roof crude oil bulk storage tank (ref: T4103),
- Fixed roof diesel bulk storage tank (ref: T4311) and
- Spherical pressurised LPG bulk storage tank (ref: T4803).

Table 1 below presents a summary of the hazards identified in terms of tonnage present, known risk to the environment and human health. The determination of an Upper Tier or Lower Tier Seveso site is dependent on the quantity of dangerous substances stored on-site. The Safety Report includes a comprehensive assessment of risks to people, both on and off-site, as well as environmental risks. However, the human risk aspects are not included in this paper.

Substance/ Classification		Total (tonnes)	Lower Tier Threshold (tonnes)	Upper Tier Threshold (tonnes)	Fraction of Lower Tier Threshold	Fraction of Upper Tier Threshold
Named Substances						
Liquefied Petroleum Gas (LPG)	F+; R12	1395	50	200	27.9	7
Petroleum products (Diesel)	Xn; R20, Xi; R38, Carc. Cat. 3; R40, N; R51/53	20127	2500	25000	8	0.8
Petroleum products (Crude oil)	Carc. Cat. 2; R45, N; R51/53	115,230	2500	25000	46	4.6

Table 1 Summary of Quantities and Categories of Dangerous Substances with Factorisation

Evaluation of the hazards present for Seveso assessment requires an understanding of the storage, operating and foreseeable accident conditions. These are summarised in Table 2 below and it can be seen that a release of diesel to the environment is the highest risk to the soil and water environment. Figure 2 below presents the location of Crude, Diesel and LPG tanks at the refinery.

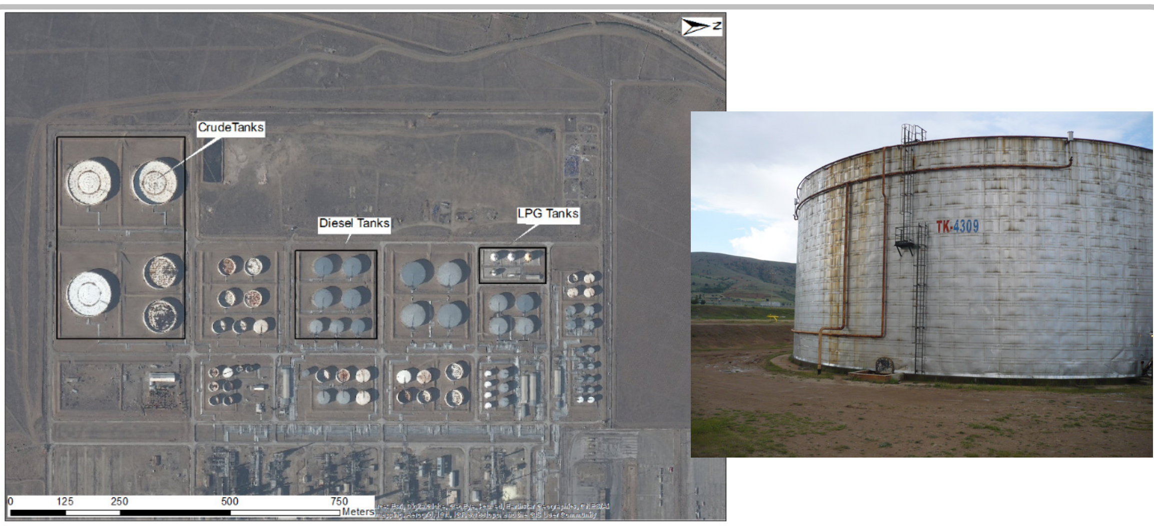


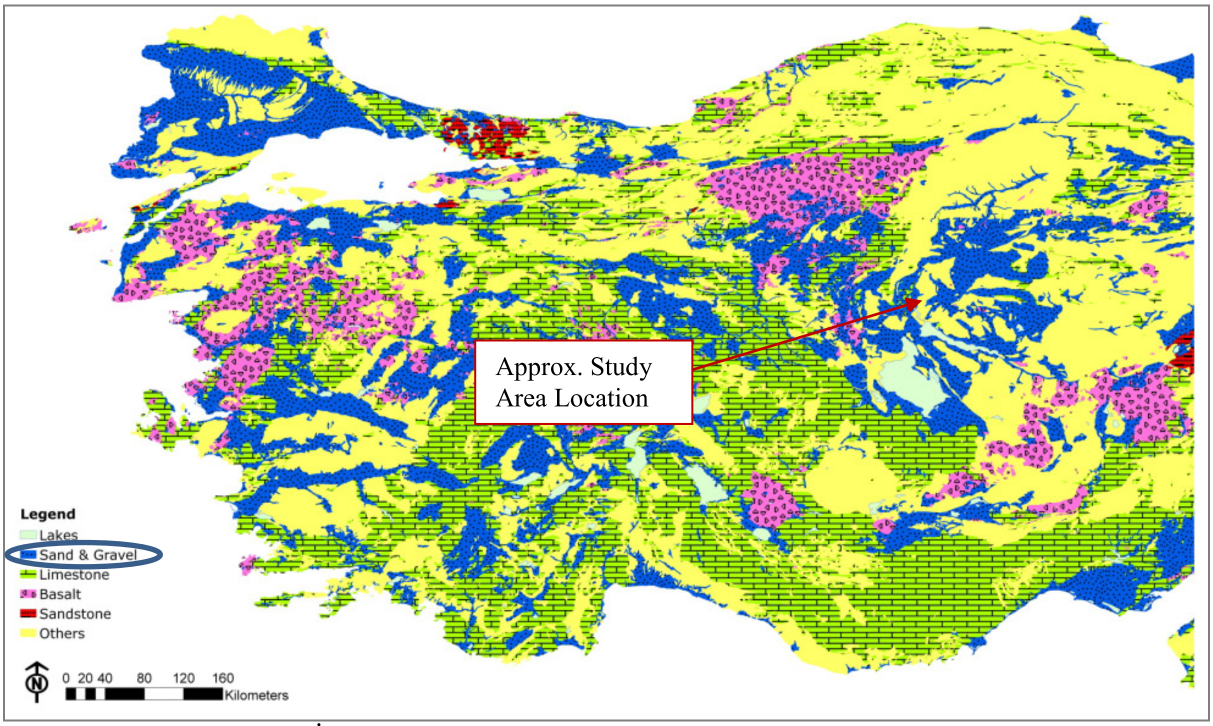
Figure 2 Tanks at Tüpraş Oil Refinery

AQUIFER (PATHWAY) CHARACTERISTICS

Kirikkale is located in a semi-arid region of Turkey which means hot and dry summers and cold winters with temperature and precipitation influenced by the higher altitude to the west of the study area. Available studies on precipitation within the Kirikkale region indicates on average 368.9mm/pa. Direct infiltration is reduced on site due to extensive areas of hard stand discharging through stormwater drains. However, many of the oil bunds have permeable bases thereby facilitating direct discharge to ground.

The region is underlain by Quaternary sediment deposits overlying rock; Mesozoic-aged granite (low porosity basement rock) lies further west of the site boundary. Eocene and Neogene-aged sedimentary rock outcrops are widespread throughout the region and comprise conglomerate, sandstone and limestone sequences.

The Quaternary sediments (comprising gravels and sands) are considered the main aquifer units within the study area. Figure 3 below presents the regional scale hydrogeological map outlining the principal types of water-bearing rocks/ sediment in Turkey.



Source: Hatice Meltem İpek, 'Development of Risk Based Soil Quality Standards for Turkey', unpublished PhD thesis, March 2011

Figure 3 Regional Scale Hydrogeological Map of Turkey

Eocene and upper Neogene sediments were observed throughout the project area and consist of clay, and clayey sand and gravel bands with depth. A review of boreholes logs completed at the site provide site-specific descriptions of the superficial geology. A simplified geological cross section completed for the site indicates a clay layer with discontinuous gravel lenses of c.20m in thickness in the west, decreasing in thickness towards the east. The thickness of the underlying more permeable sand and gravel stratum is not proven extensively. However exploratory boreholes proved the depth of this stratum to c. 33m below ground level (mbgl) at a borehole location within the refinery (K9).

The potentiometric surface was encountered at a depth range of between 5.0 to 20.0mbgl. A review of monitoring data showed a range of static water levels (SWLs) of between 9.4mbgl and 27.7mbgl for June, and between 9.7mbgl and 27.7mbgl for December, indicating a degree of consistency across a six-month monitoring period for the site (see Figure 4 below).

The estimated hydraulic gradient across the study area is 0.008 from west to approximately 0.003 towards the east. A review of available pumping tests undertaken at the site indicated the following hydraulic properties for the aquifer within the study area:

- Transmissivity (T) = 7.22x10-6 m^2/s (approx. 0.624m^2/day)
- Storage co-efficient (S) = 0.155
- Average hydraulic conductivity (k) pumping test = 8.5×10^{-7}m/s (approx. 0.073 m/day)
- Average hydraulic conductivity (k) slug tests = 6.5x10-5^{m}/s (approx. 5.62m/day)

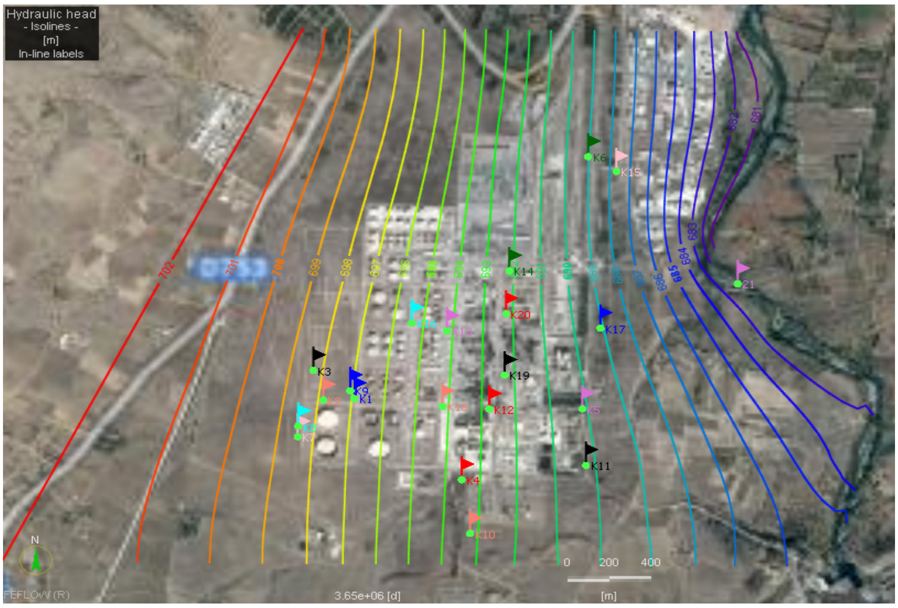


Figure 4 Site showing borehole locations (colours) and groundwater contours

Groundwater quality data is limited for the facility. However, the presence of hydrocarbon contaminants detected in a number of wells indicate historical leakage to groundwater and a more permeable pathway than borehole logs might indicate.

2007 Hydrocarbons	Unit/ Location	K6	K9	K12	K13	K14	K15	K16	K18	K19	K20
Total Aromatic Hydrocarbons	ug/l	0	0	0	2.5	0	0	0	0	0.9	0
Total Aliphatic Hydrocarbons	ug/l	0	0	121	1228	0	0	0	0	2760	0
Total Petroleum Hydrocarbons(TPH)	ug/l	0	0	121	1230.5	0	0	0	0	2760.1	0
BTEX	ug/l	0	0	0	931	0	0	0	0	23.6	0
TOC	mg/l	-	95	150	140	120	120	140	150	220	120

Table 2 Hydrocarbon Test Results for Year 2007 Monitoring Report, Kirikkale

As most of the surface area around the diesel and heavy fuel oil bunds is not hardstanding, discharge to ground is a pathway in the event of a product release.

SURFACE WATER (PATHWAY) CHARACTERISTICS

The surface water system is designed so that contaminated water can be contained on site and treated. This is achieved through two separate drainage systems; one for clean rainwater and one for contaminated water from the 'process areas'. If contamination is identified in the main surface water system it can be manually diverted to the Wastewater Treatment Plant (WWTP). However, during normal operation, all surface water is discharged directly to the Kizilirmak River.

ENVIRONMENTAL RECEPTORS

The facility is located within the Kirikkale Basin which has a drainage area of approximately 1,127Km^2. The site is relatively flat to gently sloping terrain towards the Kizilirmak River which flows c.500m to the east of the site. It flows in a south to north direction with the Kapulukaya Dam (up-gradient of the facility) and a drinking water abstraction point (for Ankara) located down-gradient of the plant. The Kizilirmak River is the longest river in the country at ca. 1,355Km and flows into the Black Sea to the north at Samsung. It is fed by snow melt and rainfall and exhibits an irregular discharge pattern with a maximum level of discharge generally observed in April of each year. Discharge patterns are further influenced by the six dams constructed along its course. There are signifcant gaps and variance in the acurracy of available flow data. Review of reports compiled on behalf of Tüpraş the following flow data was obtained for the Kızılırmak River near the site which are based on 20-year observations: Average flow: 184 m^3/s, Min flow: 18.4 m^3/s (July-Feb), Max flow: 1,673 m^3/s (March-April).

The underlying sand and gravel aquifer is a regionally important aquifer with local wells abstracting for potable and agricultural supply. There are no local areas currently designated as important groundwater dependent ecosystems.

CONSEQUENCE MODELLING

A fundamental element of the Seveso III Directive is that the Operator of a Seveso III site *'take all measures necessary to prevent major accident hazards and limit their consequences for man and the environment'*.

Tüpraş understand that risk assessment is a fundamental requirement of the Seveso III Directive and apply risk assessment to identify, minimise, manage and control risks associated with the tank farm at Kirikkale Oil Refinery. At the time of our work, a process hazard analysis programme was being implemented at the establishment which included HAZard and OPerability (HAZOP) studies and risk assessment. A Hazard Identification Study (HAZID) was undertaken to identify Major Accident Hazard (MAH) scenarios associated with the bulk crude oil, diesel and LPG storage tanks. Personnel from a number of different disciplines within Tüpraş, as well as AWN specialists, participated in the HAZID Study.

The results of quantitative risk assessment of major accident hazards are compared to the Risk Tolerability Criteria outlined in Figure 5 below. The UK HSE generally uses a three-tier framework for risk tolerability.

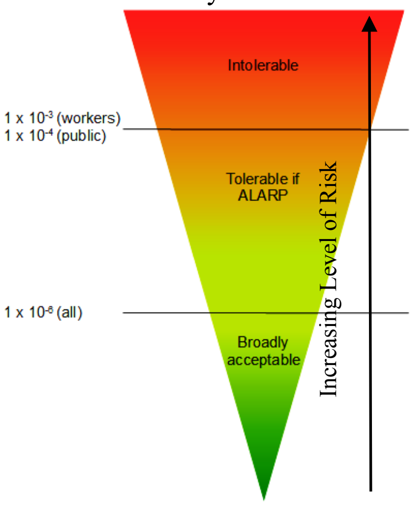


Figure 5 Acceptable Risk

An approach for assessing MATTEs (major accidents to the environment) is outlined in CDOIF (2013) '*Chemical and Downstream Oil Industries Forum: Guideline - Environmental Risk Tolerability for COMAH Establishments.* For COMAH, environmental risk can be assessed within the established 'As low as reasonably practicable' (ALARP) framework and evaluated to be either*:* Intolerable, Tolerable if ALARP (TifALARP) or Broadly Acceptable. The level of environmental risk can be used to guide the type and depth of assessment that would be expected and this may include either qualitative or quantitative risk assessment depending on the assessed environmental risk.

	Frequency per establishment per receptor per year (**unmitigated**)						
Frequency at which CDOIF Consequence Level is equalled or exceeded	10^{-8}–10^{-7}	10^{-7}–10^{-6}	10^{-6}–10^{-5}	10^{-5}–10^{-4}	10^{-4}–10^{-3}	10^{-3}–10^{-2}	$>10^{-2}$
D - MATTE						Intolerable	
C - MATTE				TifALARP			
B - MATTE	Broadly Acceptable						
A - MATTE							
Sub MATTE	Tolerability not considered by CDOIF						

Table 3 Risk Tolerability Continuum

For those substances and credible scenarios which do have MATTE potential, their risks to the relevant receptors should be determined and these should then each be categorised using the MATTE tolerability matrix to give a consequence level of either A, B, C or D - this in turn provides *the frequency per receptor per establishment per year* and thus the thresholds for 'Broadly Acceptable' and 'Intolerable' as per Table 3 above. Tank rupture and catastrophic diesel oil release can be due to:

- Mechanical failure;
- Earthquake occurs and exceeds design standard of diesel tank;
- Impingement (Missile (vessel rupture on site), Aircraft strike or Sabotage);
- Release through hole in vessel (liquid release);
- Bottom leak (Outlet pipe rupture or leak, Slop pipe rupture or leak, Water drain line rupture or leak, Inlet pipe rupture or leak or Valve rupture or leak); or
- Sinking of floating roof due to Earthquake or Rainwater/ other loading on roof.

Kırıkkale is located in central Turkey, forming part of the Central Anatolian Plateau region. It stands on the North Anatolian Fault, and is currently in an earthquake warning zone. The Tüpraş oil refinery is sited within a Category 1 zone (which includes active faults) (Source: URL: http://www.deprem.gov.tr).

Following Seveso guidelines, the most likely scenarios were identified and modelled to predict possible impacts. For the diesel tanks these were considered to be:

- Tank fire or vapour cloud explosion (following sinking of floating roof);
- Pool fire in bund following direct ignition of crude oil release;
- Vapour cloud explosion following delayed ignition of crude oil release;
- Bund over-topping and pool fire/ delayed VCE within and adjacent to bund; and/ or
- Release to ground and surface water following tank leak or catastrophic tank failure.

Due to the proximity of the river (a water supply), a quantitative risk assessment of a release to ground was undertaken, using a FEFLOW model to simulate an over-topping event.

For the Tüpraş project, the size of the model was selected to include all the parameters that contribute to the groundwater flow regime below the site. Boundary conditions were determined by the mountain range to the west (hydraulic head of ~700m) and the Kizilirmak River to the east (hydraulic head of

~680m) with no flow boundaries selected for the Northern and Southern boundaries. A simple two-layered model was used with low permeability clayey gravels overlying more permeable gravels. To allow some inflow to the underlying permeable gravels the clay was 'pinched' beneath the storage tank areas.

The hydraulic heads for the model were obtained from groundwater monitoring and river level monitoring undertaken by Tüpraş. A water balance was developed to closely match existing known measurements. The model was run to a steady state condition and a stable groundwater flow regime was obtained. Once the steady state was obtained it was possible to model the contaminant transport process at the site and the estimated contamination plume from potential spills on site. The plume, due to an over-topping event, discharging to ground was found to be quite localised and would require greater than 1,150 days to reach the Kizilirmak River. The over-topping event was found to have a more direct pathway to the river receptor through the stormwater drainage system. A possible risk exists as the containment within the WWTP is 'manually controlled' in the event of a spill event.

Using the CDOIF approach for this MATTE loss of containment event, the un-mitigated risk to the river (drinking water abstraction source) was determined to be Category C (based on a Severity of 3 and a Harm duration of 3) (Figure 6). The frequency of the loss of containment event was determined to be $1.0E^{-4}$/annum (source: CPR18E - The Purple Book). As such, the un-mitigated risk is considered to be TiFALARP (Table 3).

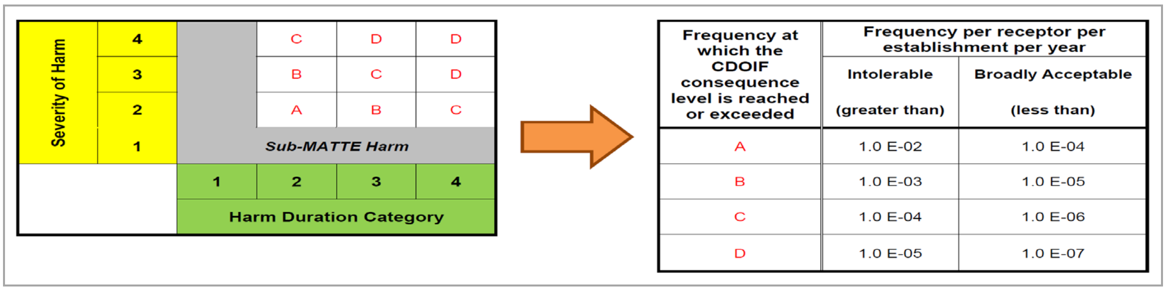


Figure 6 MATTE Matrix

CONCLUSIONS

Seveso III requires an assessment of risks to the environment as well as risks to humans. A comprehensive risk assessment requires a specialist team which must include hydrogeologists. The Tüpraş case study identified the importance of assessing the pollutant linkage between un-lined storage bunds and the underlying aquifer and receiving surface water. Consequence modelling and assessment of a loss of containment event highlighted the risk to the aquifer due to the un-lined bunds and to surface water due to the manual operation of the diversion of stormwater to the wastewater treatment plant. Following the CDOIF risk assessment methodology, further risk reduction was recommended to reduce the risk to the environment through the use of an alarmed and automated system for diversion of contaminated water to the wastewater treatment plant.

It is of note that in the UK the HSE (Health and Safety Executive – the Central Competent Authority for Seveso) and the EA (Environment Agency) collaborate closely on the regulation of Seveso sites, undertaking joint inspections and joint assessment of Safety Reports to assess all major accident scenarios in a timely and structured manner. This type of collaboration does not take place formally in Ireland where it is considered that a joint assessment process would be beneficial.

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Guidelines for Quantitative Risk Assessment, "Purple Book", CPR18E, 1999

Seveso III Directive - Directive 2012/18/EU of the European Parliament and of the Council of 4 July 2012 on the control of major-accident hazards involving dangerous substances, amending and subsequently repealing Council Directive 96/82/EC

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HYDROGEOLOGICAL CHARACTERISATION AND CATCHMENT MANAGEMENT AT FARDRUM AND ROOSKY TURLOUGH SAC, COUNTY FERMANAGH, NORTHERN IRELAND

Dr. Les Brown (Arup), Richard Langford (Parkmore Environmental)

Introduction

NIEA (initially as Environment and Heritage Service of Northern Ireland) initiated monitoring of the Fardrum and Roosky Turlough SAC in 2005. The monitoring included the collection of data on the fill level in the turloughs and stream flows into and out of the catchment as well as monitoring of climate. This work was originally undertaken by Prof John Gunn and Dr Les Brown, the most recent monitoring has been undertaken by Dr Les Brown and Richard Langford (Parkmore Environmental).

The Fardrum and Roosky ASSI / SAC is located near Ely in County Fermanagh. NIEA collectively identified Greenlough, Fardrum and Roosky turloughs in 1996 under the UK national nature conservation review. These are the only turloughs in Northern Ireland and are amongst the most northerly occurrence of the landform. The site is one of only two in the United Kingdom, the other being Pant y Llyn in south Wales (Hardwick & Gunn, 1995).

The Fardrum and Roosky Project is a quantitative assessment of the water volumes in the Fardrum and Roosky SAC catchment based on monitoring for the period October 1st, 2005 to September 30th, 2010 as well as additional monitoring for the period December 2012 to April 2014.

The project objectives are to:

- Characterise the three turloughs in terms of their fill and drain cycles to the seasonal groundwater fluctuation as well as responses to storm events
- Assess the volumetric inputs and outputs from the karst aquifer as a catchment water balance and develop a conceptual model of the groundwater system and its seasonal variation.
- Use the above data to assess potential impacts on the turlough system from two quarries that are located centrally in the catchment and consider how these impacts have developed since quarrying began in the 1950s.

The turlough monitoring record provides a monthly balance of the inputs to the groundwater system and the outputs there from. These hydrometric data are assessed in terms of the point recharge at stream sinks (allogenic) and diffuse recharge within the limestone catchment (autogenic), as well as the fill and drain cycles of the individual turloughs. The water balance allows assessment of the groundwater system as a whole to provide information on the pathways between turloughs and risings.

Instrumentation and Monitoring Data

Each turlough has water level instrumentation comprised of a manual stage board with data logger at 15minute time interval, which is anchored to the bed of the turlough. The topographic depression of each turlough was surveyed during low flow so that the water level stage data recorded by the logger and calibrated using the stage board could be converted to volume of water stored in the turlough depression. The hydrographs for the turlough monitoring stations are provided below (Figures 1-3) for the full dataset for each turlough which initiated in October 2005.

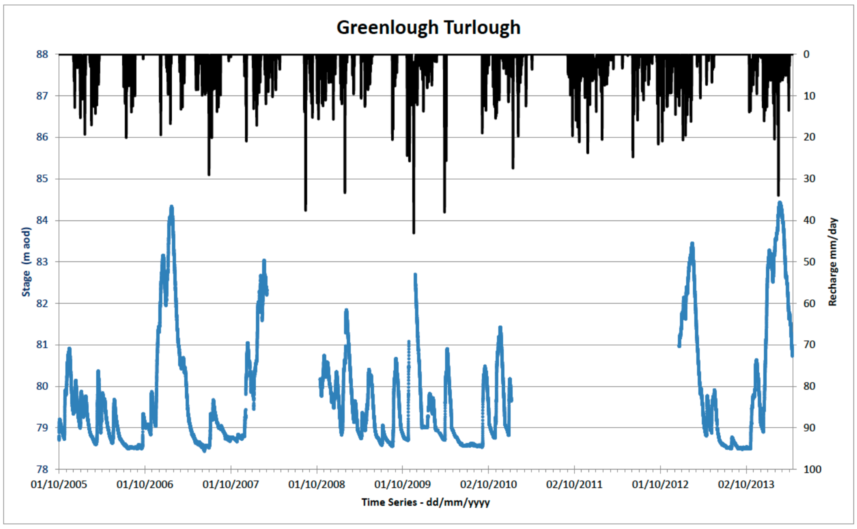

Figure 1. Hydrograph Greenlough Turlough

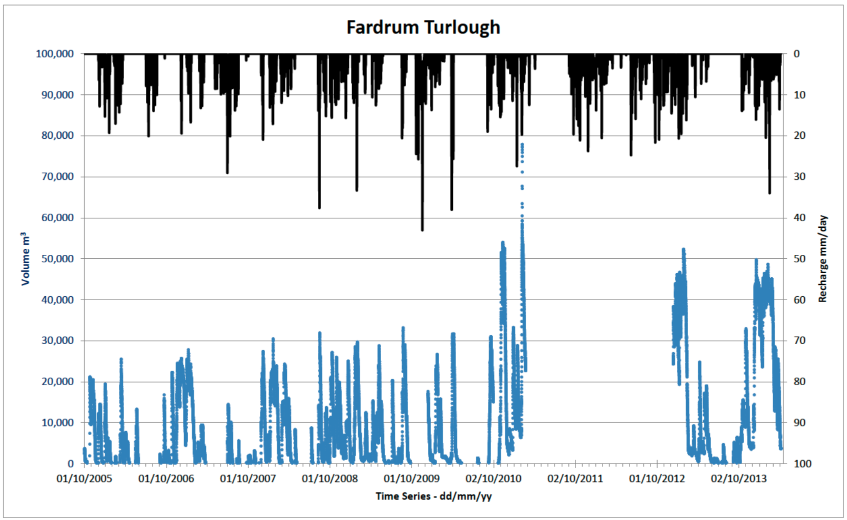

Figure 2. Hydrograph Fardrum Turlough

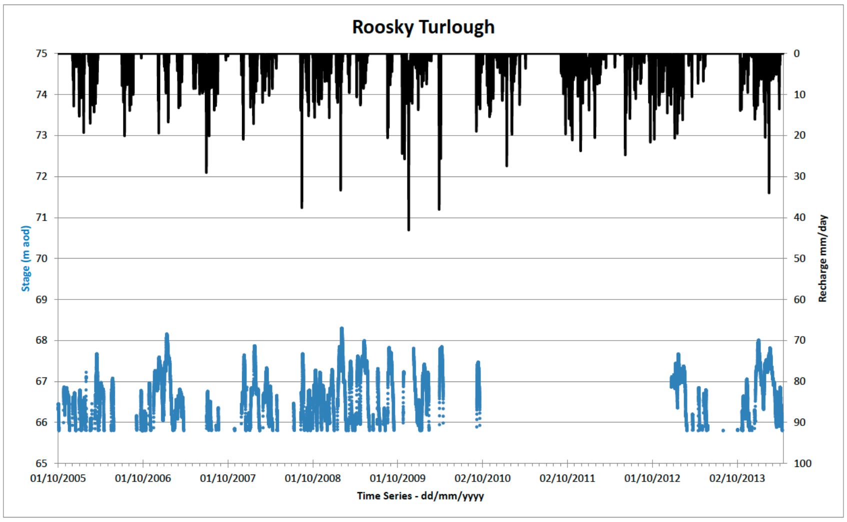

Figure 3. Hydrograph Roosky Turlough

Catchment Water Balance

Inputs to the system comprise of effective rainfall to the catchment either in the form of diffuse recharge on the autogenic limestone part of the catchment (Figure 4) or by sinking streams draining from the allogenic sandstone and shale part of the catchment (Figure 5). Output from the system comprises of spring discharges either in the form of natural springs or those from the quarries.

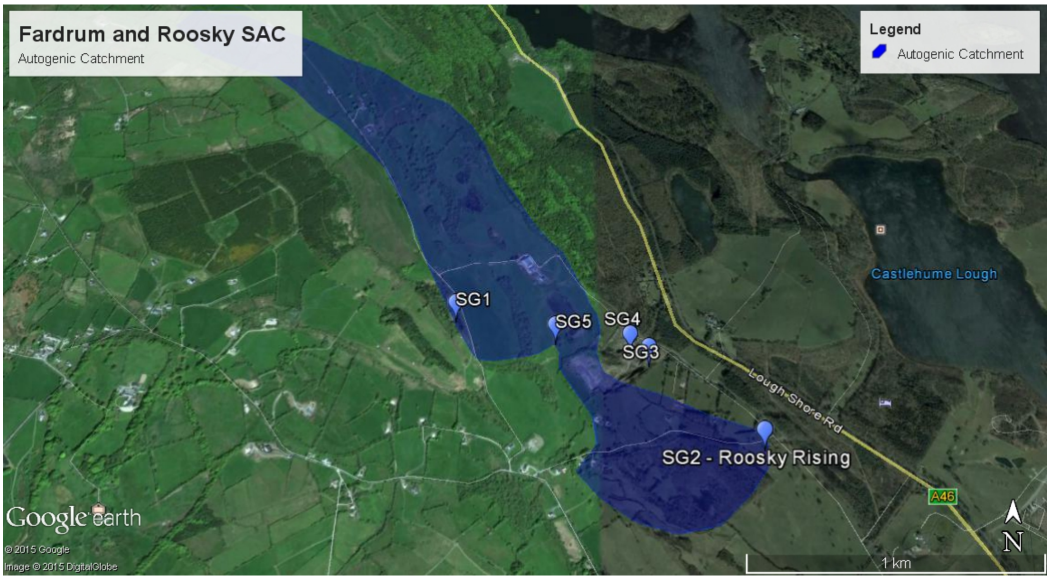

Figure 4. Autogenic catchment for Fardrum and Roosky SAC

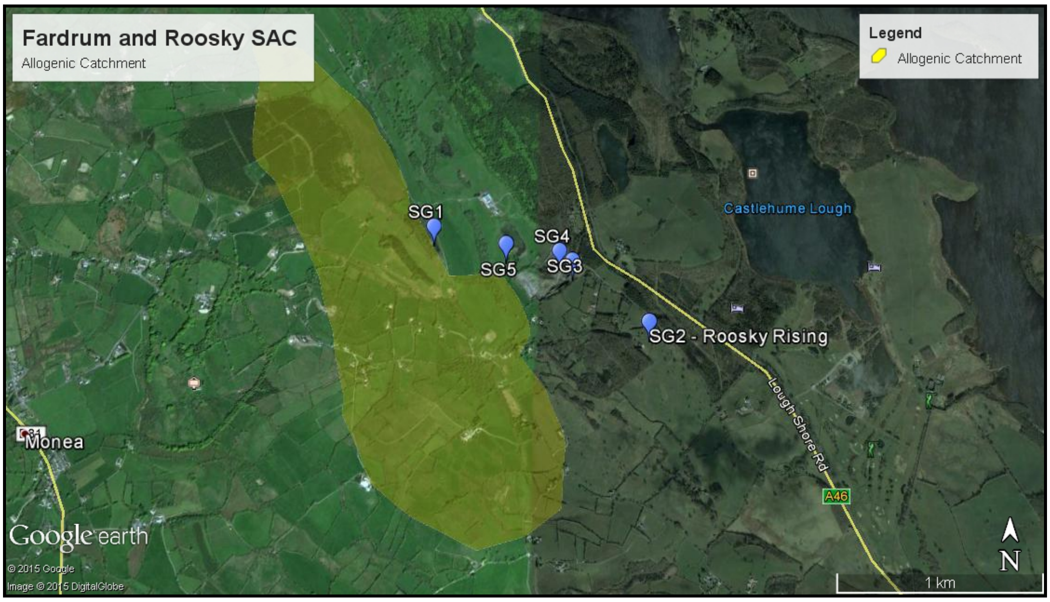

Figure 5. Allogenic catchment of Fardrum and Roosky SAC

The calculation of recharge is by the FAO soil moisture deficit formulae, which is undertaken for the data period and calculated on a daily time step (Figure 6). These data are used to provide a monthly recharge value. Evaporation from the loughs is accommodated.

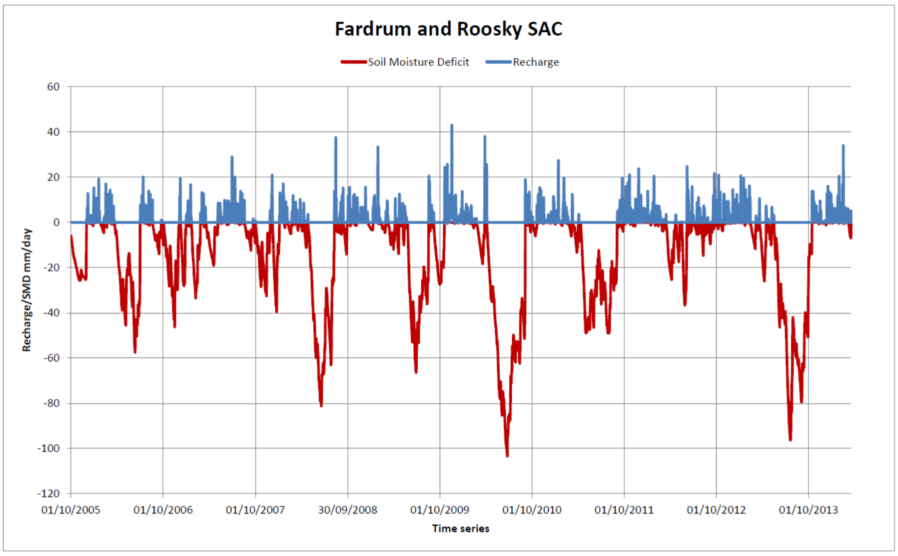

Figure 6. Assessment of autogenic recharge based on soil moisture deficit (FAO Penman Monteith).

The allogenic catchment for the SAC is measured based on the topographic divide and the boundary between the limestone and overlying sandstones and shale (refer to Figure 3). The catchment area for the allogenic recharge is measured as being 2,083,449m^2. This is near twice the area of the autogenic recharge area (1,182,166m^2), with the autogenic/allogenic catchments being split 36%/64% out of a combined catchment area of 3,265,615m^2. Whilst the autogenic recharge is calculated from recharge over the catchment area, allogenic recharge is taken from the mean monthly flows measured at the two stream sinks.

The output from the groundwater system is measured at the main spring outlet for the catchment as well as discharges measured at both quarries.

Water tracing experiments in the catchment have demonstrated that flow paths can be very rapid. However, there will also be slower movement in the matrix and fractures, as evidenced by tracer dye continuing to emerge for several months after injection. The limitation of water balance type calculations is that in an aquifer with mixed storage there will be delays or lag within the system. Conceptually, it is anticipated that there will be a disparity between the monthly balance between input to the groundwater system and output from it. This is the case for each groundwater system as there is an increase in the water table over the winter months as recharge increases. In this regard there will be a monthly excess of input during the winter. However, this is matched by the spring and summer excess of output over input when recharge reduces and ceases.

Characterisation

In general terms the data sets for Greenlough and SG2 Roosky Spring show the greatest seasonality to the inputs, they both change with the seasons and whilst individual major events can be identified the responses are gradual and not immediate.

The stream sinks and quarry outflows as well as Fardrum Turlough can be described as being notably more flashy to the rainfall responses. The characteristics of these flashy groundwater responses indicate that Fardrum Turlough and the quarries are more likely associated with allogenic recharge rather than the autogenic recharge.

Roosky Turlough falls more so into the category of a response to autogenic recharge. However, its characteristic drying out during extended periods of below average rainfall, even if during the winter, stands it out from the response of Greenlough Turlough.

The balance between input and output for 2012-2014 data period shows a deficit of input with the output total being 4% greater.

Landuse and Impacts

The data collected during this project has provided measurements of the inputs and outputs from the groundwater system. From these data it is apparent that the cumulative quantity of water discharged from two quarries (Roosky and McGowan) from the SAC catchment is significant. It is also apparent that the springs in the quarries would not be present prior to quarrying. Based on the quantitative assessment of this project the cumulative quantity of flow from the quarries then discharge from the SAC catchment comprises:

Roosky Spring	49.4%
Roosky Quarry	50.5%
McGowan's Quarry	<1%

From this dataset the water discharges from Roosky Quarry and McGowan's Quarry contribute 51% of the discharge for the data period, with near all water being discharged from Roosky Quarry.

The quarrying at Roosky Quarry and McGowan's quarries initiated in the 1950s. At that time significant changes were made to the drainage network in the area and these changes, which included the diversion of a stream into Fardrum Turlough appear to have had significant changes to groundwater input and these changes remain today but also may be in part the cause of the discharges from the quarries. Both of which are now abandoned.

From the characterisation and data presented it is apparent that Greenlough Turlough is unlikely to have been impacted from the quarrying and changes in local drainage that have occurred in the catchment but that Fardrum Turlough has been significantly impacted. Roosky Turlough is particularly sensitive to groundwater change and has likely been impacted by groundwater intercepted by groundwater discharges in the quarries as a consequence the duration that Roosky Turlough remains flooded is likely significantly less than it was prior to quarrying.

SESSION IV

NATURAL ATTENUATION OF CHLORINATED SOLVENTS IN THE HYPORHEIC ZONE: INSIGHTS FROM A MULTI-SCALE FIELD INVESTIGATION ON A GAINING LOWLAND RIVER IN THE UK

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ABSTRACT

Chlorinated aliphatic hydrocarbons such as trichloroethene (TCE) and its dechlorination products cis-1,2-dichloroethene (cDCE) and vinyl chloride (VC) are among the most frequently detected volatile organic compounds (VOCs) in groundwater. TCE is a dense, non-aqueous phase liquid (DNAPL) which forms persistent dissolved-phase plumes that may reach surface water via groundwater baseflow. Of particular concern are 'gaining' rivers where net flow accretion occurs from adjacent contaminated groundwater bodies. Discharging VOC plumes must transit the aquifer-river interface (hyporheic zone) which is often characterised by increased heterogeneity and steep biogeochemical gradients.

This research investigates processes which control the fate of a TCE plume in the hyporheic zone of a lowland river where 77% of mean flow is derived from groundwater storage. The unconfined Permo-Triassic sandstone (PTS) aquifer is aerobic with elevated nitrate (>50 mg/l as NO_3) to depths of 80 m where TCE concentrations of 180 µg/l have been observed. The plume source is unknown but advective transport simulations indicate a possible source area associated with an RAF facility one kilometre away. A well-defined plume discharge zone was delineated with networks of diffusion samplers, pore water samplers, multi-level piezometers and alluvial monitoring wells. Multi-scale geological flow controls and heterogeneity were investigated using electrical resistivity imaging surveys, coring, nested piezometers and high-resolution riverbed temperature mapping. Biogeochemical gradients were investigated using depth-discrete profiles of dissolved organic carbon (DOC), dissolved oxygen (DO), nitrate (NO_3), soluble iron and manganese (Fe^{2+} and Mn^{4+}), sulphate (SO_4) and dissolved methane (CH_4). In-situ reductive dechlorination of TCE was quantified using a chlorine number reduction approach based on mass balances of cDCE and VC.

The plume mass flux through the hyporheic zone was found to be dominated by discrete zones where hydraulic continuity with the underlying PTS aquifer was enhanced. Effective contaminant residence times in the riverbed sediment sequence ranged from one week to nearly three years. Elevated diffuse NO_3 created a large stoichiometric demand for DOC capable of buffering the onset of Mn-reducing conditions and inhibiting plume dechlorination. Locally efficient dechlorination of TCE (as far as cDCE and VC) was observed in DOC-rich sediment 'hotspots' supporting accelerated methanogenic activity beneath stands of submerged macrophytes.

PROVENANCE, PATHWAYS AND GEOTHERMAL POTENTIAL OF IRISH THERMAL SPRINGS: A MULTI-DISCIPLINARY INVESTIGATION

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ABSTRACT

The geothermal energy of thermal groundwater is currently being exploited for district-scale heating in many locations world-wide. The Carboniferous bedrock in the south and east of Ireland hosts a number of thermal springs with temperatures ranging from 12 – 25 °C. These temperatures are elevated with respect to average Irish groundwater temperatures (9.5 – 10.5 °C), and represent a geothermal energy potential, which is currently under evaluation. A study was carried out to further our understanding of the sources, circulation pathways and temporal variations of the Irish thermal springs, and a multi-disciplinary methodology was used (including audio-magnetotelluric (AMT) geophysical surveying, time-lapse temperature and chemistry measurements, and hydrochemical analysis) to develop hydrogeological conceptual models for several of these springs.

A sub-set of six springs in the Carboniferous limestones of the Dublin Basin was examined. Seasonal hydrochemical data were explored using multivariate statistical analysis to investigate the source aquifers of the thermal groundwaters. The analysis indicates that the thermal waters flow within the limestones of the Dublin Basin, and there is evidence that some springs receive a contribution from deep-basinal, saline fluids. Three-dimensional electrical resistivity models of the subsurface were constructed from AMT data collected at Kilbrook spring (maximum of 25.0 °C) and St. Gorman's Well (maximum of 21.8 °C). These models revealed two types of geological structure beneath the springs; (1) Carboniferous normal faults, and (2) Cenozoic strike-slip faults. The karstification of these vertically-persistent structures, particularly where they intersect, has provided conduits that facilitate the operation of a relatively deep hydrothermal circulation pattern (likely estimated depths between 240 and 1,000 m) within the Dublin Basin. The thermal maximum and simultaneous increased discharge observed at several of the springs each winter must be the result of rapid infiltration, heating and re-circulation of meteoric waters within a structurally- and recharge-controlled hydrothermal circulation system.

THE IMPACT OF DOMESTIC WASTEWATER EFFLUENT ON PRIVATE WELLS: AN EVALUATION OF CONTAMINATION FINGERPRINTING TECHNIQUES

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ABSTRACT

In rural areas the absence of a public water supply network necessitates the reliance of many households on private wells for their water provision. In many cases such rural areas are also not connected to centralised sewerage network and therefore require onsite domestic wastewater treatment systems (DWWTS). In Ireland approximately 438,000 dwellings use DWWTS of which approximately 162,000 households also have their own private wells. The necessity for the disposal of domestic wastewater and the attainment of safe drinking water within a spatially confined household site requires an in-depth understanding of the contaminant transport and attenuation processes for the DWWTS effluent in parallel with suitable water well design and construction in order to ensure groundwater resources (and hence human health) are adequately protected. However, previous sampling studies of private wells for the presence of faecal indicator bacteria have shown that approximately 30% are polluted, at least intermittently, with one of the main sources of microbial pathogens believed to be DWWTS, mainly septic tanks. As faecal indicator bacteria are not source-specific, the aim of this current research is to compare and evaluate a range of chemical and microbiological fingerprinting techniques in an attempt to identify a robust method for apportioning groundwater contamination to a specific source.

Across four geologically distinct study areas in Ireland a total of 212 households dependent on private wells and DWWTS have been evaluated by individual site assessments. These assessments recorded variables including the hydrogeological setting (soil characteristics, aquifer type, groundwater vulnerability, etc.), the individual construction features of each well (borehole headworks protection etc.) and the well siting relative to the DWWTS. Subsequent well sampling and analysis for a range of chemical parameters and faecal indicator bacteria found that 15% of the wells were at least intermittently contaminated by E.coli. Subsequent monthly monitoring of 24 wells found 45% to be contaminated with E. coli at least once. These 24 wells have been used to assess a range fingerprinting techniques, including fluorescent whitening compounds (FWC), faecal sterols, anion ratios and Bacteroidales faecal source tracking (FST).

FST tests on an expanded subset of monitoring wells (n=42) targeting regions of Bacteroidales 16S rRNA genes found 62% were positive for human specific Bacteroidales. However, no wells to date have tested positive for FWCs using fluorometry and UV degradation methods. The research is also evaluating faecal sterols and a range of emerging organic contaminants, namely artificial sweeteners, caffeine and pharmaceuticals as tracers. With effluent from DWWTS recognised as a major factor in the incidences of waterborne disease worldwide, accurate identification of private wells impacted by human effluent is required to help guide corrective action and protect householder health.

SESSION V

CHANGES IN GROUNDWATER STORAGE UNDER FUTURE CLIMATE CHANGE

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ABSTRACT

Freshwater is fundamental to human and ecological well-being and provides resources for socio-economic demands. Resources are partly, or in some regions entirely, provided by groundwater (the groundwater store, GWS) and sources are at risk from abstraction and climate change. This study investigates future climate influences by quantifying changes to aspects of land hydrology and groundwater storage. A global vegetation and hydrology model (LPJmL) is extended to include a heuristic model of the renewable GWS and to investigate future changes, at grid cell and aquifer scales, using 20 simulations to sample climate uncertainties. Increases in GWS (beyond doubling) are simulated in northern mid-latitudes, India and East Asia. Decreases are simulated over southern Europe, the Middle East, North Africa and parts of Central America, southern Africa and Australia. GWS in some aquifers (e.g. North Africa and Mexico) may decrease at rates exceeding adaptive capacity. Together, renewable GWS and surface water may be insufficient to meet future irrigation demands in northeast China, northwest and Central America, parts of southern/central Eurasia and North Africa, posing serious challenges to future food production, especially under emissions scenario RCP8.5. These risks are conservative estimates given likely additional socio-economic pressures unaccounted for here.

INTRODUCTION

Estimates suggest that 35% of all global freshwater use is obtained from groundwater (Döll *et al*., 2012). Depletion of this groundwater store (GWS) can arise from both socio-economic and environmental factors (Gleeson *et al*., 2012; Döll *et al*., 2014). Climate change may increase pressures on GWS via evolution of climate and surface hydrology, and through the climate-driven evolution of water demands. Past studies have investigated potential climate impacts by examining changes to groundwater recharge (R_g), readily calculated in many global hydrological models (GHMs) as percolation from the bottom of the soil scheme. In recent work, such GHMs have been forced by future climate scenarios provided by General Circulation Models (GCMs) to show possible changes in the pattern of R_g, revealing sizeable increases and decreases for the 21st century reflecting the interplay of climate with the soil and vegetation of the land surface (Portmann *et al*., 2013; Döll, 2009). R_g can reflect renewable groundwater but does not account for the local storage potential of groundwater (i.e. GWS itself). Although conceptual GWS schemes, or in one case an actual groundwater flow model, have been added to existing GHMs (Döll, 2009; Döll *et al*., 2014), applications have been limited to present-day analyses and within the context of human water abstractions. In this study, the LPJmL GHM (Rost *et al*., 2009) was extended to include a two-layer scheme representing shallow and deep GWS and to drive this model with 21st century GCM climate data. Analysis of the model simulations focuses primarily on GWS, rather than R_g, in order to calculate areal means representing major aquifers.

DATA AND METHODS

LPJmL dynamically simulates vegetation (natural and agricultural), carbon cycling and hydrology on a regular 0.5° by 0.5° grid and at a daily time step. LPJmL has been widely used for global environmental impact studies (Schaphoff *et al.*, 2013; Gerten *et al.*, 2013). The new GWS implementation presented here follows a budget approach. Input, R_g, is the percolation flux from the bottom soil layer which, previously, formed subsurface runoff. Instead, R_g is partitioned between an upper and lower GWS layer. Export from each layer to the surface water store is assumed to be proportional to the groundwater volume according to a spatially differentiated hydraulic coefficient, K_g. A smaller coefficient is used for the deeper layer to reflect degradation of hydraulic connections between deeper groundwater and the surface.

Similar approaches have applied a spatially-constant K_g (Portmann *et al.*, 2013) but here the approach is to estimate a spatially-varying K_g, for each LPJmL grid cell, using an empirical relationship between K_g and local precipitation (Peña-Arancibia *et al.*, 2010). Precipitation is taken from the gridded CRU TS 3.10 dataset (Harris *et al.*, 2013). K_g values derived in this way show marked spatial variations and significantly refine the budget approach.

To implement the new GWS scheme, G (the groundwater store volume in a cell), at time, t, in each of the two groundwater layers is given as:

$$G_{(t)} = G_{(t-1)} - K_g A G_{(t-1)} + R_g C \qquad \text{eq. (1)}$$

A and C are scaling parameters reflecting the different input and output characteristics of the upper and lower layers. C allows the upper level of the store to receive the majority of R_g (C = 0.95), whilst the remaining R_g enters the lower layer (C = 0.05). For the export behaviour, K_g, the upper layers export at the full rate (A = 1), while the lower layer, assumed to have limited connections with the surface store, exports at 100^{th} of K_g (A = 0.01). There is no interflow between the two stores and indirect recharge (from the surface water store) is not simulated.

LPJmL is further modified so that surface runoff and infiltration better reflect topography while maintaining realistic total runoff. In the pre-modified version, infiltration, I, is a function only of precipitation, P, and the hydraulic conductivity of the grid cell soil, a:

$$I = P * a \qquad \text{eq. (2)}$$

and surface runoff, S, is 100% of non-infiltrating precipitation:

$$S = P - I \qquad \text{eq. (3)}$$

Using empirical observations, S can, in fact, be scaled according to a coefficient B that depends on the local slope gradient (Haggard *et al.*, 2005). B is derived per LPJmL grid cell by applying the observed relationship to mean slope gradients obtained from a global-gridded elevation data set (Verdin, 2011). After scaling, S becomes:

$$S = BP(1 - a) \qquad \text{eq. (4)}$$

and I then becomes the difference between precipitation and this scaled surface runoff:

$$I = I(1 - B + Ba) \qquad \text{eq. (5)}$$

In this final form, infiltration and surface runoff both reflect local topography, in addition to the hydraulic conductivity of the soil. Consequently the contribution of excess surface water to surface runoff becomes moderated allowing enhanced infiltration (and potential R_g) within less steep terrain.

In summary, GWS in each grid cell is a function of R_g and K_g, resulting in a lower GWS for higher K_g values and *vice versa*. It is important to stress that GWS is not the total groundwater availability as per the real world, since fossil groundwater stores are not accounted for (e.g. North Africa; Abouelmagd *et al*., 2012; MacDonald *et al*., 2012). Rather, GWS is the renewable component. Here the combined amount of the two-layer storage system is allowed first to reach equilibrium and then to respond to climate-driven changes in R_g. Although LPJmL accounts for soil permeability and hydraulic conductivity, real-world GWS also reflects hydrogeological characteristics (e.g. Gleeson *et al*., 2012). Explicit groundwater flow models have recently been coupled to GHMs, which are able to simulate groundwater processes reflective of the local hydrogeological characteristics. Although the budget approach applied here does not account for these characteristics, the experimental design does account for other hydrological processes that influence surface and subsurface fluxes and which are absent from flow models, namely a dynamic vegetation scheme.

Gridded precipitation, surface temperature and radiation are prescribed as input climate data for the LPJmL experiments. A 'present-day' simulation is performed with monthly climate fields obtained from the CRU TS2.1 data set (Mitchell & Jones, 2005) for the period 1901-2002 and disaggregated to the daily time scale internally by LPJmL. For the climate change experiments, climate data are prescribed from a subset of five GCMs used for the fifth international Coupled Model Intercomparison Project climate change experiments (CMIP5; Taylor *et al*., 2012). GCMs are forced with historical radiative forcings (1951-2005) and each then by four radiative forcing pathways (representative concentration pathways, RCPs; Van Vuuren *et al*., 2011) to 2099. The GCM subset used here is the ISI-MIP daily GCM data (Hempel *et al*., 2013) selected because it offers multiple GCMs (HadGEM2-ES; IPSL-CM5A-LR; MIROC-ESM-CHEM; NorESM1-M; GFDL-ESM2M) whose data are interpolated to the LPJmL grid. The ISI-MIP data are direct daily GCM fields (thus no disaggregation is performed) and data are first bias-corrected using a technique retaining both the climate change trend and daily characteristics. For both the present-day and climate change experiments, a spin-up phase of 5000 years is performed. For the present-day simulation the spin-up data are the CRU TS2.1 1901-1930 period cycled. In the case of the climate change experiments, the spin-up data are the cycled and de-trended 1951-1980 ISI-MIP GCM climate data. For the GCM experiments, anthropogenic influences upon hydrology (independent of climate) are also accounted for by allowing grid cell land use to change in accordance with observations (Fader *et al*., 2010) to 2000. Thereafter, land use patterns are fixed. LPJmL vegetation is simulated as dynamic plant functional types and crops, free to grow and recede within the allocated fraction of each cell.

For the climate change experiments, LPJmL also simulates potential irrigation calculating irrigation water demand (IWD) per grid cell, defined as the additional water required within each cell to ensure *optimal* crop growth. Crops are represented in the form of 13 crop functional types (either irrigated or rain-fed) within LPJmL and are free to grow to the limit of the allocated land use fraction of each cell. Whether a crop type is potentially irrigated is based on a land use dataset (Fader *et al*., 2010). Also, whether and to what degree irrigation actually occurs (i.e. the magnitude of IWD) is simulated in dependence of daily weather, soil moisture, and country-scale irrigation efficiencies (Rost *et al*., 2008; Konzmann *et al*., 2013). LPJmL also accounts for the carbon "fertilization" effect, where certain crop types respond beneficially to higher atmospheric CO_2 via enhanced growth and water use efficiency. Thus, changes in simulated IWD through the 21^{st} century are a combination of local hydro-climatic changes and (CO_2-driven) changes in crop water use efficiency. Irrigated areas, irrigation efficiencies, and overall crop management is held constant in the future simulations at a year 2000 level in order to isolate the climate change effect. Irrigation water demand is assumed always to be met in the LPJmL simulations, firstly via accessing local surface water stores, and thereafter, as is common practice in the real world, via an assumed remote surface water, or fossil groundwater, store.

RESULTS AND DISCUSSION

For the ‘present-day’ simulation, the spatial 1971-2000 mean R_g (Fig. 1) resembles comparable GHMs (Döll & Fiedler, 2008) with high (low) values for the principal zones of high (low) precipitation, modified by temperature influences on potential evapotranspiration. Comparison with observations (Hiscock *et al*., 2011) suggests simulated R_g values are realistic over Europe (e.g. ~150mm/yr for southeast UK; ~30mm/yr for southern Spain). A more detailed comparison is possible with US hydrological records (Wolock, 2003): the broad patterns of R_g across varied geographical regimes agree, but LPJmL values are higher in the southeast US and lower over some mountain zones. High GWS volumes are simulated within equatorial and maritime-influenced Northern Hemisphere zones. Lower values occupy regions of limited precipitation and R_g. The simulated global total renewable GWS is 18,683 km^3.

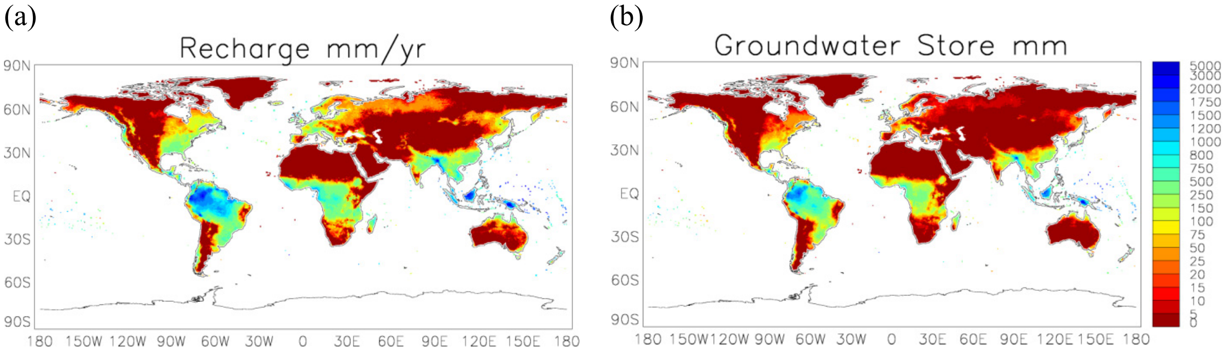

Figure 1: (a) Mean 1971-2000 LPJmL R_g and (b) GWS when driven with the gridded CRU TS 2.1 observational climate record.

Increases in global total R_g and GWS are simulated under all RCPs with stronger increases under stronger emissions scenarios. Geographical patterns of GWS changes (Fig. 2) show increases over the Northern Hemisphere mid-to-high latitudes, amplified under RCP6.0 and RCP8.5. This change is less coherent in East Asia and parts of western North America. In southern Europe, the Middle East and sub-tropical/Central America reduced GWS is simulated. Reductions exceed 75% under RCP8.5 within Turkey, the Iberian Peninsula, western Mexico, and sections of the Gulf Coast. Regions of GWS decrease are also simulated in Australia, South America (southern Chile and Venezuela) and southern Africa. For Africa, strong increases are simulated within the east and equatorial belt. In southeast Asia a band of GWS increase extends from India into China, following the eastern coast into the agriculturally-important Yellow River Basin.

To illustrate agreement between LPJmL results under multiple GCM forcing, a consensus map (Fig. 3) indicates where the sign of GWS change is the same in at least four of the GCM-LPJmL simulations per RCP. The predominant zones of both reduced and increased GWS (Fig. 2) show such consensus, although, notably, there is limited consensus over India and southeast Asia where increases in mean GWS for the former are the result of strong signals in just two GCM-LPJmL experiments (consistent with earlier studies noting similar uncertainty; Portmann *et al*., 2013).

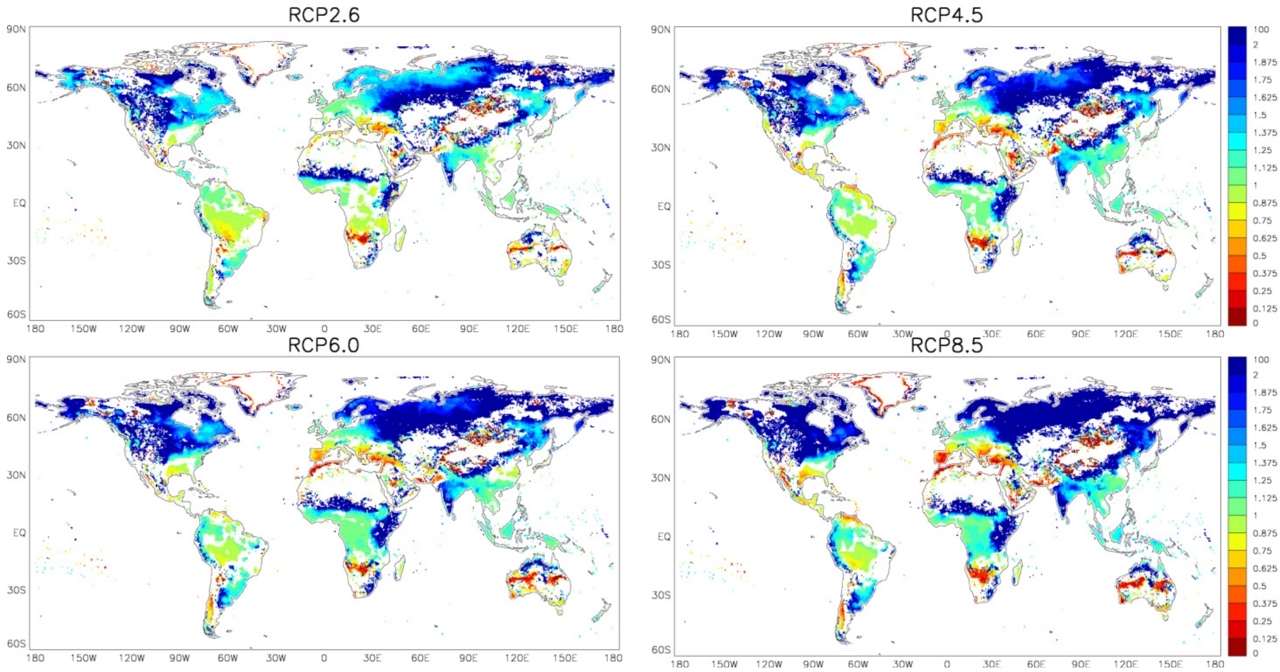

Figure 2: Fractional change in mean simulated 2070-2099 GWS, for each RCP experiment, with respect to simulated 1971-2000 values. Values are the mean of all 5 GCM LPJmL simulations per RCP. Changes not significant at the 99% level are white.

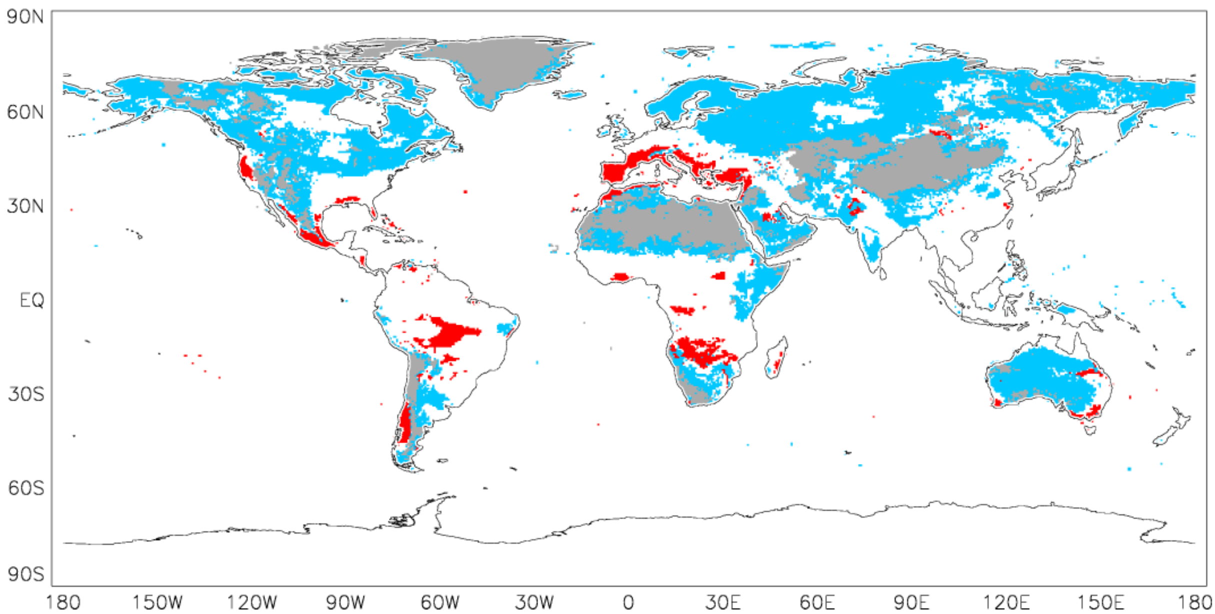

Figure 3: Consensus pattern for RCP4.5 calculated where sign of the grid cell GWS change is the same in at least four of the five GCM LPJmL simulations (Blue: increase; Grey: no change (i.e. smaller than ±0.1%); Red: decrease).

To investigate GWS change at the aquifer scale, gridded results are aggregated into 22 groundwater basins selected for their known unsustainable condition (Gleeson *et al*., 2012) and/or proximity to agricultural and populated zones. Even for the RCP2.6 and RCP4.5 scenarios, the Western Mexican and Nile aquifers exhibit notable GWS reductions, and within RCP8.5, the GWS content falls to ~55% and ~75% of simulated 1971-2000 values (Fig. 4), respectively. These, and projected decreases in the North African aquifer, far exceed simple, generic thresholds of possible human and natural adaptive capacity, such as ±20% (Schewe *et al.*, 2013). More moderate GWS decreases (e.g. 15%, RCP8.5) are simulated for the Gulf Coastal Plains and Danube aquifers.

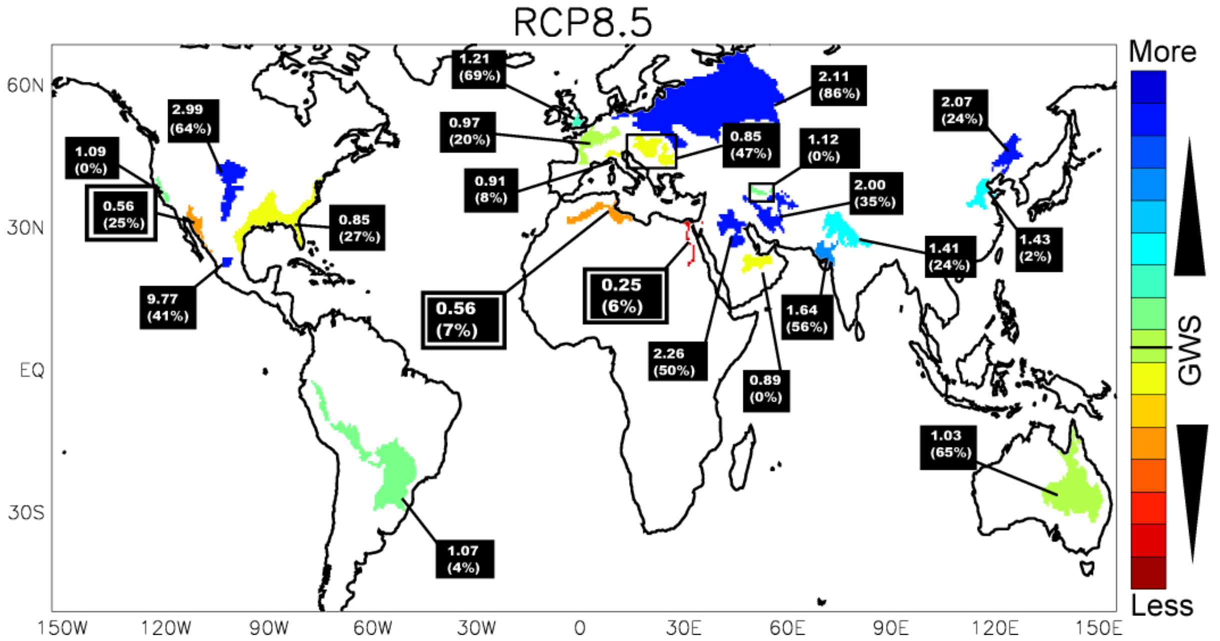

Figure 4: Mean-aquifer GWS content by 2070-2099 for RCP8.5 expressed as fraction of 1971-2000 values. Values for 2070-2099 of <0.8 are highlighted. Parentheses denote percentage of component cells where sign of change was consistent in at least four LPJmL GCM simulations.

The robustness of aquifer-scale results can be represented by the percentage of component grid cells for which at least four GCMs agree upon the sign of GWS change. Robustness is low for both the Western Mexican and Nile Delta aquifers. Strong, and robust, increases in GWS are simulated in the Central Mexican, High Plains and Eastern European aquifers even under moderate radiative forcing. Within the socio-economically intensive zones of India and eastern China, the GWS of regional aquifers (Lower Indus, Upper Ganges, Northern China and North China Plain) are projected to increase by around 50-100% under RCP8.5, with moderate consensus between GCM experiments.

CONCLUSION

To conclude, extensions to the LPJmL global hydrological model presented here allow grid cell and aquifer scale projections of potential GWS behaviour under future climate change encompassing uncertainty via a GCM ensemble and four RCP scenarios. Regionally, the fossil GWS may be much larger than the renewable GWS and, although this study does not consider fossil GWS, it has identified regions where surface water and renewable GWS may be inadequate to meet irrigation water demand. Therefore, particularly in regions where irrigated food production is endangered by decreasing surface and GWS resources (Elliott *et al.*, 2013; Steward *et al.*, 2013), water-saving options in both irrigated and rain-fed systems must be promoted (Rost *et al.*, 2009). The pressure on surface water and groundwater resources is likely to be even higher than indicated in this study, which does not quantify future increases in food demand and related increases in irrigated area and water abstractions.

ACKNOWLEDGEMENTS

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SESSION VI

MAKING THE RED ONE GREEN – RENEWABLE HEAT FROM ABANDONED FLOODED MINES

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ABSTRACT

Abandoned mines are often allowed to flood, sometimes overflowing at the surface to form discharges of potentially contaminated (often ochreous, acidic or metal-rich) mine water. Other such mines are actively pumped and managed to prevent contaminated water overspilling at the surface. They are usually regarded as environmental or economic liabilities. At increasing numbers of locations throughout the world, the huge reservoir of warm(ish) water contained in these mines is being utilised as a thermal resource or store, providing "green" space heating or cooling. The underground network of tunnels and shafts provides a heat exchange interface with the rocks in the mined area. In this way, it is possible to convert an ochreous reddish-orange environmental liability into a green renewable energy asset. Five main factors hinder the adoption of mine water as a thermal resource: (i) the lack of proven heating and cooling demand in the vicinity of some mines; (ii) the major investment required in district heating/cooling systems to optimally utilise the resource; (iii) legislative and licensing uncertainty; (iv) the perceived risk of ochre/metal precipitate clogging of heat exchangers and injection wells; (v) the perceived risk of rapid thermal breakthrough of re-injected thermally spent water at the production well. This paper examines how these issues have been tackled at a number of European mine water sites.

*"Will all great Neptune's ocean wash this blood
clean from my hand? No; this my hand will rather
the multitudinous seas incarnadine,
making the green one red."*

William Shakespeare, Macbeth, Act II, Scene 2

MINE WATER AS A THERMAL RESOURCE

MINE WATER - AN INTRODUCTION

When working, almost any mine that penetrates below the regional water table will require active dewatering to keep it dry. While working, water and air freely circulate throughout the mine, accelerating many of the geochemical reactions which would otherwise be limited by lack of access to oxygen in undisturbed ground. Many mineral deposits (including coal, oil shales and many metals) contain sulphide minerals, which tend to oxidise in a mining environment to release sulphate and dissolved metals. Some of these (e.g. pyrite) also release acid:

$$2FeS_2 + 7O_2 + 2H_2O \leftrightarrow 2Fe^{2+} + 4SO_4^{2-} + 4H^+$$

When a mine is abandoned (as many coal mines were in the UK in the 1980s and 1990s), the pumps may be switched off and the mine water gradually refills the mine, possibly overflowing at the surface as a contaminated mine water discharge (Banks et al. 1997a,b).

On further exposure to oxygen, the ferrous (Fe^{2+}) iron oxidises to ferric (Fe^{3+}), and hydrolyses, to precipitate as iron oxyhydroxide or “ochre”.

$$4FeS_2 + 15O_2 + 14H_2O \leftrightarrow 4Fe(OH)_3\downarrow + 16H^+ + 8SO_4^{2-}$$

Thus, coal mine water discharges in the UK are often characterised by an “apron” of ochre at the discharge point and ochre staining of river beds downstream of the discharge. The discharge may be treated to remove the dissolved iron (or manganese), either by active methods or by a range of passive methods (typically involving aeration, sedimentation and polishing wetlands - Banks & Banks 2001, PIRAMID 2003).

In some cases, the consequences of uncontrolled discharges of mine water are deemed unacceptable, and an agency (such as the UK’s Coal Authority) continues to dewater the mine complex by pumping, in order to prevent such outbreaks. The pumped water typically requires treatment. The management of minewater is often at a regional scale (Younger & Harbourne 1995), given that collieries in UK coalfields often interconnect over many tens of km (Burke & Younger 2000).

MINE WATER - A THERMAL RESOURCE

Thermogeologists and hydrogeologists are increasingly recognising that flooded mines represent a thermal resource. They contain enormous reserves of groundwater at or (in deep mines) somewhat above the annual average air temperature. Flooded mines thus have the potential to provide space heating (via heat pumps) in winter and space cooling in summer. The network of tunnels and shafts represents an enormous heat exchange interface with the rocks contained in the mined area. If a shaft or borehole penetrates a mine roadway, the water yields available can be very high. For example, if a heat pump extracts 5°C worth of heat from a stream of groundwater, the heat available is:

5°C x 4180 J/L/°C x 1 L/s = 20900 J/s or 20.9 kW, from 1 L/s of water.

If 100 L/s mine water are available, the amount of extractable heat is 2.1 MW.

Such mine water-based heating and cooling systems occur throughout the world, and reviews are provided by Banks et al. 2003, 2004; Watzlaf & Ackman 2006; Hall et al. 2011; Preene & Younger 2014; Ramos et al. 2015 and Bracke & Bussmann, 2015. In the UK, mine water heating schemes are operational or have been trialled at Shettleston, Glasgow; Lumphinnans, Fife (Banks et al. 2009); Markham, near Bolsover, Derbyshire (Athresh et al. 2015); Caphouse, near Wakefield, Yorkshire (Burnside et al. *in press*), Dawdon, Co. Durham (Watson 2012), Crynant, South Wales (Farr & Tucker 2015) and Florence Mine, Egremont, Cumbria.

BARRIERS TO CONCEPT

Despite the technology having been demonstrated at numerous sites worldwide, there are several key hurdles which act as obstacles to implementation of the mine water heating / cooling concept.

LACK OF LOCAL DEMAND

Heating and cooling are not readily transferable over large distances; thus, for the mine water heating and cooling concept to be viable, proven demands for heating and cooling need to exist in the immediate vicinity of the flooded mine (or, more specifically, of the access point to the mine water - shaft or borehole - JHI 2016).

In some cases, open mine shafts, providing access to warm mine water, may exist in an urban centre. A good example of this is Katowice, Poland, where open pumped mine shafts in the city centre yield warm mine water (Figure 1; Janson et al. 2009). In other cases, a colliery or mine site provides an ideal location for redevelopment as commercial and industrial space (or even housing developments), with its own heating and cooling demands. This scenario has occurred at several sites in the UK and elsewhere, but the potential of minewater to provide heating and cooling was not “sold” to the developer at an early enough stage, before conventional heating and cooling systems had been locked in (Figure 2).

Figure 1. Katowice mine shaft (with dewatering pumps) in an urban environment in Poland (photo by © David Banks).

Figure 2. Redevelopment of the Kleofas mine site, Katowice, Poland (photo by © David Banks).

In yet other cases, flooded mine workings underlie a development site with proven heating and cooling demands, but no open shafts exist. Thus, accessing the mine water demands a potentially costly drilling operation, maybe to encounter a 5 m diameter roadway at several hundred m depth. The expense and potential risk of such an operation can prove off-putting to investors.

NEED FOR INFRASTRUCTURAL INVESTMENT

For a large-scale mine water heating / cooling scheme, a significant infrastructural investment may be required before the thermal resource can be utilised by surrounding residents and businesses. A *centralised* heat pump plant room may be constructed, from which hot (for space heating) or cold (for air conditioning) fluids can be distributed to nearby users. Alternatively, the mine water (or a heat transfer fluid thermally coupled to the mine water) can be distributed to users via flow and return pipes, and individual users' heat pumps extract heat from or reject heat to this fluid flow (a *distributed system*). In either case, the cost of laying mine water or district heating and cooling pipes, especially in urban areas, can be a dominant capital cost in the total development. Additionally, where retrofitting heating to existing properties, it may be necessary to invest capital in installing the modern, low-temperature radiators / underfloor circuits that function efficiently with heat pumps.

LEGISLATION - WHAT TO DO WITH THE THERMALLY SPENT WATER?

Another set of obstacles is potentially legal: will an operator be granted an abstraction licence for the mine water? And how long will that licence last? For the size of capital investment in a large-scale mine water heating and cooling project, the investor must be sure that the legal right to abstract water can be guaranteed over at least several decades. And, if an operator extracts mine water from the ground, do they accrue liability for any contamination arising from that water, and how long might that liability last?

It is not enough to pump mine water from the ground and extract heat or "coolth" from it. One must also be able to dispose of the thermally "spent" mine water legally and cost-effectively. The mine water can be rejected to a surface water recipient. However, this will typically require that the water be treated to remove potential contaminants before discharge (another cost). Will temperature changes in the water affect the efficiency of water treatment? Alternatively, the mine water can be reinjected to the mine following usage, but this often incurs the cost of drilling and maintaining one or more injection boreholes. There is also the thermal risk that the cool, reinjected mine water will find its way back to the production well within the mine system (a phenomenon known as thermal feedback).

Of course, not all mines yield contaminated water. The water pumped through a heat pump of nominal 123 kW capacity at Florence ironstone (Fe_2O_3) mine, in Cumbria, UK, during a trial was of rather good quality and was able to be discharged directly to the local stream. Similarly, the water from Barredo colliery at Mieres, Asturias, Spain, is discharged after heat exchange, to the local river.

THERMAL FEEDBACK WITHIN THE MINE

Where thermally spent water (e.g. cool water from a space heating operation) is reinjected to the mine, there is a risk that it will find its way back to the abstraction well. Of course, the walls of the mine tunnels and shafts act as heat exchange surfaces, and the cool water reacquires heat from the surrounding rocks during its passage. If the flow pathway is too short or too direct, however, the cool water enters the production well before it has had a chance to reacquire its initial temperature, cooling the production water and lowering the efficiency of the heating operation.

Thus, a detailed mapping of subsurface pathways, coupled to a thermal modelling exercise, needs to be undertaken to prove the heat exchange capacity of the main flow pathways. The predominant models for this are the Lauwerier-Pruess-Bodvarsson model (Lauwerier 1955, Pruess & Bodvarsson 1983) and the Rodríguez-Díaz model (Rodríguez & Díaz 2009). Loredo et al. (*in preparation*) have reviewed these models and concluded that the Rodríguez-Díaz model, possibly with some minor modifications, is the preferred approach for quasi-circular tunnels. Authors such as Ferket et al. (2011) have taken this approach further by coupling such heat exchange algorithms to pipeline network models such as EPANET, to simulate heat flow and transfer within a network of mine passages.

Numerical modelling can, of course, also be brought to bear on this problem (Renz et al. 2009).

OCHRE CLOGGING AND HYDROGEOCHEMICAL RISKS

The perceived risk that iron or manganese oxyhydroxides may precipitate in pumps, pipes, heat exchangers or injection wells has also deterred several potential investors from mine water based heating / cooling schemes. This is, for most coal mine waters, a real risk - the waters typically have a circum-neutral or slightly acidic pH and concentrations of several mg/L or even tens of mg/L Fe, which will oxidise, hydrolyse and precipitate if allowed in contact with oxygen. Several studies lead us to conclude that, if iron is reduced (Fe^{2+}) and dissolved at the point of abstraction, and if contact with oxygen can be prevented during the abstraction-heat exchange-reinjection process, then iron can be kept in solution and ochre clogging will not occur in significant amounts.

The Dawdon mine water heat pump scheme (Watson 2012) in County Durham, UK initially passed mine water (pumped from Dawdon Colliery) through a heat pump system after it had been treated by aerobic methods. Significant clogging problems were experienced and the scheme was thus altered to pass the raw, untreated mine water (prior to access to oxygen) through the heat exchanger, which greatly reduced the clogging issues.

At Shettleston, Glasgow and Lumphinnans, near Cowdenbeath in Fife, Scotland, two modest heat pump schemes have been running off mine water from shallow flooded colliery workings since around 1999. There have been relatively few clogging problems in the heat pumps themselves - such issues as have arisen have been connected with the re-injection borehole, especially following vandalism at the Lumphinnans site, which resulted in the thermally spent water coming into contact with oxygen prior to reinjection and thus significant ochre clogging of the reinjection borehole (Banks et al. 2009).

Modelling also suggests that many mine waters have a significant partial pressure of CO_2, which can degas if it is exposed to the atmosphere. This brings about a rise in pH which promotes precipitation of metal oxyhydroxides and carbonates.

The message thus appears to be: keep the abstraction-heat exchange-reinjection circuit pressurised and sealed, without atmospheric contact.

The EU-funded LoCAL (Low Carbon AfterLife) project (see Acknowledgements) has tentatively found that some mine waters have already apparently been exposed to oxidising conditions in the subsurface, such that ferrous iron oxidation and hydrolysis have commenced prior to abstraction (e.g. Caphouse mine, Yorkshire). Thus, the water may already contain small particles of ochre which can cause clogging issues regardless of the recommended precautions suggested above. The LoCAL project plans to trial the use of environmentally benign reducing additives (sodium bisulphite and sodium dithionite) to assist in keeping iron in its dissolved, ferrous state, during heat exchange and/or reinjection.

LoCAL CASE STUDY SITES

The LoCAL project specifically seeks to overcome some of the barriers discussed in this paper. It is monitoring a range of case study sites in the UK, Poland and Spain, all of which have differing heat exchange configurations.

OPEN-LOOP SITES

An “open loop” system actively abstracts groundwater (or mine water) and passes it through a surface heat exchanger or heat pump, where heat is extracted from or rejected to the flow.

Caphouse: A Pilot-Scale Open Loop Scheme with Discharge to Surface Water

The National Coal Mining Museum of England at Caphouse, near Wakefield, Yorkshire, UK, hosts a pilot-scale scheme to heat an audio-visual display room by means of a Vaillant 10 kW heat pump. The heat pump can be coupled either (a) via shell-and-tube heat exchangers, to the flow of mine water pumped each night from the 197 m deep Hope Shaft (“open loop”), or (b) to a closed loop “Energy Blade” heat exchanger submerged in a mine water treatment pond (Burnside et al. *in press* - see below).

The Hope Shaft at Caphouse is pumped every night and early morning from a submersible pump at c. 170 m bgl to keep regional mine water levels low enough to prevent (a) regional break out of uncontrolled mine water discharges, and (b) the museum’s underground “show gallery” from being flooded. The pumped water is treated passively via a system of aeration cascade, settlement basins and polishing wetlands before being discharged to the local stream. The open loop option has been operated by passing a small fraction of the pumped flow through a shell and tube heat exchanger coupled to the heat pump. The museum staff have found, however, that this option requires quite a lot of routine maintenance to keep filters on the mine water line free from ochre clogging. It appears that the iron in the pumped water may have started to oxidise and form ochre prior to abstraction from the Hope Shaft. Hitherto, however, provided routine de-clogging of filters has been performed, the system runs satisfactorily.

Mieres: A Large Open Loop Scheme with Discharge to Surface Water

The Barredo colliery at Mieres, Asturias, Northern Spain (Loredo et al. 2011, Ordóñez et al. 2012, Jardón et al. 2013) is also an open loop scheme. The shaft is no longer actively mined but is pumped in order to control mine water levels in a regionally interconnected network of collieries. Mine water, of rather good quality and temperature c. 23°C, is pumped from the 362 m deep Barredo shaft. A system of heat pumps and heat exchangers delivers several MW of heating and cooling effect to nearby University and Hospital buildings before the thermally spent water is discharged to the local river.

Shettleston: A Modest Open Loop Scheme with Reinjection Borehole

The mine water scheme at Shettleston has also volunteered to take part in the LoCAL project, being based on a c. 100 m deep borehole to coal workings beneath eastern Glasgow. The abstracted mine water is pumped directly through the evaporators of two Danfoss BW10-025 heat pumps, which provide heating to 16 social housing apartments. The water is thereafter directed to a reinjection borehole to a shallower depth (Banks et al. 2009). This arrangement is termed “open loop with reinjection”.

STANDING COLUMN SYSTEM - MARKHAM NO. 3 SHAFT

Markham No. 3 is a c. 490 m deep, 4.6 m diameter colliery shaft near Bolsover, Derbyshire, UK. It was closed in 1993-94 and mine water levels are still rising in the interconnected mine water complex associated with it.

The site is owned by the LoCAL Partner, Alkane Ltd. In around 2012, Alkane installed a submersible pump at 235 m bgl. Some 2 L/s of rather saline mine water was pumped from this depth, and passed through a shell-and-tube heat exchanger, thermally coupled to a Danfoss DHP-R 20 kW heat pump (Athresh et al. 2015). The cooler, thermally spent water was then returned to the same (No. 3 shaft) at

250 m bgl (15 m deeper than the pump). This is termed a “standing column” arrangement. Hitherto, no major problems with ochre precipitation in the heat exchanger, nor with thermal feedback of cool water, have been observed. This is ascribed to the highly reducing, methane-rich nature of the water keeping the iron dissolved, and to the large volume of water in the shaft section relative to the very modest heat extraction and pumped water circulation.

In January 2015, the pump was raised to 170 m bgl, and the reinjection diffuser repositioned at 153 m bgl (17 m *above* the pump). This was possible due to the mine water levels having recovered (risen) regionally. Under this new standing column regime, it was found that the pumped water was much fresher, indicating that the water in the shaft is hydrochemically stratified. The system continues to be monitored to ascertain if the new water chemistry will have any adverse effect on the clogging potential.

CLOSED LOOP SYSTEM - CAPHOUSE

Finally, at the Caphouse site described above, an “Energy Blade” (a radiator-like steel heat exchanger) has been submerged in the uppermost minewater treatment pond (aeration pond No. 1) and connected, via a closed loop of propylene glycol heat transfer fluid, to the heat pump. This has operated very successfully and the museum staff find it much more user-friendly and lower-maintenance than the “open loop” option (see above). This is because no mine water is actively pumped through the heat pump in the closed loop option, negating any clogging issues inside pipes and heat exchangers. Also, the treatment pond is full 24 hrs per day, allowing the heat pump to run whenever there is a demand. As noted above, mine water is only pumped through the aeration pond at night time and early morning. Thermal response testing has demonstrated that, while the closed loop system performs adequately without the need for mine water throughflow, its performance is enhanced when mine water is actively flowing through the aeration pond past the heat exchanger.

ACKNOWLEDGEMENT

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ZOOMING IN WITH GROUNDWATER 3D: FOCUSED GSI INVESTIGATIONS IN PRIORITY AREAS

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ABSTRACT

Groundwater 3D ("GW3D") is a multi-annual groundwater mapping project funded by the Department of Communications, Energy and Natural Resources (DCENR). By means of data collection, mapping and, ultimately, 3D modelling, "GW3D" aims to address stakeholder needs and data gaps; improve national maps and conceptual models; and provide more localised information on groundwater systems in priority areas. The following themes are being pursued: Karst; Sand and Gravel; Fractured Aquifers and Hydrochemistry. Since commencing in 2015, key achievements include:

Advances in the mapping and understanding of important karst terrains that provide large groundwater water supplies in counties Cork and Roscommon; and, of the extent and geometry of known and previously unknown sand and gravel bodies and aquifers in counties Donegal, Mayo, Sligo and Roscommon;

A national groundwater hydrochemical (geo)database has been prepared, enabling the roll-out of a national hydrochemical map series – a groundwater hardness map being the first to be published;

A new geospatial database was constructed allowing assessment of the variability and pattern of critical groundwater pathways across the various rock types. An associated on-line story map has been set up to enable visual communication, education and contribution amongst geoscientists; and,

Software applications were developed for field data acquisition, ensuring consistent data collection that can be readily incorporated into GSI's digital databases, and a new groundwater viewer that also includes a mobile phone version has been launched and integrated into an updated GSI singular data viewer.

This paper aims to introduce "GW3D" and summarise outputs from its first year.

INTRODUCTION

Groundwater is a significant natural resource that currently supplies an estimated 30% of public drinking water in Ireland[1] and nearly all private domestic supplies. It also provides significant contributions to wetlands and rivers, with an especially important role of maintaining flows through dry periods. Groundwater in Ireland is protected under European Community and national legislation. The responsibility for enforcing the legislation resides with the Local Authorities and the Environmental Protection Agency (EPA). The GSI completed a national Groundwater Protection Scheme, including the component layers (aquifer, intrinsic groundwater vulnerability, subsoil permeability) in 2014 to assist in WFD implementation and the regulatory functions of local authorities.

Building on this seminal work the GSI seeks to improve and provide higher resolution information. This is required for several reasons[2]. Firstly, data gaps identified during the GSI's national mapping process[3] and newly available data and techniques/research need to be addressed and utilised, respectively. Secondly, specific stakeholder needs in terms of better resource management, for instance, with regard to greater geoscientific understanding of groundwater sourced public and group water scheme drinking water supplies. Thirdly, the second planning cycle of the WFD places a greater emphasis on implementing appropriate measures to achieve water quality improvement. In order to do this, specific localised characterisation is required. Fourthly, GSI has an agency-wide imperative to develop 3D models of the subsurface environment for resource management in a number of different sectors. The GSI commenced a new project to provide higher resolution mapping, improve conceptual models and provide relevant information on groundwater systems in priority areas, which will ultimately improve the national maps. This project is called Groundwater 3D ("GW3D"): a multi-annual priority groundwater mapping project funded by the Department of Communications, Energy and Natural Resources (DCENR).

THEMES

The Groundwater Programme has identified the following themes to further develop within "GW3D": Karst, Sand and Gravel; Fractured Aquifers and Hydrochemistry.

KARST

Many public, group water scheme and private supplies are dependent on groundwater from expanses of karst terrain with a wide ranging degree of karstification. Consequently, an understanding of flow patterns and (potential contaminant) pathways is important.

SAND and GRAVEL

The current national sand and gravel maps vary in the level of information provided as they originate from different mapping strategies. GSI's sand and gravel aquifers are based on a combination of GSI Groundwater records and mapping, GSI Quaternary mapping, and Teagasc subsoils mapping. The degree of confidence around the sand and gravel aquifers varies with a heavy reliance on surface extents from the original Teagasc mapping and its inherent methodology. Further characterisation is considered to be important as sand and gravel deposits can constitute an important resource and pathway. With the ultimate aim of national coverage, "GW3D" focused in northwest Ireland in 2015.

FRACTURED AQUIFERS

Insights from the EPA STRIVE and Griffith programmes on pathways in poorly productive aquifers have advanced the conceptual models in these rock units. Given the large proportion of the country that is underlain by these aquifers there is a need to continue and further this work. Within the "GW3D" project this includes developing a better understanding of a) the 'transition zone' (the broken, weathered zone between the subsoil and bedrock; and b) the groundwater throughput in poorly productive aquifers, which will help to develop the GSI's groundwater recharge map.

HYDROCHEMISTRY AND NATURAL GROUNDWATER QUALITY

An understanding of hydrochemistry at various scales is required to improve the understanding of behavioural characteristics in groundwater. A hydrochemistry database will be used to produce a series of national groundwater chemistry maps as well as undertake investigations into bedrock derived denitrification and other processes.

KARST INVESTIGATIONS

During the first year, "GW3D" focused on North Cork[4] and Roscommon's Rathcroghan Uplands, due to specific issues with drinking water supplies and significant uncertainties with the existing conceptual models, especially in the North Cork region, which has already undergone significant hydrogeological investigation[5, 6], and to actively link with current research being conducted by Trinity College Dublin[7] into 3D modelling of karst terrains (SISKA, TCD[7]) which was showcased at the IAH

2015 Conference[8]. The aim of this on-going project is to determine its applicability to model and assist in groundwater resource management of Irish karst groundwater systems.

HYDROGEOLOGICAL MAPPING IN NORTH CORK

The study area is in the Upper Blackwater river catchment, specifically, the fluvio-karst terrain cut by the Awbeg and Funshion river systems (Figure 1). The work included an extensive well survey across an area of approximately 100 km^2; bedrock drilling; logging and surveying key bedrock outcrops; karst feature mapping; river surveys; high resolution spring monitoring of temperature and electrical conductivity; and water sampling for rare earth elements.

Outputs include interpreted groundwater contours and an updated geology map that distinguishes the undifferentiated Visean, tying together the stratigraphy on either side (Figure 1, Figure 2)[9]. As anticipated, a regional north-south groundwater flow component was confirmed. However, complicated groundwater flow patterns and a large east-west trending fault coupled with significant deformation have been identified. The localised groundwater deviations evident from the water level surveys may be related to impure limestones. Preliminary results from the water sampling suggest that the springs are sourced solely from the adjacent pure limestones. This work corroborates current source protection zones[6].

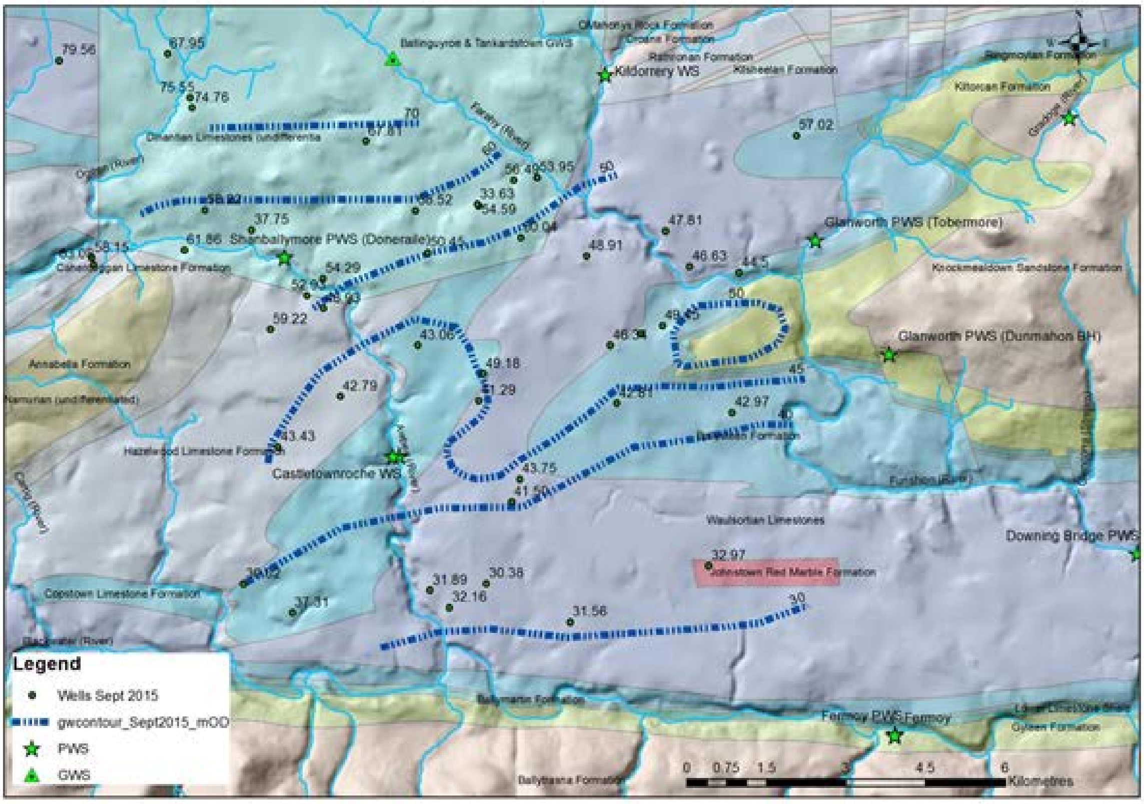

Figure 1: Groundwater contours in North Cork

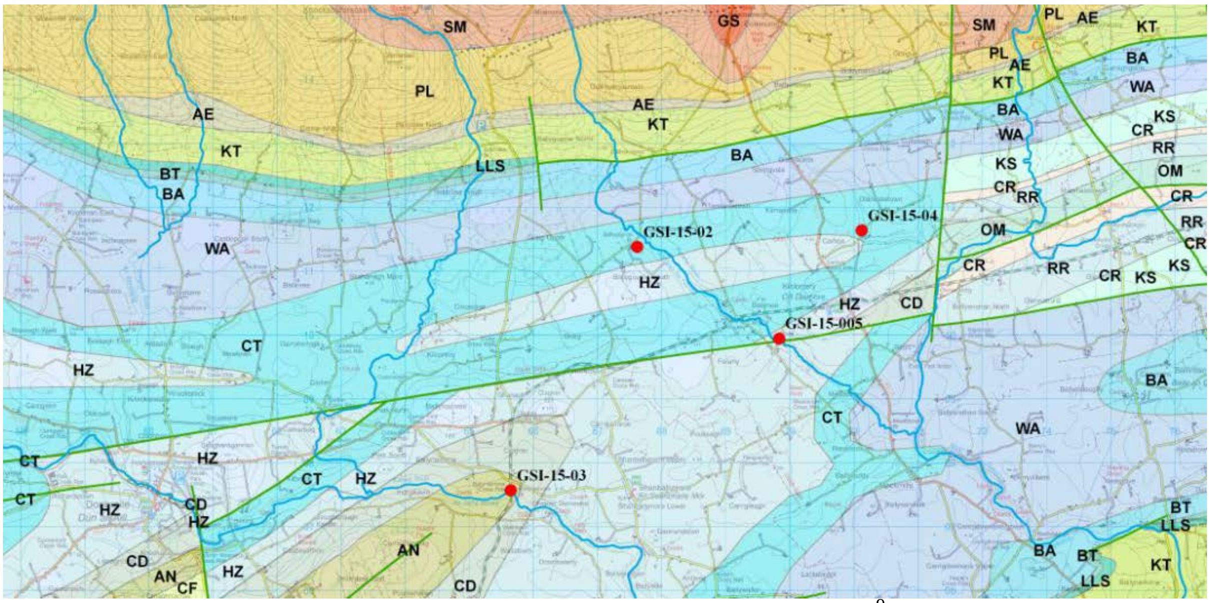

Figure 2: Bedrock Geology map in North Cork[9]

DYE TRACING IN ROSCOMMON

In regions like the Rathcroghan Uplands, Roscommon, karst feature mapping and dye tracing has been successful and play fundamental roles in defining Zones of Contribution (ZOCs). The Rathcroghan Uplands is a region with several large group and public water supply schemes, some of which have been persistently contaminated and occasionally grossly polluted, e.g. Mid-Roscommon Ogulla Spring 2014[10].

Tracers were inserted into nine swallow holes and approximately 40 sites were monitored. Seven traces were positive; proving underground connections to springs, and, indicating patterns coincident with the main structural trends. This improved understanding of the groundwater flow is enabling the refinement of currently defined ZOCs[10,11,12,13]. Figure 3 shows the positive traces from the 2015 work.

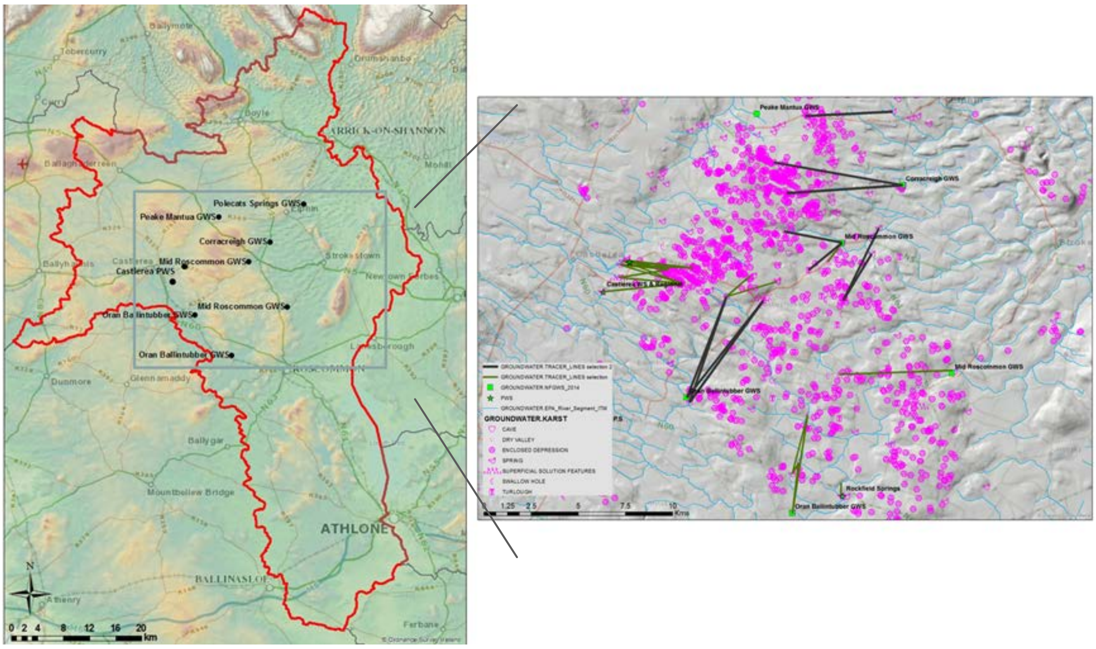

Figure 3: Tracing in Rathcroghan Uplands, Roscommon with black lines representing “GW3D” traces

SAND AND GRAVEL INVESTIGATIONS

The sand and gravel mapping element of "GW3D" focussed on field based geological surveys across Donegal, Mayo, Leitrim, Sligo and Roscommon and included hydrogeological mapping, logging of exposures and well surveys. By utilising the GSI's databases in advance, the objectives of the field mapping were constrained and priority areas were marked for investigation, which maximised the most from the fieldwork period.

Two software applications (apps) based on the Cybertracker platform were developed for data collection during fieldwork. These were called the 'Sand & Gravel App' and the 'Well App'. The applications were designed to allow immediate geo-referenced digital input of data.

The data collected at each sand and gravel exposure included: location; height/thickness; width; clast lithology; evidence of sedimentary structure; evidence of water/dampness; material classification to BS5930; geotagged photograph of the exposed material; depth to water level where possible. This data was integrated and interrogated with other data to conceptualise in 3D each deposit. An outline of the process is shown in Figure 4.

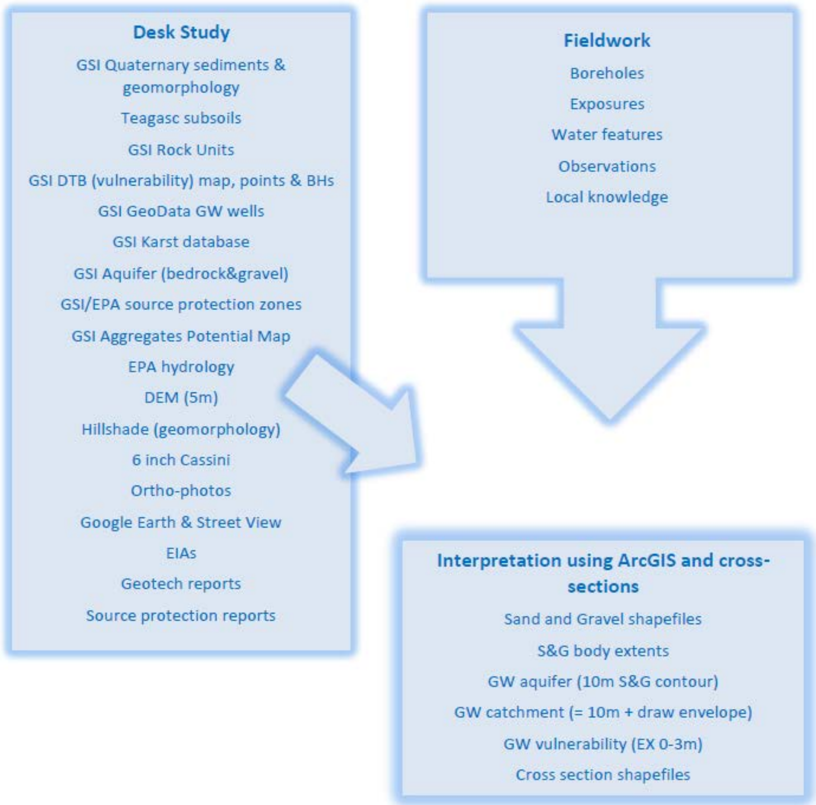

Figure 4: Interpretation Process of Data

The investigations have resulted[14] in updated definition of existing sand and gravel deposits, previously unknown sand and gravel deposits, some of which are classified as potential aquifers. Almost 800 exposures in the northwest region were logged and photographed. Almost 200 well locations and water levels were recorded. Figure 5 indicates in numerical terms the achievements under "GW3D". Importantly, the confidence in extents and geometry is expressed, which will be used to promote areas/deposits that may be selected for further investigation.

One technique which has proved to be very useful is the facility within ARCGIS to draw cross sections. This tool has enabled a rapid assessment of the 3D geometry, which has been particularly useful to define and project the water table in the sand and gravel aquifer. This is enabling maps of 'extreme' groundwater vulnerability (less than 3 m to the water table in sand and gravel aquifers) to be produced.

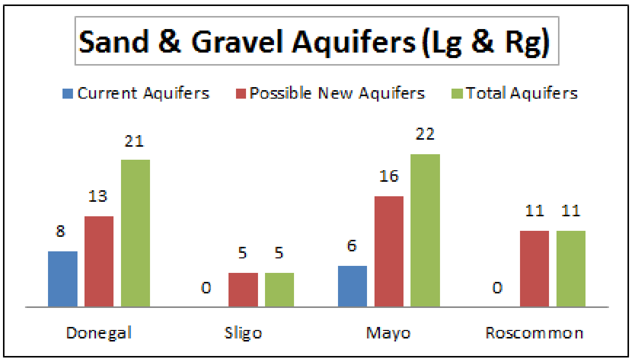

Figure 5: Sand & Gravel Aquifer Updates after “GW3D” 2015 mapping

FRACTURED AQUIFERS INVESTIGATIONS (GROUNDWATER FLOW PATHWAYS)

The groundwater flow investigations centred on an assessment of the groundwater throughput capacities of the poorly productive aquifers. The work carried out builds on the concept of maximum recharge capacities for Irish Poorly Productive Aquifers and the “recharge caps” which are applied in the estimation of groundwater recharge for the National Recharge Map[15, 16].

Based on the collective evidence from a suite of different methods, it is suggested that 200 and 300 mm/a may be representative of national annual average deep and shallow groundwater throughput capacities in Irish poorly productive bedrock aquifers. As this is a national annual average value, the deep and shallow groundwater throughput capacity of any single Irish poorly productive bedrock aquifer may vary significantly. Given the uncertainties further work is required to:

- Improve the estimates of aquifer and groundwater flow system properties;
- Improve the characterisation of other pathways; and
- Use the improved information to better model groundwater and surface water flow.

The Transition Zone has been identified as important for groundwater flow in these types of aquifer. The “GW3D” project has initiated a geodatabase and an online story board using relevant, georeferenced photographs either held in the GSI from the various mapping programmes or submitted by external sources. It is anticipated that the story board will focus future field mapping and will enable further assessment of the variability and geospatial patterns across the various rock types.

Transition Zone photographs collated to date have been set in an ESRI GIS story map on-line. This has been published to illustrate the Transition Zone in different geological settings (http://j.mp/groundwaterstorymap) (Figure 6).

HYDROCHEMICAL GEODATABASE AND MAP SERIES

”GW3D” initially focussed on national data collection, data collation, building of a hydrochemical database, preliminary data analysis and interpretation. The analysis was conducted in-house using hydrogeological techniques and methods and standard MS Office and ESRI GIS software. The database is being collated from a range of disparate sources, with the aim of producing a comprehensive hydrochemical database and associated Map Series. A preliminary groundwater total hardness map is the first in a series of national groundwater chemistry maps that will be produced (Figure 7).

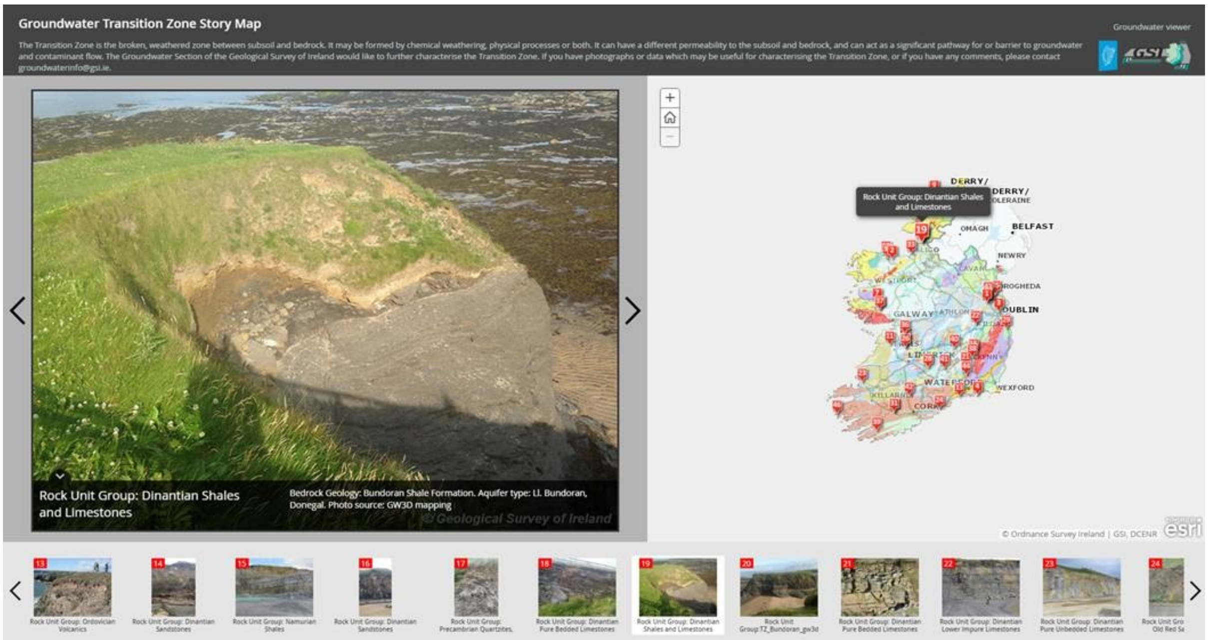

Figure 6: Transition Zone Story Map

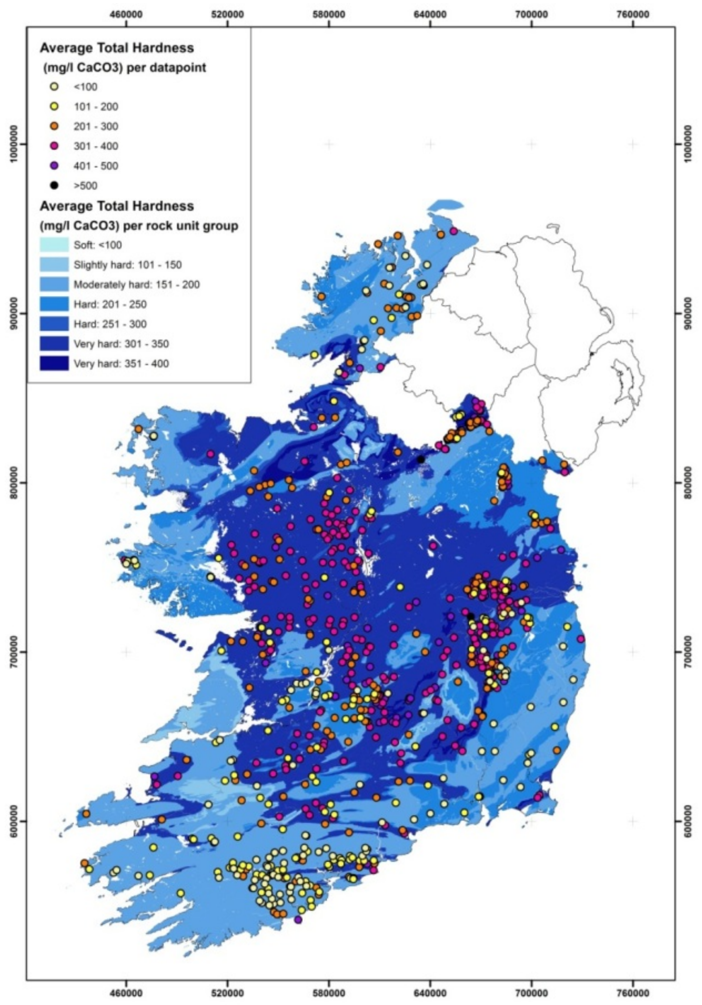

Figure 7: Preliminary National Groundwater Total Hardness map

CONCLUDING REMARKS

"GW3D" is a groundwater mapping project aimed at addressing stakeholder needs and data gaps; improving national maps and conceptual models; and providing more localised information on groundwater systems in priority areas. The early achievements include:

- A greater understanding of the geological and groundwater characteristics that supply groundwater drinking water supplies in Roscommon and in North Cork.
- Greater geoscientific definition of existing sand and gravel aquifers and 'new' sand and gravel aquifers across the northwest of the country.
- A national groundwater hydrochemical (geo)database has been prepared, enabling the preparation of a national hydrochemical maps series.
- A geodatabase has been built that allows an assessment of the variability and pattern of critical groundwater pathways across the various rock types. To support this, an on-line story map has been set up to enable visual communication and education with geoscientists.

Future work will extend to other karst terrains; continue to geocharacterise sand and gravel deposits across the country; improve the estimates of aquifer and groundwater flow system properties; continue to better understand the transition zone; continue to populate the hydrochemical database and produce national hydrochemical maps, e.g. iron, and seek to better understand denitrification in relevant areas.

Such renewed, localised focus to improve national maps resonates and echoes the Groundwater Section's local (Roscommon) and catchment (R.Nore) programmes undertaken in the 1970s and 1980s, reflecting that the Groundwater Section objectives have come full circle over the last 40 years, since the IAH (Irish Group) was founded. Indeed, C.R Caldwell's lecture notes[17] from the opening meeting of the Irish branch refer to karst, "fissures in the weathered zone" and the need for "accurate mapping of" sands and gravel deposits.

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SESSION VII

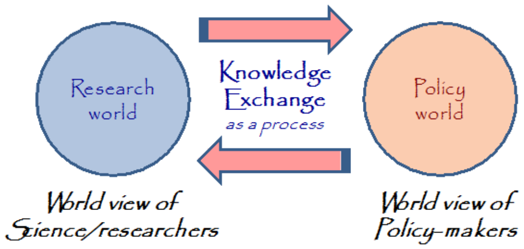
GETTING THE BUGGERS TO LISTEN – SOME OBSERVATIONS OF THE TRIALS, TRIBULATIONS AND SUCCESSES IN DELIVERING (AND USING) RELEVANT SCIENTIFIC RESEARCH

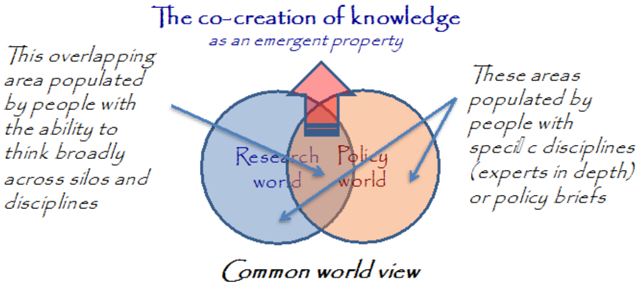
Bob Harris
University of Sheffield

Why won't people listen to your great ideas, or your fantastic research findings? Maybe they can't understand you because you don't make sense to someone who doesn't have your language, or relates to your issues. Or maybe they don't need to understand; what you're saying is actually irrelevant, a lower priority than you think it is, or not important to them given their priorities… which are different from yours. Or perhaps they don't want to understand. They could understand you… if they wanted to. But you're giving them inconvenient information.

A common perception is that there's not enough time to understand through dialogue and learning. Policy makers would like the evidence (that they want) to be wired directly into their brains. They like years of research condensed to a half page of soundbite messages. And your information is just one input amongst many. But pity the poor policy maker. We live and work in complex systems, no longer able to hide in our own compartments. They have to acknowledge all interests and consequences.

One problem is that (academic) research seldom delivers immediate impacts on policy/management practices. The pathway from research project to impact is often long and convoluted. Usually a cumulative body of knowledge is necessary. Policy-makers like multiple lines of evidence improving the certainty of the evidence they are acting on. However, the timescale to take-up of knowledge can be much shorter for tools, applications etc for practical use, which usually involve the ultimate users and some demonstration of the science. Confucius said "tell me and I will forget, involve me and I will understand".

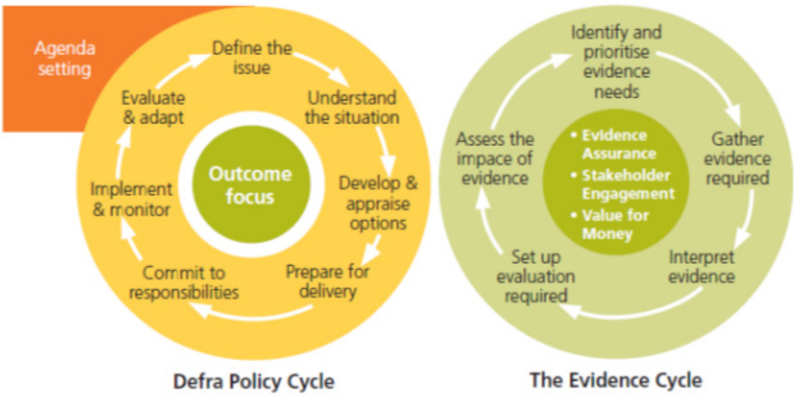




There is a need to develop common worldviews, a common conceptual understanding about the subject in hand in order for good communication to take place. The ultimate goal is the co-creation of knowledge where the researcher and the policy-maker (or the end-user) are partners.

Windows of opportunity are vital, but they need to be actively sought out rather than trusting to serendipity. For example, researchers wishing to influence policy need to understand policy-cycles and how they rotate - often in 5 yearly sequences, but sometimes in 5 weeks. Conversely policy-makers should be aware of the research funding cycles that academics relate to and are often driven by.

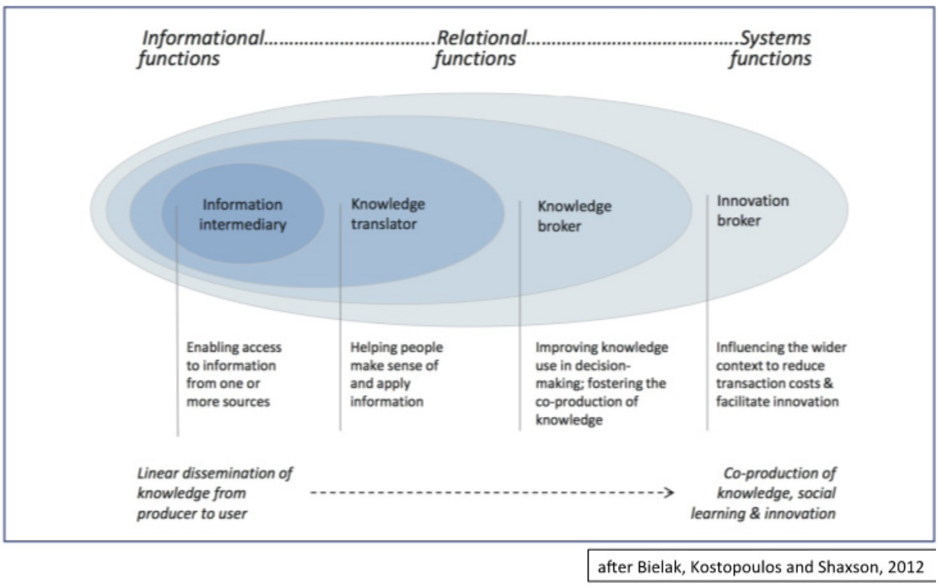
Cycles rotate in 5-years or (sometimes) in 5 weeks!



Governments access evidence in three broad areas that operate in different timescales and allow differing windows of opportunity for different sorts of evidence:

- Understanding the context - there are on-going scientific evidence requirements to understand the context and changing pressures to policy development.
- Agenda setting - which takes place episodically. There are only certain times when science can influence this agenda.
- Separate legislative strands/Individual policy drivers and the levers for delivery: scientific evidence is required in the build up to deadlines. There are critical but very discrete windows of opportunity.

Knowledge transfer/exchange is a more complex process than we think



Translating research to users (and users needs to research) needs different sorts of intermediaries with differing skill sets to ensure (research/learning) activities are translated into outcomes.

The talk will be illustrated with some personal examples of both success and failure in getting the buggers to listen.

"IT MAY BE EXCRETA TO YOU, BUT IT'S MY BREAD AND BUTTER"– RESEARCH INTO ONSITE WASTEWATER TREATMENT

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ABSTRACT

Field research into the performance of on-site wastewater treatment has been carried out by the Environmental Engineering Group in Trinity College Dublin across different parts of Ireland over the past 15 years. This research has particularly focused on the transport and attenuation of contaminants in the on-site wastewater effluent as it percolates through the vadose zone beneath percolation areas to the underlying groundwater. Much of this research has been funded by the Environmental Protection Agency and it has been used to inform that national legislation such as the Code of Practice: Wastewater Treatment and Disposal Systems Serving Single Houses. A summary of the main findings from the series of studies is presented.

INTRODUCTION

The domestic wastewater of one third of the population in Ireland (~500 000 dwellings) is treated on-site by domestic wastewater treatment systems (DWTS) of which more than 87% are septic tanks (CSO, 2011). Approximately 162,000 of these households also depend on private water sources, mainly wells, for their water supply. Sampling studies of these wells for the presence of faecal indicator bacteria have shown that approximately 30% are polluted, at least intermittently, with one of the main sources of microbial pathogens believed to be DWTS. If situated and constructed incorrectly the potential impacts of such on-site effluent treatment systems include the pollution of either groundwater and/or surface water. In particular, areas with (i) inadequate percolation due to low-permeability subsoils and/or (ii) insufficient attenuation due to high water tables and shallow subsoils present the greatest challenge in Ireland for dealing with effluent from DWTS. If there is insufficient permeability in the subsoil to take the effluent load, ponding and breakout of untreated or partially treated effluent at the surface may occur with associated serious health risks. There will also be a risk of effluent discharge/runoff of pollutants to surface waters and to wells which lack proper headworks or sanitary grout seals (Hynds et al., 2012). Alternatively, if the permeability of the subsoil is excessive, the effluent loading on the subsoil is too high, or there is an insufficient depth of unsaturated subsoil (e.g. high water table or shallow bedrock), then the groundwater beneath a percolation area is at risk of pollution, in particular from microbiological pathogens and/or nutrients.

Field research into the performance of on-site wastewater treatment has been carried out by the Environmental Engineering Group in Trinity College Dublin across different parts of Ireland over the past 15 years. Much of this research has been funded by the Environmental Protection Agency and it has been used to inform that national legislation such as the Code of Practice (EPA, 2009). A summary of the main findings from the different research studies are thus presented.

PERCOLATION AREAS

Field study based research focused on the transport and attenuation of contaminants in the on-site wastewater effluent as it percolates through the vadose zone beneath percolation areas to the underlying groundwater (Gill et al., 2007; 2009a). The performance of six separate percolation areas in different subsoils was intensively monitored with respect to the on-site wastewater effluent discharge of both septic tank effluent (STE) and secondary treated effluent (SE) from packaged treatment plants, as detailed in Table 1. The percolation areas were constructed according to best practice at the time (EPA Guidelines) and instrumented to capture soil moisture samples across the area and at different depths from which the three-dimensional performance of the percolation areas with respect to pollutants transport and attenuation was determined.

Table 1. Summary of site characteristics

	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
Effluent type	STE	STE	STE	SE	SE	SE
No. residents	6	4	4	3	5	4
T-value	3.7	15	33	4.5	29	52
Subsoil classification	sandy, SILT	sandy CLAY	gravelly, clayey SAND	sandy GRAVEL	sandy CLAY - sandy SILT	gravelly, clayey SAND
Field sat. hyd. cond. - k_{fs}, m/d	1.05	0.28	0.13	0.84	0.15	0.08

The results showed that the development of a biomat across the percolation areas receiving SE was restricted on these sites compared to those sites receiving STE. This created significant differences in terms of the potential nitrogen loading to groundwater (Fig. 1a). The average nitrogen loading per capita at 1.0 m depth of unsaturated subsoil equated to 3.9g total-N/d for the sites receiving SE, compared to 2.1 g total-N/d for the sites receiving STE. Relatively high nitrogen loading was, however, found on the septic tank sites discharging effluent into highly permeable subsoil on Site 1 that counteracted any significant denitrification. Phosphorus removal was generally very good on all of the sites although a clear relationship to the soil mineralogy was determined

The higher areal hydraulic loading on the percolation areas receiving SE also created significant differences in the potential microbiological loading to groundwater. Greatest *E. coli* removal in the subsoil occurred within the first 0.35 m of unsaturated subsoil for all effluent types. Analysis showed, however, that more evidence of faecal contamination occurred at depth in the subsoils receiving SE than that receiving STE, despite the lower bacterial influent load (O'Luanaigh et al., 2012). Bacteriophages (MS2, ΦX174 and PR772) which were spiked into the effluent to mimic viral transport, were all reduced to their minimum detection limit (<10 PFU/mL) at a depth of 0.95 m below the percolation trenches receiving STE (Fig. 1b), although isolated incidences of ΦX174 and PR772 were measured below one trench. However again, slightly higher breakthroughs of MS2 and PR772 contamination were detected at the same depth under the trenches receiving secondary treated effluent.

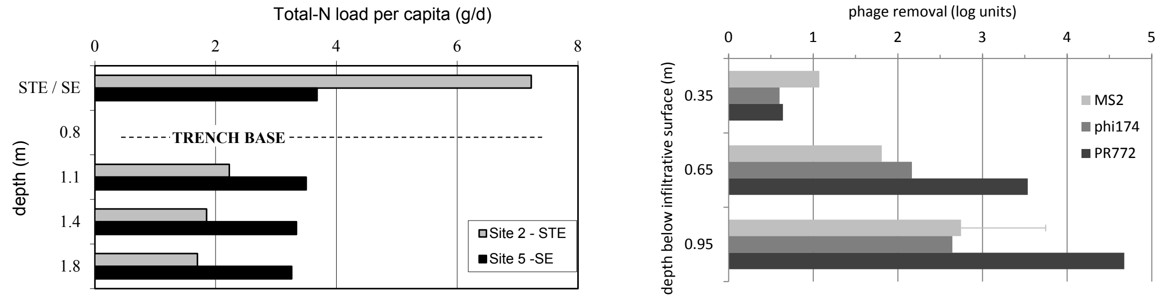

Fig. 1. (a) Total N-loading per capita with depth (Site 2 compared to Site 5) and (b) phage log-unit removal (Site 1) with depth beneath the infiltrative surface.

Some analysis was also carried out on the fate of selected Endocrine Disrupting Compounds (EDCs). The results showed the oestrogens (oestrone, oestrdiaol, ethynyloestradiol and oestriol) percolating though the unsaturated subsoil were significantly degraded with depth down to very low values (<1 ng/L), with the exception of oestriol in the secondary treated effluent plume which seemed to be more persistent. The organic oxygen compound, bisphenol A, was not significantly reduced in the aerobic secondary treatment processes although some degradation was evident with depth through the subsoil in all trenches. The study also investigated the fate of caffeine as a potential indicator of on-site effluent which showed considerable removal in the aerobic subsoil conditions beneath all the trenches (Gill et al., 2009b; O'Súilleabháin et al., 2009)

The field trials also found that gravity flow distribution devices currently available were not able distribute the effluent effectively across percolation areas under real wastewater loading conditions from single houses. The on-site results suggested that the uneven deposition and biofilm growth were responsible for erratic distribution and therefore the long-term performance and sustainability of such devices is questionable for such a function where regular maintenance is rarely carried out by house owners (Patel et al., 2008). A new low-head gravity distribution device was therefore designed during the project which proved to operate effectively under such low intermittent flow rates of varying effluent quality.

TREATMENT SYSTEMS CONSTRUCTED ON SITE

In parallel to the studies on percolation areas, field research was also carried out on secondary and tertiary treatment systems constructed on site (sand filters and reed beds). Respective STE and SE were pumped into intermittently dosed, stratified sand filters with samples taken at different depths within and beneath the sand filters (Gill et al., 2009c). The attenuation performance of the sand filters was tested at various hydraulic loading rates. Although the sand filters require a much smaller surface area, the respective pollutants on each site were attenuated to the same level in the subsoil when compared to the percolation trenches. As a result of the trials, the recommendations for design hydraulic loading rates in Ireland were 30 L/m^2 day for filters receiving septic tank effluent and 60 L/m^2 day for filters receiving secondary treated effluent.

Horizontal subsurface flow reed beds were also constructed and rigorously monitored over several years. Nitrogen removal was found to be poor across reed beds receiving both STE and SE (O'Luanaigh et al., 2010), with only 29% removal of TN across the secondary treatment bed and 41% removal across the tertiary treatment bed, with little distinctive seasonal change. A ^{15}N stable isotope tracer study revealed, in line with the results from the chemical analysis, that nitrogen kinetics in the secondary treatment bed were dominated by continuous plant litter decomposition and mineralisation processes converting stored org-N to NH_4-N indefinitely. Similar analysis on the tertiary treatment bed indicated that only limited denitrification of the oxidized forms of N was occurring in the anoxic environment of the bed, while NH_4-N and org-N were merely changing form on a cyclic basis. Removal of PO_4-P from the secondary and tertiary treatment beds was equally poor at rates of 45% and 22%, respectively. The total phosphorus in the stems and roots of the macrophytes in the reed beds equated to less than 10% of the total P removed over the duration of the bed's operation. Total coliforms and *E.coli* analysis showed similar mean removal rates (~1.6 log) across both beds with an exponential decrease in removal measured with bed length (Gill et al., 2009d). Recovery of bacteriophages ΦX174 and MS2 in both the secondary and tertiary treatment reed beds was shown to be high, as anticipated, indicating their potential suitability as viral indicators in wetland systems and highlighting the poor capacity of reed beds to successfully remove viruses. Finally analysis carried out on the fate of the same selected EDCs discussed earlier in relation to unsaturated subsoil revealed, in contrast, little or no degradation of oestrogens, Bisphenol A or caffeine under the saturated anaerobic conditions in the reed beds (Gill et al., 2009b).

SOLUTIONS FOR LOW PERMEABILITY SUBSOILS

Traditional on-site wastewater treatment systems have proven to be unsuitable in areas of low permeability subsoils, representing a risk to human health and the environment. With large areas of Ireland being covered by low permeability tills, alternative treatment and disposal options need to be investigated to be able to allow further development in these areas and to deal with polluting legacy sites. Hence, a research project was carried out which assessed the performance of existing soakaway systems in a range of different soil permeability settings and then evaluated a range of potential solutions for the treatment and discharge of on-site domestic wastewater into low- permeability soils by field research, desk studies and geospatial modelling (Gill et al., 2015).

Two sites located on low permeability soil with existing poorly performing soakaways were upgraded with alternative pressure-dosed distribution (low pressure pipe (LPP) and drip dispersal (DD)) systems (see Fig. 2) which could be fed with either STE or SE. Extensive soil moisture instrumentation was installed across the percolation areas in order to determine the three-dimensional transport and attenuation of the pollutants. The LPP and DD systems both resulted in a decrease in faecal contamination of groundwater as well as the prevention of surface ponding of effluent at both sites. Furthermore, the field results and calibrated models of the unsaturated zone concluded that DD systems could be used in subsoils with T-values up to T<120 using secondary treated effluent (but not STE) and designed at an areal loading rate of 2.8 l/m^2d with the required depth of unsaturated subsoil should be a minimum of 600 mm. For LPP systems the conclusion was that septic tank (with effluent filter) effluent can be used up to T<75 and then secondary treated effluent be used for soils up to T<90, based on a trench loading rate of 18 l/m^2d but requiring 900 mm of unsaturated subsoil.

Fig. 2. (a) Installation of DD tubing, and (b) LPP system.

A series of field trials were also carried out on evapotranspiration (ET) systems using willow trees with the aim of creating a zero discharge solution for areas of low permeability soils. Continuous monitoring of rainfall, reference evapotranspiration, effluent flows and water level in 13 full-scale sealed systems revealed varying evapotranspiration rates across the different seasons (Fig. 3a). However, the continuous monitoring of water levels showed that such systems are unlikely to be able to act as totally zero discharge systems in the Irish climate if the in-situ low permeability subsoil is used as a backfill. No system managed to achieve zero discharge in any year remaining at maximum levels for much of the winter months, indicating some loss of water by lateral exfiltration at the surface. The systems were, however, shown to promote excellent pollutant attenuation and significantly reduce net effluent discharge to the environment and so should be considered as a viable passive treatment for either existing (legacy) and/or new developments (Curneen & Gill, 2015). It should be noted that this would require a change in current consent procedures to allow for such a controlled discharge to surface water.

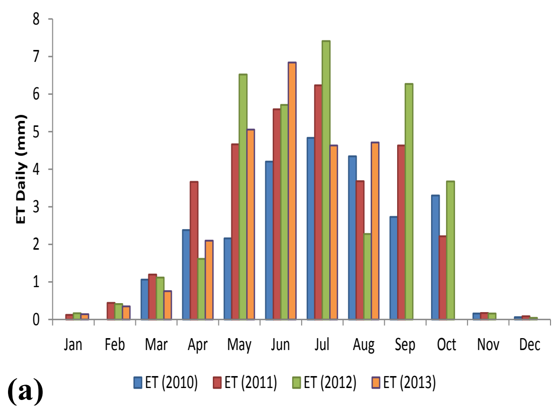

Fig. 3. (a) Monthly ET rates for ET system and (b) photo of initial growth of willows.

Alongside the field trials, a geographic information system (GIS)-based decision support toolset was also developed to evaluate possible alternative strategies / solutions to the discharge of on-site effluent in low permeability areas using geospatial modelling (Dubber & Gill, 2014; Dubber et al., 2014). Six potential solutions have been considered: (i) connection to a nearby existing sewer network, (ii) clustering of houses with decentralised wastewater treatment and surface water discharge, (iii) discharge onto bedrock through imported media filter, (iv) LPP system, (v) DD system, and (vi) ET system. Through a series of interconnected GIS geoprocesses the model outputs appropriate solutions for a site, ranking them in terms of environmental sustainability and cost. However, the final decisions are still dependent on on-site constraints so that each solution is accompanied by an alert message that provides additional information for the user to refine the output list according to the available local site-specific information. This tool, which could be used for strategic assessment at a Local Authority level, has shown that the concept of clustered decentralised systems could target a significant proportion of potentially poor sites in low permeability areas and could lower the burden of monitoring associated with discharge consents. Furthermore, analyses indicate that they can be economically favourable compared to single house systems. Hence, this option should be investigated and developed further from a technical, social, economic and legal (e.g. ownership, liability etc.) perspective.

IMPACT OF CLUSTERED DEVELOPMENT ON GROUNDWATER

The net impact on groundwater quality from high density clusters of unsewered housing across a range of hydro(geo)logical settings has been assessed (Morrissey et al., 2015). Four separate cluster development sites were selected, each representative of different aquifer vulnerability categories. Groundwater samples were collected on a monthly basis over a two year period for chemical and microbiological analysis from nested multi-horizon sampling boreholes upstream and downstream of the study sites. The field results showed no statistically significant difference between upstream and downstream water quality at any of the study areas, although there were higher breakthroughs in contaminants in the High and Extreme vulnerability sites linked to high intensity rainfall events; these however, could not be directly attributed to on-site effluent. Linked numerical models were then built for each site using HYDRUS 2D to simulate the attenuation of contaminants through the unsaturated zone from which the resulting hydraulic and contaminant fluxes at the water table were used as inputs into MODFLOW MT3D models to simulate the groundwater flows. The results of the simulations confirmed the field observations at each site, indicating that the existing clustered on-site wastewater discharges would only cause limited and very localised impacts on groundwater quality, with contaminant loads being quickly dispersed and diluted downstream due to the relatively high groundwater flow rates (Fig. 4). Further simulations were then carried out using the calibrated models to assess the impact of increasing cluster densities revealing little impact at any of the study locations up to a density of 6 units/ha with the exception of the Extreme vulnerability site.

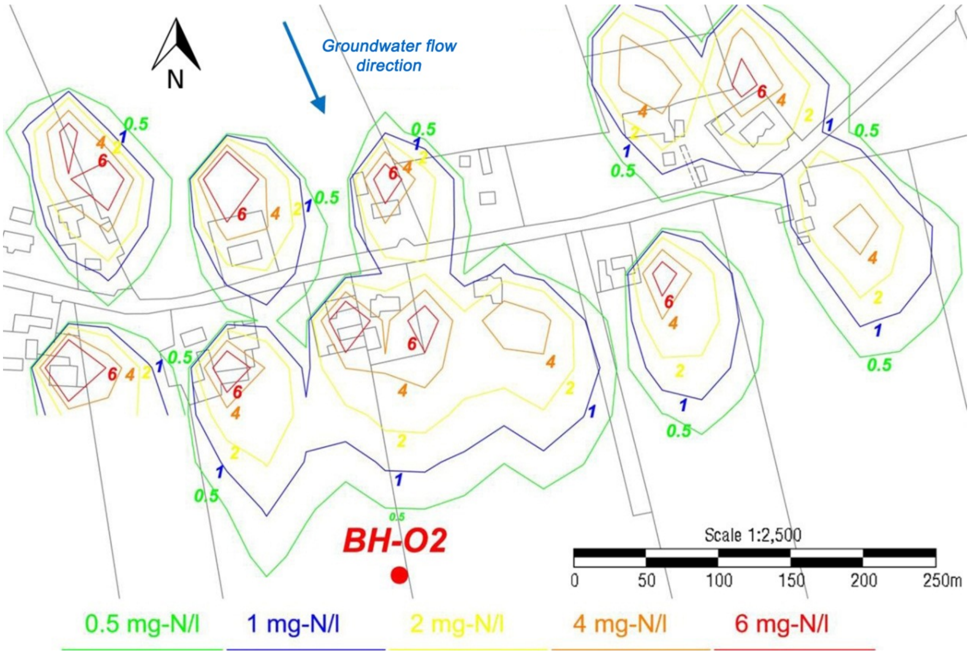

Fig. 4. Steady state nitrate plume from the cluster development at the *Moderate* vulnerability site.

IMPACT ON PRIVATE WELLS AND AS NUTRIENT SOURCES IN CATCHMENTS

An ongoing study is aiming to evaluate DWTS effluent as a source of nutrient pollution to surface water in small catchments as well as its impact as a health hazard to consumers of groundwater from private wells. Four small study catchments (<5 km^2) in areas of low permeability with high DWTS densities are being monitored, sampling surface water quality upstream and downstream of the DWTS locations during different hydrologic conditions. The main aim is to detect and quantify changes in phosphorus levels which may be attributable to DWTS from natural background and diffuse agricultural signals. Results to date have shown phosphorus loads at the downstream monitoring points are significantly greater than those upstream, although it is too early in the project to determine what proportion of this is due to the presence of DWTS compared to the concurrent nutrient impact from agricultural practices in the catchments. In parallel to the catchment based studies, a total of 212 households dependent on private wells and DWTS have been evaluated by site assessments and sampling of chemical and microbial parameters. A total of 15% of the wells were at least intermittently contaminated with *E. coli*. Subsequent monthly monitoring of 24 wells found 45% to be contaminated with *E. coli* at least once.

Methods that can distinguish between contamination sources will significantly increase water management efficiency as they will allow for the development and application of targeted remediation measures. Hence, this research project in both groundwater and surface water is also being used to assess a range of chemical, biochemical and microbiological fingerprinting techniques for on-site effluent, as indicators for human faecal contamination in rural Irish catchments. Compounds being investigated include human specific faecal sterols, fluorescent whitening compounds, anion ratios, artificial sweeteners, caffeine and pharmaceuticals. In addition, faecal source tracking is being carried out by molecular methods targeting host-specific *Bacteroidales* bacteria during these trials and has showed promise. For example, tests of 42 wells water samples targeting *Bacteroidales* 16S rRNA genes found 62% were positive for human specific *Bacteroidales* (BacHum).

MODELLING

The data from the extensive field studies into the fate and transport of water-borne pollutants through the vadose zone into groundwater has been used to develop mathematical models to gain further insight into the processes, as referred to previously. This has taken the form of detailed fine resolution models of pollutant transport through the variably saturated zone, through to more averaged lumped models of the impact of DWTS at a catchment scale.

VADOSE ZONE

The HYDRUS 2D/3D finite element-based software has been used to simulate the percolation of on-site effluent beneath percolation areas. The model is able to simulate variably saturated transient water content and volumetric flux using a numerical solution to the Richards equation. In addition to calculating soil moisture throughout the model space (Fig. 5), nutrient and microbial transport can also be implemented using convection–dispersion equations as well as additional equations to simulate chain reactions, adsorption, attachment–detachment processes etc. Hence, the field studies have been used to develop and calibrate models, which have then been used to make predictions as to how the processes might change under different conditions by varying parameters such as soil permeability, percolation area architecture, hydraulic loadings etc.

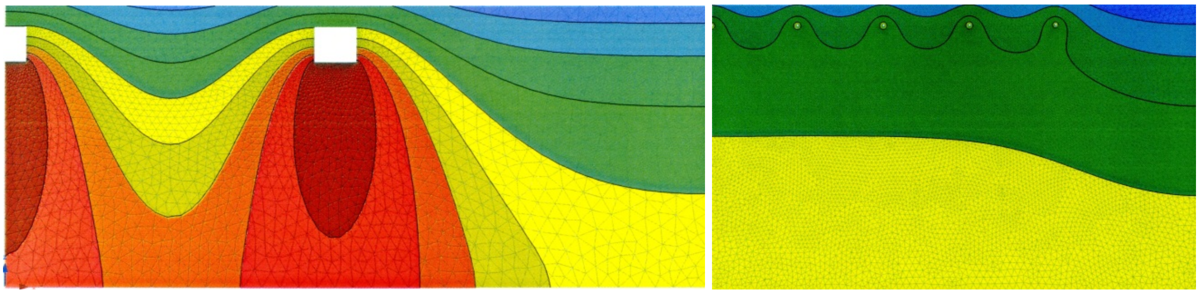

Fig. 5. Hydrus 2D soil moisture simulations through (a) LPP distribution (c) DD (summer).

CATCHMENT

A mass balance based model has been developed to determine annual nutrient loading from individual DWTS at a catchment scale into rivers in Ireland. The transport and attenuation of nitrogen and phosphorus in DWTS effluent to groundwater and surface water has been formulated using the results from the field research (as discussed previously), as well as being informed by other international studies. This work has developed a conceptual model in order to produce ranges of suitable attenuation factors which have then been converted into nitrogen and phosphorus loads to both groundwater and direct to surface water that would be expected from a generic DWTS in different hydro(geo)logical environments. Conceptually the model splits the transport of nutrients to the river into three pathways (Fig. 6.): direct to surface water (for areas of inadequate percolation), a near surface (subsoil) pathway, and a groundwater pathway. This Source Apportionment of Nutrients in Irish Catchments for On-Site Effluent (SANICOSE) model provides annual contaminant nutrient loads from DWTS linked to available GIS data which is currently being integrated into the EPA's Source Load Apportionment Model (SLAM) that is being developed as a tool for catchment nutrient characterisation in response to the requirements of the European Union's Water Framework Directive. This SLAM model will be used to help to identify high risk areas (from a nutrient pollutant perspective) from which a targeted programme of measures can be more strategically developed.

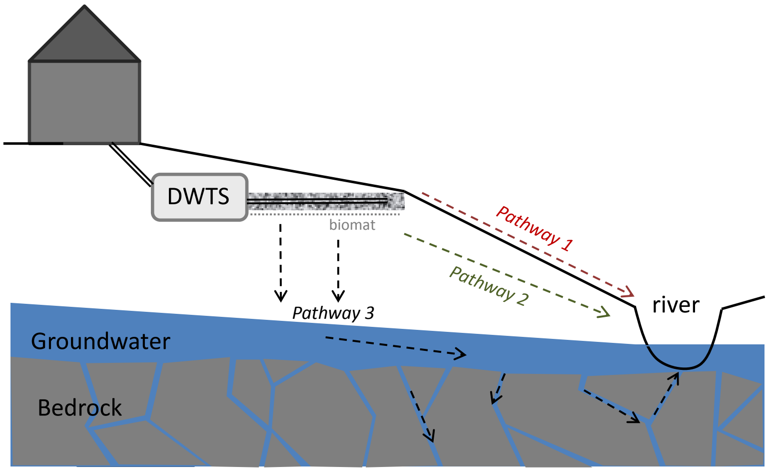

Fig. 6. Schematic cross-section showing the three conceptual pathways for DWTS contaminants on which the SANICOSE model is based.

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GROUNDWATER RESEARCH IN COASTAL CATCHMENTS: NEW RESULTS, NEW CHALLENGES

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NOTES

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