INTERNATIONAL ASSOCIATION OF HYDROGEOLOGISTS – Irish Group

Groundwater and Catchment Management

Proceedings of the 33rd Annual Groundwater Conference
Tullamore, Co. Offaly, Ireland

23rd and 24th April 2013

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/current/events.htm*
IAH Membership (new or renewal):	*http://www.iah.org/join_iah.asp*
	http://www.iah.org/payonline

2013 Conference Objective

As with previous years, the 2013 IAH (Irish Group) Groundwater Conference can be expected to benefit hydrogeologists, engineers, local authorities, consultants, planners, environmental scientists, public health officials, professionals and practitioners from a variety of sectors involved with groundwater.

2013 is the 33rd Anniversary of the Annual IAH (Irish Group) Groundwater Conference. This year's theme is entitled '*Groundwater and Catchment Management*'. The two-day event is being held at the Tullamore Court Hotel and combines an impressive array of national and international speakers with exhibits, poster presentations, fine dining and social evening. In general the Conference will be broken down into three main areas.

1. The Catchment Approach
2. Catchment Science
3. Catchment Management

IAH (Irish Group) President David Drew will initiate proceedings with an introduction and welcome address. David will chair the opening session on 'Catchment Management' and will begin by introducing the keynote speaker – Bob Harris, from DEFRA and University of Sheffield who will discuss the catchment based approach. Our keynote speaker intends to unpick what goes in to a catchment approach and how it can be used to help attain policy objectives. We will hear from different speakers how this wholesome strategy is being applied in Ireland and abroad, and how it is being continually developed. Donal Daly of the Environmental Protection Agency follows with a presentation on a healthy catchment initiative for Ireland. Delegates are encouraged to engage with the various panels of speakers within regular fifteen minute question and answer sessions. After a coffee break, Steve Buss from ESI will present the application of a catchment approach for a private water company which will be followed by Mark Whiteman of the Environment Agency who will give a technical presentation of the groundwater modelling tools used in catchment management.

Before lunch, postgraduate students who have agreed to present posters at the conference will be invited to summarise their ongoing research in the field of hydrogeology.

After lunch, we will commence Session 2: Catchment Science. We will delve a little deeper and learn about the scientific work underpinning the catchment approach in both Ireland and the UK. Session 2 opens with Per-Erik Mellander of Teagasc explaining the Teagasc agricultural catchments programme. This will be followed by Melinda Lewis of the British Geological Survey who will discuss the complexities involved in the development of groundwater conceptual models for UK test catchments.

Jenny Deakin of Trinity College Dublin and Tiernan Henry of the National University of Ireland Galway will bring their expertise of catchment management in Ireland to the final session on Day 1. Jenny and Tiernan will present two seperate case studies, the Nuenna catchment and Kinvarra catchment, respectively. At the end of a hard day, weary delegates will be treated to an evening of whisky tasting as part of a tour at the redeveloped Tullamore Dew Distillery.

Session 3, titled 'Catchment Management', commences on Day 2 and will address the more practical application and delivery of the catchment approach. This session opens with presentations from Eva Mockler (University College Dublin) followed by Phil Jordan (University of Ulster) and Lærke Thorling (Geological Survey of Denmark and Greenland). Each of these presenters will discuss an aspect of catchment management including the development of a catchment management tool by Eva Mockler, development and implementation of programme of measures in Ireland by Phil Jordan and a presentation on trend reversal of nitrate concentrations in Danish groundwater by Lærke Thorling.

The final session on Day 2 continues with the topic of Catchment Management with Anne Goggin (Limerick County Council) discussing a Local Authority Approach in Ireland, Tim Besien of the Environment Agency discussing monitoring catchment measures in the UK and finishing up with Bernie O'Flaherty (Monaghan County Council) presenting another Irish local authority approach to water quality and source protection. Local authorities will discuss how they are applying catchment approaches to protect groundwater drinking water supplies, and to gain a better understanding of surface water - ground water interactions. Prior to lunch on Day 2 a final Q&A session will be followed by a closing address by the IAH (Irish Group) Conference Secretary, Colin O'Reilly.

For the first year, the IAH (Irish Group) has arranged that the conference will be followed by a technical workshop. It is hoped that this will take place in an informal and interactive environment where delegates can learn about some lesser-practiced or newly developed field techniques, the pros and cons, and add their own experiences to the mix. Alec Rolston of Dundalk IT will describe the perils of attempting to install shallow piezometers in a wetland environment and Janka Nitsche (Queen's University Belfast) will talk about the application of various downhole methods in boreholes to identify hydraulically active intervals.

2013 IAH (Irish Group) Committee:

President:	David Drew
Secretary:	Jenny Deakin, Trinity College Dublin
Burdon Secretary:	Morgan Burke, Stream BioEnergy
Treasurer:	Catherine Buckley, ARUP
Northern Region Secretary:	Paul Wilson, GSNI
Fieldtrip Secretary:	Caoimhe Hickey, Geological Survey of Ireland
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Conference Secretary:	Colin O'Reilly, Envirologic

2013 Conference sub-committee:

Eleanor Burke, Malone O'Regan;
John Dillon, Tobin Consulting Engineers;
Cecilia Gately;
Katie Tedd, Environmental Protection Agency.

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

The IAH would like to sincerely thank ARUP for their help with the Conference administration.

Sources of photographic imagery on the proceedings cover courtesy of Jenny Deakin (TCD).

The proceedings for the 33rd Annual Groundwater Conference 2013 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 33rd Conference:

David Drew

envirologic

epa
Environmental Protection Agency
An Ghníomhaireacht um Chaomhnú Comhshaoil

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Geological Survey of Ireland
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Department of Enterprise, Trade and Investment
Geological Survey of Northern Ireland

MOR
MALONE O'REGAN

‘Groundwater and Catchment Management’
33rd Annual Groundwater Conference

International Association of Hydrogeologists – Irish Group
Tullamore Court Hotel, Tullamore, Co. Offaly: Tues 23rd & Wed 24th April, 2013

Programme Day 1, Tuesday 23rd April

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

INTRODUCTION

09:30 – 09:40	Welcome and Introduction David Drew – *President IAH Irish Group*
SESSION 1:	**THE CATCHMENT APPROACH**
09:40 – 10:25	Keynote speaker: Bob Harris (Defra and University of Sheffield) ‘The Catchment Based Approach’
10:25 – 10:55	‘A healthy catchment initiative for Ireland – making integrated catchment management happen’ – Donal Daly (Environmental Protection Agency)
10:55 – 11:10	Discussion, Q&A (15 mins)
11:10 – 11:35	*Tea and coffee*
11:35 – 12:00	‘Is catchment management feasible for improving quality of public groundwater supplies?’ – Stephen Buss (ESI Ltd.)
12:00 – 12:25	‘Groundwater modelling tools used in catchment management.’ – Mark Whiteman (Environment Agency)
12:25 – 12:40	Discussion, Q&A (15 mins)
12:40 – 12:55	Student Poster Presentations
12:55 – 14:10	*Buffet lunch in Tullamore Court Hotel*
SESSION 2:	**CATCHMENT SCIENCE**
14:10 – 14:35	‘Phosphorus attenuation potential along the nutrient transfer continuum in a karst spring zone of contribution’ – Per-Erik Mellander (Teagasc)
14:35 – 15:00	‘Developing groundwater conceptual models for the UK demonstration test catchments’ – Melinda Lewis (British Geological Survey)
15:00 – 15:15	Discussion, Q&A (15 mins)
15:15 – 15:45	*Tea and coffee*
15:45 – 16:10	‘Hydrogeological pathways in two contrasting catchments – implications for management’ – Jenny Deakin (Trinity College Dublin)
16:10 – 16:35	“…and then it goes to the sea”: The ecological approach to understanding coastal catchments – Tiernan Henry (National University of Ireland Galway)
16:35 – 16:50	Discussion, Q&A (15 mins)

18:30 *The final panel discussion on Day 1 will be followed by a social event, including refreshments, at the Tullamore Dew Distillery, sponsored by IAH (Irish Group).*

‘Groundwater: Recent Developments in Discharge & Dewatering’
33rd Annual Groundwater Conference

International Association of Hydrogeologists – Irish Group
Tullamore Court Hotel, Tullamore, Co. Offaly: Tues 23rd & Wed 24th April, 2013

Programme Day 2, Wednesday 24th April

9:00 – 9:30	*Tea, Coffee & Exhibits*
SESSION 3:	**CATCHMENT MANAGEMENT**
9:30 – 9:55	‘Pathways Catchment Management Tool – investigating critical source areas with hydro(geo)logical knowledge’ – Eva Mockler (University College Dublin)
9:55 – 10:20	‘Programme of Measures’ – Phil Jordan (University of Ulster)
10:20 – 10:45	‘Trend reversal of nitrate concentrations in groundwater’ – Lærke Thorling (Geological Survey of Denmark and Greenland)
10:45 – 11:00	Discussion, Q&A (15 mins)
11:00 – 11:30	*Tea & Coffee*
11:30 – 11:55	‘Catchment Management – A Local Authority Approach’ – Anne Goggin (Limerick County Council)
11:55 – 12:20	‘Groundwater Safeguard Zones in England’ – Tim Besien (Environment Agency)
12:20 – 12:45	‘Water Quality and Source Protection – A Local Authority Approach’ – Bernie O’Flaherty (Monaghan County Council)
12:45 – 13:00	Discussion, Q&A (15 mins)
13:00	Conference closing address: Colin O’Reilly (*Conference Secretary* – IAH Irish Group)
13:05	*Buffet lunch in Tullamore Court Hotel*

TECHNICAL WORKSHOP

14:10	‘Simplified approach to wetland monitoring’ – Alec Rolston (Dundalk Institute of Technology)
14:50	‘Locating hydraulically active intervals using downhole methods in low permeability aquifers’ – Janka Nitsche (Queen’s University Belfast).
15:30	End of Workshop

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TECHNICAL WORKSHOP:

KEYNOTE SPEAKER

THE CATCHMENT BASED APPROACH

Bob Harris
Defra and University of Sheffield

ABSTRACT

The development of the second round of river basin plans will use a different approach in England than previously. Top-down uniformity has been superseded by a more participative and collaborative approach whereby local communities will have more of a say in setting priorities and delivering solutions. At the heart of this is the Catchment Based Approach, and the establishment of Catchment Management Fora to act as intermediaries between national policy and overarching objective setting and the local communities setting priorities and co-ordinating action. The role of national agencies becomes more of a supporting and facilitating one. The new approach is still being developed and draws on a trial period where 25 'Pilot Catchments' developed catchment plans during 2012. The paper describes the background and rationale behind the approach and discusses both the benefits that can be gained from successful implementation and some of challenges yet to be overcome.

BACKGROUND

Managing water resources in catchments is not new. The concept of describing the area within which rainfall is captured and then managing it in terms of both quantity and quality dates back to early civilisations. But as society has become more urbanised and technologically dependent we have slowly lost touch with the ecosystem goods and services that we gain from our environment. Few people could say where the water from their tap comes from… and few care. Catchment management is an approach to managing both land and water resources that first developed in those places where specific resources were being pressurised and the solutions to solve one ecosystem service were found to compromise another. One such example is the Goulburn-Broken catchment in the Murray-Darling basin of Australia, where the complex relationship between deforestation, agricultural land use, rainfall and irrigation has led, from a productive landscape to a series of farming crises due to a rising water table flushing salt in groundwater to the surface. A realisation of the connectedness of land and water systems led to a series of community-led approaches and groups, such as "Landcare". These were established to have a broader perspective than single focus community groups and in due course the state government devolved responsibility for catchment management to regional communities in the form of Catchment Management Authorities (CMAs) (Walker and Salt, 2006). Other countries have developed similar bottom-up approaches in preference to the more top-down traditional approaches that have tended to prevail in places where resources are not under such immediate and sustained pressure or where environmental matters are organised and managed at relatively high levels of governance. However, now we are waking up to the challenges of protecting and restoring our aquatic environments, prompted largely by the EU Water Framework Directive (WFD), some countries are beginning to consider alternative approaches, and catchment management offers a promising way forward.

CATCHMENTS AND CATCHMENT MANAGEMENT DEFINED

What do we mean by a catchment? A catchment (or, in American terminology, a watershed) is the area drained by a river, stream or other body of water. The boundaries of a given catchment area are defined by the topography separating it from neighboring drainage systems. So, although we use the concept for managing water, catchments relate to an area of **land**. Some understanding of the complex linkages between land and water and how we impact upon both is at the heart of catchment management. The way we manage the land has consequences for the water that drains from and through it so that the quality and quantity of water in the streams, river, lakes and groundwater of a catchment reflect the pressures of the surrounding land use.

Catchments can technically be any size. Large river basins, such as the Danube and Rhine, are catchments, but we tend to use the term for rivers that are much smaller. Even first order streams have catchment areas. Because we need to relate protection of and improvements to the quality of water and its associated ecology to the management of the land, it is important to relate the physical characteristics of a catchment to sociological ones. People have a sense of place, of belonging. In hilly areas this may be as geographically small as a single valley, while in other places the cohesiveness of the community could be spread across a larger area. Sometimes the natural and social systems are linked – through geology and topography for example. It is important to recognise the scales at which people and communities operate since, whatever the overall objective of, say, achieving good ecological status at a downstream point in a river system, in a catchment management approach the solutions will depend upon these local communities taking action.

Integrated Catchment Management is therefore a **process** that recognises the catchment as the appropriate organising unit for understanding and managing ecosystem processes in a context that includes social, economic and political considerations, and guides communities towards an agreed vision of sustainable land and water resource management for their catchment[1].

The above definition comes from a catchment in New Zealand, which has been exploring such approaches for many years. The RELU project[2] *"Developing a Catchment Management Template For the Protection of Water Resources: Exploiting Experience from the UK, Eastern USA and Nearby Europe"* looked at some other examples across the world and distilled out several principles for a catchment management approach which should be:

- Catchment based
- Holistic
- Informed
- Twin-tracked (understand through investigation but take action as soon as you can)
- Adaptive
- Co-ordinated
- Locally led
- Trusted
- Legitimate

THE ENGLISH EVOLUTION

River basin management has evolved in England and Wales through three distinct, but overlapping, phases that relate to the social, political and economic imperatives of the time (Woods 2006):

- Sanitation provision phase – 1850s to 1950s
- Pollution control phase – 1950s to 1990s
- Sustainable development phase – 1990s to present

In the primary phase the focus was on clean and safe water supply through a better understanding of the linkage between contaminated water and infection. The health of the population was the driver for better sewerage while the rivers and their associated ecology deteriorated. By 1960 many reaches of rivers draining industrial areas were effectively dead. The pollution control phase shifted the focus somewhat to improving river water quality through the control of polluting discharges and, although River Boards were formed in 1951 followed by a smaller number of River Authorities in 1961 based

[1] Definition from the Motueka River catchment, New Zealand - http://icm.landcareresearch.co.nz
[2] www.watergov.org

on catchment areas, the emphasis remained on pollution source reduction and end-of-pipe treatment. Legislative and governance evolution continued with the creation of ten Regional Water Authorities (RWAs) in 1974 based on river basins or a collection of smaller catchment areas and heralded the first comprehensive catchment based approach to water management. Fifteen years later the recognition that the combination of poacher and gamekeeper and the need to prioritise investment between water supply, sewerage services and the protection of other ecosystem services (recreation, navigation, fisheries, biodiversity etc) led to the separation of the regulatory and non-profit making functions of the RWAs from the operational ones and the creation of the National Rivers Authority (NRA) and private water utility companies in 1989.

This development effectively ended further development of catchment management approaches as the private companies concentrated their focus on infrastructure and their immediate customers. The creation of the NRA did allow the principles of river basin regulation to continue but its life was short-lived and it was subsumed into the new Environment Agency (EA) in 1996. For the next sixteen years there was a slow but clear retreat from holistic environmental management through an integrated approach, to a more compartmentalised concentration on better regulation of industry at the point of release/discharge. Point sources from industry and sewage works were the main target for control and improvement with the emphasis on uniformity and consistency of the regulatory approach. This led to a strong top-down control and uniformity by and within the regulatory body that did not take much allowance for the local environmental circumstances. By 2005 point sources were considered to have been largely brought under control. Rivers were reported to be cleaner and indicators, like the repopulation of lowland England by otters, were heralded as positive signs that ecosystems were improving, but there was an underlying perception, amongst the environmental NGOs particularly, that the health of our rivers was not as it should be and government was relying too much on the wrong indicators of ecological health.

The WFD had appeared on the horizon in the 1990s in various draft forms and would demand a different way forward that was more integrated and participatory, requiring collaboration and co-operation. However, for a long time it was considered to be yet another European directive to be complied with at least cost and was not recognised as the force for change that it is turning out to be. The initial risk assessments carried out as part of the characterisation exercise confirmed that diffuse pollution, particularly from agricultural land, was now the biggest threat to not achieving the goals demanded by the WFD. The warning signs had been there for some time for those who wished to look and listen, such as the continuing decline in groundwater quality from nutrients, but controlling agricultural diffuse pollution had been seen as being in the ‘too difficult’ box while there were still piped discharges to control. No-one really had the answers to controlling diffuse sources from agriculture, particularly since there was a continuing push to produce more home-grown food.

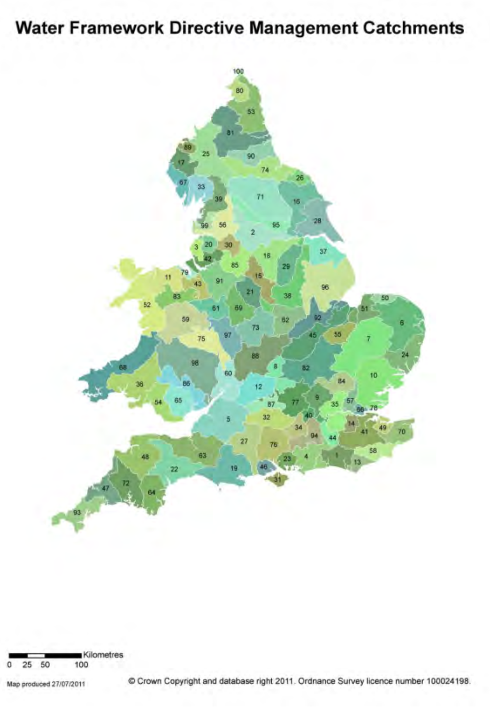
THE WATER FRAMEWORK DIRECTIVE AND THE CATCHMENT BASED APPROACH

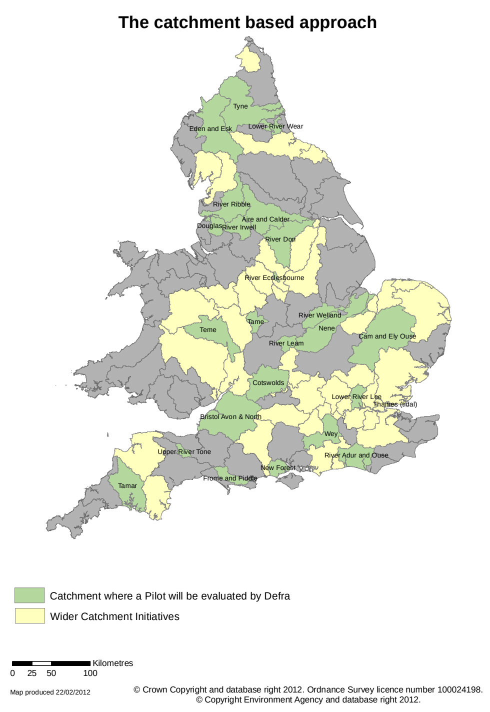
In England the first round of river basin plans (RBPs) published by the EA was heavily criticised by stakeholders for being too heavily ‘top-down’ with minimal participation from, and recognition of, local people and community groups in identifying issues and setting priorities. It was seen to be more about complying with the process of implementation than a genuine desire to secure some real improvements to water quality. NGOs, such as the emerging Rivers Trusts movement who, realising that to improve the water environment for fish and aquatic ecology in general you had to address land management, had been working on the ground with stakeholder and community-led groups for some time and were dismayed at the top-down uniformity of approach displayed in the RBPs. The concerns were such that in March 2010 the Worldwide Fund for Nature (WWF) together with the Angling Trust applied for a judicial review of the implementation of the WFD and the river basin planning process. This action was closely followed by a change in government and the consequent opportunity for the development of fresh thinking and new policy. So on 22 March 2011 Richard Benyon, junior Environment Minister at Defra announced a new approach stating: “…*there is a clear appetite for a more integrated, holistic and Big Society approach to managing our water environment. A catchment* *management based approach to implementing the WFD will focus on delivering multiple environmental benefits and bring together all the relevant players to decide on what these should be and how we attain them. It is certainly not just about meeting EU objectives. It is about trying to enhance the local environment for people, businesses and for wildlife."*

The catchment based approach was one of a number of space based initiatives that Defra introduced via a Natural Environment White Paper that was produced in 2011 followed closely by a Water White Paper. These include Nature Improvement Areas and Local Nature Partnerships. Although these have been initiated to tackle specific environmental pressures, what they have in common is the engagement of the local community to raise awareness of and the value placed on the natural environment.

The EA were first asked to look at how they might adopt a more participatory approach to RBPs through developing catchment plans in ten catchments with more locally based stakeholders than were currently sitting on River Basin Liaison Panels. This was quickly followed with a 12-month trial period to December 2012, whereby any organisation was invited to apply to lead on producing a catchment plan for their particular catchment by this date. The aim of the pilots was to develop a clear understanding of the issues in each catchment, to develop ways of involving local communities in decision-making by sharing evidence and, to work out priorities for integrated action that addressed local issues cost effectively.

Over 60 expressions of interest of hosting a 'Pilot Catchment' were received and 15 chosen to complement the 10 led by the EA. The catchments ranged in size and character and included urban catchments as well as those that are predominantly rural. The outcomes of this exercise are currently (March 2013) being evaluated.





WHAT NEXT?

Defra plan to roll out the Catchment Based Approach across the rest of England[3] with an announcement in the spring of 2013. At the core of the approach is the need to support river basin management planning – both for identifying measures and delivering them on the ground – in order to achieve good water quality and ecosystem status. Many of the pilot catchments worked in this way in their initial phase, demonstrating how river basin management planning objectives can form a central part of activity at this scale, for example in the Nene and Cotswolds catchments (see below).

> ***The Nene Integrated Catchment Management pilot – Partnership at the heart of planning, innovation and growth:*** *Recognising the numerous on-going initiatives in the Nene catchment, area, the River Nene Park Authority, who hosted this pilot, viewed the catchment process as developing an overarching plan across existing Strategic Spatial Plans, Green Infrastructure plans, and Local Enterprise Partnerships. Rather than setting up a separate steering group on river basin planning, relevant issues were discussed at meetings of existing groups. Urban walkovers were used to draw together organisations that might not otherwise meet, to look at waterside sites and discuss issues in an open forum. This provided an opportunity to influence urban planning and regeneration through the integration of water quality and WFD objectives at the earliest possible stage. Comments, proposals and photographs were mapped to allow for an easier and more immediate understanding of the issues and bring forward investment to deliver WFD objectives and Green Infrastructure benefits through the catchment.*
>
> ***The Integrated Local Delivery approach (ILD):*** *In the Cotswolds Catchment, Gloucestershire Farming and Wildlife Advisory Group (FWAG) has been using an ILD to inspire local communities to work up projects and business plans together. The ILD approach starts at the farm or parish level and can be targeted to water bodies where there are known WFD failures. Local knowledge is used to enhance the overall understanding of the area, identify shared problems and prioritise action. Actions are then matched against funding streams supporting a wide range of regional, national or international objectives, which are mapped using GIS over layering. By levering in wider opportunities to strengthen and match funding, ILD thus provides a delivery mechanism for meeting a wide range of objectives for WFD, Local Enterprise Partnerships and Local Nature Partnerships.*

A policy approach is now being developed that will deliver more locally relevant RBPs for 2015. Some of the challenges being faced and which have yet to be fully addressed are briefly discussed below.

GOVERNANCE

In England environmental matters concerning water, biodiversity and food production are managed largely through national bodies (government department and agencies) with local authorities in charge of issues of more immediate concerns to people such as waste collection and disposal, lighting, noise, traffic etc. The disconnect of people with their environment, as mentioned above, is therefore perpetuated. The catchment based approach, by giving authority and purpose to local community groups and stakeholders to work on environmental issues, helps to develop some reconnection. However, there is no obvious governance structure to support the approach and so it will need to evolve in an adaptive manner.

Because of the traditional top-down approach to environmental management, lower levels of governance for the environment are missing in England. It is therefore proposed to develop Catchment Management Fora in each of the 80 catchments identified in England to act in a non-

[3] The arrangements for Wales are not currently clear following the creation of the new integrated environmental body, Natural Resources Wales (NRW) on 1st April 2013

statutory way as a force for co-ordination, transmission, targeting and translation. They will be intermediaries between the higher-level policy and objective setting and the activity that needs to happen on the ground. They will have four broad areas of activity:

- *Planning* and facilitating to establish partnerships, collate existing evidence and identify and manage activities going forward.
- *Collaborating* to build relations with stakeholders in the catchment and develop a common view on pressures, objectives and activities.
- *Delivering* the activities required to achieve the objectives and to link with other initiatives to support integration and resourcing.
- *Checking* to support learning, evaluation and adaptive management.

On the Scotland/England border a Tweed (Catchment Management) Forum has been in existence for several years. They describe themselves as the "glue, the oil and the fuel" for effective river management – founded on effective governance at local level. (www.tweedforum.org)

Groups working at catchment level will have to be supported through local funding arrangements and develop ways of collaborative working through engaging with a broad range of local organisations, businesses and people with the knowledge, credibility and ability to work with, and influence, other local strategic decision makers.

It is through the three levels of working: local communities, catchment groups/fora, and river basin liaison panels, that catchment management will develop. A weakness in any one of these makes the whole weak or even unviable.

IDENTIFYING THE PROBLEMS - ISSUES OTHER THAN WATER

Common issues that people in communities can identify with are the essential starting point. A community-led catchment management approach will be doomed from the start if the main (overt) objective is to achieve WFD objectives. The problem to be addressed needs to be related to an ecosystem service that provides an identifiable benefit, from which other more detached issues might be addressed with them. However, when community-led groups start to set the priorities for action then they may not choose those that government or its agencies would like, in order to fulfil obligations under the WFD. For example, lack of access to the river bank for recreation and the degraded quality of the landscape are often major concerns raised. Lowering the phosphate levels in the river when it looks clear and unpolluted presents more of a challenge in corralling local action. The setting of different goals by communities to those national agencies would want is a facet of the catchment approach. It is imperative to not over-ride the wishes of the community or all future co-operation may be forfeited.

When issues have been identified then it is critical that they are thoroughly understood before expensive management solutions are put in place. For example, the ecology of a watercourse may be denuded, as represented by a reduction in the annual catch of trout reported by an angling club. There is likely to be a multitude of reasons (often acting in synergy) why fish numbers are denuded and to address the perception of the cause rather than the reality can be both ineffective and inefficient. Having the right data and transforming this into information and knowledge is therefore critical. An iterative, risk-based approach using a conceptual model and identifying the critical source-pathway-receptor linkages is often a good approach to use.

In summary we must understand the issue(s) before we start to manage it

What are we trying to find a solution to?

What outcomes are we trying to reach and in what timeframes?

Is it the same problem (set of problems) as the people who will have to help with the solutions identify with?

In reaching solutions we will usually need to negotiate trade-offs and establish win-wins.

NEW TYPES OF PEOPLE

The EA has evolved over time away from the integrated thinkers that characterised its field staff in its precursor organisations to more specialised personnel with expertise in specific fields. The catchment based approach requires a new breed of regulators who are able to see the bigger picture, develop and use conceptual models and work closely with other stakeholders, sometimes to the disbenefit of their own objectives. Such people are hard to train and usually develop skills from practical experience. We may face a short gap therefore in having the 'right' people to do the job required.

TOOLS TO SUPPORT COMMUNITIES

If community-led approaches are to gain ground then they need to be supported with resources (money, people and technical advice) as there are limits to volunteering and catchments are complex systems. One view is that resources are available, but not necessarily lined up to aid the catchment based approach. At present the technical resources that could be used are spread between: academics, research institutes, government agencies, consultancies and 'expert pensioners', and not co-ordinated. Many tools exist that could be applied ranging from guidance on walk-over surveys to sophisticated integrated models. Models need data and interpretation, both of which happen to be in short supply unless you are in a research catchment with experts on hand. Defra's Demonstration Test Catchments project is a research project that is endeavouring to fill the gap by working at field and farm scale and then scaling up the results of how various on-farm measures are influencing water quality. (www.demonstratingcatchmentmanagement.net). (McGonigle et al 2012).

Tools are also useful in helping build communities and establish consensus about issues and priorities. Many such knowledge-brokering instruments are available such as: simulation and role-playing games, group model building, scenario planning and visioning workshops. (e.g. see www.psiconnect.eu)

CONCLUDING COMMENTS

The Catchment Based Approach in England is new and exciting. It is still evolving and will continue to adapt as we learn more about participative and more collaborative ways of working with national bodies like the EA acting as facilitators rather than being in the lead. The principles have been established many times over across different parts of the world, but some things cannot be taught;

they have to be experienced. The EU FP6 co-ordination action project Riskbase summarised the requirements of a successful approach (Brils and Harris 2009):

- Be well informed

Having a sound understanding of the functioning of the soil-water system and its interaction with the socio-economic system

- Manage Adaptively

"Learning to manage by managing to learn" as a way of addressing uncertainties in the system

- Take a participatory approach

Learning and managing together to develop "win-wins

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SESSION I

A HEALTHY CATCHMENT INITIATIVE FOR IRELAND MAKING INTEGRATED CATCHMENT MANAGEMENT HAPPEN

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ABSTRACT

Good progress has been made in recent years in mitigating the impacts of large point sources of pollution on water quality. Achieving progress in dealing with impacts of nonpoint (diffuse), small point sources and water abstractions is more complicated and challenging. Successful protection and restoration, where needed, of the status of our waters will not be achieved using current approaches, particularly in the context of the increased outputs required to achieve Food Harvest 2020 targets. An 'integrated catchment management' (ICM) approach is the only feasible means of achieving the Water Framework Directive objectives and the sustainable use of our water and land resources. It is an approach that is increasingly seen internationally as essential to successful water management. However, it needs to be adapted to suit Irish circumstances. The ICM philosophy and approach, as proposed for Ireland in this paper: i) is catchment based; ii) involves awareness raising and consultation with local communities; iii) advocates a combination of 'bottom-up' and 'top-down' approaches; iv) integrates all water types, all relevant disciplines, including social science; v) includes emphasis on pollutant pathways, both surface and subsurface, that link pressures with receptors; vi) considers ecosystem services and the value of water resources; vii) uses a broad range of 'tools' in the toolkit', ranging in a continuum for local participation and partnership to enforcement; viii) requires close collaboration between relevant public bodies; and ix) presents a 'new' vision of a healthy, resilient, productive and valued water resource, that supports vibrant communities. Achieving successful environmental outcomes will be difficult; however, by making ICM a common purpose, by giving it priority in allocating scarce resources, by overcoming or bypassing all obstacles, by collaborating in an open way, and by being determined to 'make it happen no matter what', the utilisation of our waters and associated lands can be undertaken in a sustainable and ethical manner.

WHY A NEW APPROACH TO CATCHMENT MANAGEMENT

The achievement of Water Framework Directive (WFD) objectives is critical to i) attaining satisfactory water status, ii) *Food Harvest 2020* goals and iii) creating a greater appreciation of the beneficial role of water to Irish society. Existing approaches to dealing with water quality issues have been effective to-date in improving water quality arising from major point pollution sources, such as urban wastewater treatment plants and IPPC licensed activities, although continued investment is needed. However, dealing with nonpoint (diffuse) pollution sources and small point sources is a more complicated and challenging process. While implementation of the *EC (Good Agricultural Practice for Protection of Waters) Regulations, 2010* (S.I. No. 610 of 2010) and the *Water Services Amendment Act, 2012* (S.I No. 2 of 2012) has the potential to mitigate the impacts from agricultural activities and domestic waste water treatment systems (DWWTSs), respectively, achieving actual progress requires new processes, approaches and practices. New approaches have been developed in Australia and New Zealand since the late 1990s and have been instigated in the US and Britain in recent years; while the principles are the same, they have been called various titles, such as 'integrated catchment management' in Australia, 'watershed plans to restore and protect our waters' in the US and the 'catchment based approach' in England and Wales. The objectives of this paper are i) to adapt the approaches used elsewhere to the Irish setting and ii) to promote the approach as the requirement for the progress in water management that is necessary for the future.

In deriving a new approach to catchment management, account needs to be taken to the reasons that approaches and plans to-date have not achieved and cannot achieve the required outcomes. Some of these reasons are listed below:

- Stakeholder involvement and local ownership lacking.
- Regulations, which are often unconnected and focussed on particular pollution sources and pollutants, have not resulted in an integrated environmental approach.
- Most analysis and resulting activities conducted at too generalised (regional or national) a scale.
- River Basin Plan recommendations usually too generalised and based on a 'one size fits all' approach.
- Activities have concentrated largely (and understandably up until now) on the WFD 'restoration' objective, such as 'red dot' river sites (i.e., where there is pollution from a specific major activity, such as sewage discharge).
- Often a focus on means (operation of processes) rather than ends (environmental outcomes).
- Critical pressures and conflicts in the catchments often 'skirted around'.
- Emphasis on pressures and receptors, with no or limited appreciation of the role of the 'pathway' connecting them.
- Catchment based on a 2-D conceptual model, with little or no account taken of roles of the subsurface pathways and groundwater.
- Over-emphasis on 'what' and not enough on 'where'; the critical source area concept not used.
- Main emphasis is on the 'command and control' approach, using inspections and compliance checking rather than seeking behavioural change through stakeholder awareness and involvement.
- Multi-organisational involvement and responsibilities, but with inadequate linkages and collaboration.
- Silo organisational structures, founded on either disciplines or narrowly based processes and objectives, with inadequate linkages and integration.

INTEGRATED CATCHMENT MANAGEMENT – WHAT IS IT?

Definition

Integrated catchment management (ICM) is based on the concepts of i) catchments as biophysical units in which natural resources use, and ecological and water protection takes place, ii) integration of local community and scientific involvement, and iii) appropriate organisational structures and policy objectives. Specifically, ICM is[1]:

- A ***philosophy*** – to foster an organisational culture and associated attitudes that view i) cooperation and collaboration as essential and ii) interactions between natural resources and human activities or responses in a holistic way.
- A ***process*** – an overarching planning framework and implementation process that reflects the philosophy of ICM and provides the 'vehicle' through which ICM is delivered. The process needs to provide a flexible, adaptive, on-going and dynamic integrated mechanism, which coordinates the activity of many people, both in the public sector and the community.
- An ***outcome*** – the planning and implementation of sustainable resource use practices, which will vary from place to place, depending on conditions and needs, and the achievement of planned environmental outcomes, which are based on environmental, regulatory, economic and social considerations.

[1] This definition is adapted from: Bellamy *et al.*, 2002.

ICM requires four particular elements:

- A catchment approach.
- Integration.
- A change in philosophy.
- Stakeholder involvement, particularly at local community level.

A CATCHMENT APPROACH

The catchment is the appropriate organising unit as it is defined by the natural hydrology and hydrogeology, ‘connects’ **all** relevant elements, including pressures, receptors (particularly ecosystems) and people’s needs. However, the scale needs to be appropriate so that the problems, solutions and consultations can be targeted effectively – see Figure 1.

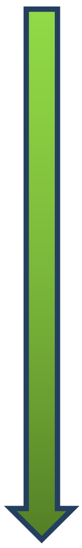
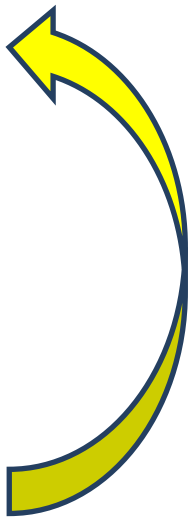
Level of Detail	Scale	Response	Continual Iteration
Low 	**National**	**Where policy is made.**	
	RBD	**Where reporting to EC is undertaken.**	
	Water Management Unit (Catchment) (e.g., 10s-100s km^2)	**Where delivery is organised; evaluation is undertaken; reports are written; plans are made.**	
	Sub-catchment	**Local community involvement. Catchment walks. Investigative monitoring. Inspections.**	
High	**Site-specific or project-specific assessments**	**Detailed investigations.**	

Figure 1: Level of detail for integrated catchment management

Requires “Integration”

Integration is a key feature:

- Integration of all stakeholders, including relevant institutions, public bodies and broad stakeholder perspectives and involvement, including local communities.
- Integration of all water types, using the 3-D hydrological cycle as the conceptual basis.
- Integration of disciplines and data, with catchment science and management as the vision.
- Integration of natural science, social science, socio-economic issues and policy issues.
- Integration of the beneficial uses of water: for drinking; for ecosystems, e.g., fish; for agriculture/food production; for disposal of sewage effluent.
- Integration of regulatory requirements to ensure effective prioritisation and resource use.
- Integration of environmental indicators, e.g., relating to differing water and terrestrial ecosystems, drinking water quality, water abstraction, flooding.
- Integration of measures to ensure effective outcomes and resource use.

A Paradigm Shift
A change in philosophy is required:

- To partnerships with local communities and emphasis on citizen engagement that includes identifying key stakeholders, public awareness and outreach campaigns, identifying issues of concern, and obtaining and taking account of feedback.
- To genuine integration.
- From the top-down, 'command and control' approach to a combination of bottom-up and top-down.
- From 'restoration' to 'protection/maintenance' and 'restoration'.
- To systematic communications between policy, science and operations as a means of dealing with the complexities caused by working cultures, remits and priorities.
- To giving a higher priority to addressing nonpoint (diffuse) sources of pollution and small point sources.
- To linkages, co-operation and networks rather than 'silos', both internally in organisations and between organisations.
- To an emphasis on pollutant pathways, both surface and subsurface, that link pressures with receptors, and enable critical source areas (CSAs) to be delineated.
- To consideration of 'ecosystem goods and services' in a systematic manner, including putting a 'value' on water resources and ecosystems and the potential contribution to the 'green economy'.
- To a broader range of 'tools' in the 'toolkit', ranging in a continuum from local participation and partnership to enforcement.
- To an emphasis on benefit to water rather than regulatory lists.
- To enhancement of the local environment for people, businesses and wildlife, while achieving the WFD objectives required by the EC.

The Context for ICM
The development and successful delivery of the ICM process will be undertaken in the context of the following:

- WFD Requirements
    - 2021 is given as the most significant deadline for achieving objectives in the River Basin Management Plans (RBMPs); major progress in improving the status of water bodies is required by this date, while water bodies with a satisfactory status must be maintained.
    - Current and potential European Court Judgements (ECJs) against Ireland.
    - Achieving the required objectives will require analysis and understanding of the role of nonpoint (diffuse) and small point pollution sources and instigation of actions to mitigate possible impacts.
- *Food Harvest 2020* (*FH2020*)
    - *FH2020* is intended to increase outputs from the agri-food industry. It will lead to some increase in intensification and use of nutrients. However, environmental sustainability is a core requirement. Maintenance of Ireland's derogation from the Nitrates Directive will be essential to achieving *FH2020* targets. This will be threatened if the necessary improvements in water quality do not occur and/or if there is any deterioration in water body status.
- New Common Agricultural Policy (CAP) Greening Proposals
    - These present the potential to use CAP payments to facilitate water quality protection and improvement.
- New Governance Arrangements
    - The planned new governance arrangements will give the EPA a greater leadership role and responsibility to deliver successful environmental outcomes. However, the local authority input will be critical. A partnership approach involving, for instance, the EPA, local authorities, Inland Fisheries Ireland, Teagasc, Marine Institute, Geological Survey of Ireland, will be required.

- Available resources
    - In a time of limited resources, a sufficient priority will need to be given to ICM implementation.

The ICM Approach

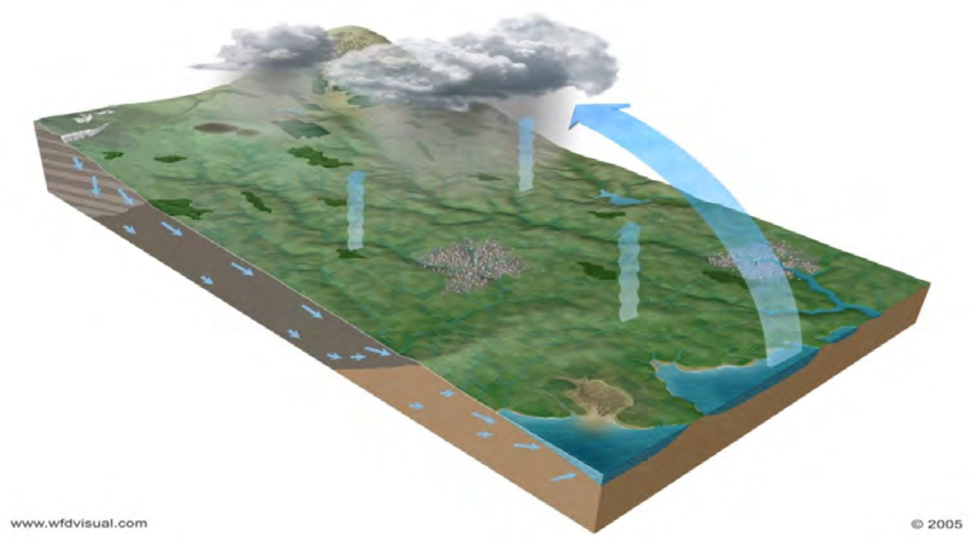
The proposed elements of ICM are given in Table 1 and the steps in the integrated catchment planning and implementation process are as follows[2] (see Table 2):

1. Create and communicate a 'new' vision.
2. Establish a sense of urgency.
3. Build partnerships.
4. Characterise the catchment.
5. Undertake further characterisation of catchment.
6. Finalise goals.
7. Identify solutions.
8. Design an implementation programme and complete the catchment plan.
9. Implement the programme.
10. Measure progress and make adjustments if necessary.

In undertaking steps 4 to 10, there is an overarching requirement for the effective use of modelling, GIS and information technology systems to input to the analysis and to record the tasks undertaken and the outcomes.

Create and Communicate a 'New' Vision,

The vision is a healthy, resilient, productive and valued water resource, that supports vibrant communities. It is based on i) a conceptual model of the catchment as a 3-D entity, ii) integrated catchment science, and iii) involvement of and collaboration with local communities. Effective 'catchment science' is based on integrating a wide range of physical factors (such as hydrology, hydrogeology, ecology, hydrochemistry), pressures (such as UWWTPs, DWWTSs, farming, forestry, landfills), IT (such as GIS and recording of inspection details), education and public participation, authorisation of activities, enforcement, etc. Communicating the vision is essential. The connection between people and water is instinctive; however, making this a means of ensuring that water is protected and, where necessary, improved requires creating a greater understanding of water itself, its value and the threats to it from human activities. **A 'healthy catchments' brand, together with an appropriate diagram illustrating water in the landscape, is proposed as a means of marketing ICM.**



[2] In developing these steps, the USEPA report "Handbook for Developing Water shed Plans to Restore and Protect Our Waters" (2008) was used extensively.

Table 1: The 'Toolkit' in the ICM Approach

	Tools	Challenges/likelihood of success
Participation & Partnership	**A 'new' vision** ➢ 3-D integrated catchment science ➢ Catchment management ➢ Both science and people	If approached properly, a high likelihood of success; this is an appropriate time for change. *[We have to take citizens with us*.]
	Behavioural Change ➢ Awareness raising ➢ Education ➢ Public participation	Resource intensive. Short term benefits may be small, but essential for long term results.
	Characterisation at catchment scale (a catchment science approach is essential) ➢ Physical (geology, biology, hydrochemistry, etc.) ➢ Monitoring (surveillance and operational) ➢ Location of pressures ➢ Analysis using SPR approach (detailed evaluation of hydrochemistry, pollutant loading, biological indicators, etc.) ➢ Evaluation of impact of specific pollution sources	More detailed analysis than currently undertaken required. Must be scientifically defensible and catchment specific. More than just monitoring. Likelihood of success high with some additional resources and training.
	Further Characterisation & Analysis ➢ Location of critical source areas (CSAs) ➢ Investigative monitoring ➢ 'Walking the catchment'	Resource intensive.
	Programmes of measures ➢ Measures targeted spatially ➢ BMPs ➢ Costed and prioritised. ➢ Concentration on outcomes ➢ Input of local knowledge	Measures must be prioritised and outcome oriented.
	Incentives ➢ Greening of the CAP	Incentives need to be focussed on CSAs and appropriate pressures
	New/Upgrading infrastructure	Continued investment needed
	Inspections Farming; DWWTSs; UWWTPs; Drinking water audits; IPPC inspections	Risk-based. Initial emphasis on awareness, with enforcement follow-up where required
Enforcement	**Court/loss of money**	The last resort!
	Policy changes/new Regulations	Proposals to DECLG on this.
	Over-arching requirement • Modelling, GIS and databases	Effective informatics & GIS input critical.

Table 2 Steps in the integrated catchment management process[3]

Steps in the Integrated Catchment Management Process

1. **Create and communicate a vision of ICM**
   - A healthy, resilient, productive and valued water resource, that supports vibrant communities.
2. **Build Partnerships**
   - Identify key stakeholders
   - Identify issues of concern
   - Conduct public outreach
3. **Characterise the Catchment**
   - Gather existing data and create a catchment inventory
   - Identify data gaps & collect additional data, if needed
   - Analyse data
   - Identify causes and sources of pollution
   - Estimate pollutant loads
   - Undertake risk assessments
4. **Undertake Further Characterisation**
   - Collect and evaluate local information
   - Locate critical source areas (CSAs)
   - Undertake investigative monitoring
   - Organise catchment walks
5. **Finalise Goals**
   - Set overall goals and management objectives
   - Develop indicators/targets
   - Estimate load reductions needed
6. **Identify & Evaluate Possible Management Strategies**
   - Evaluate existing measures
   - Get stakeholder input
   - Take account of ecosystem services, water value, pollution sources and CSAs
   - Develop management measures to achieve goals
   - Rank the measures
7. **Design an Implementation Programme**
   - Select measures
   - Develop an implementation schedule with milestones
   - Develop the monitoring component
   - Develop information/education component
   - Identify technical & financial assistance needed
8. **Implement the Programme**
   - Prepare a work plan with short- and long-term outcomes
   - Implement the measures
   - Use metrics to track progress
   - Conduct information/education activities
9. **Measure Progress and Make Adjustments**
   - Analyse tends and outcomes
   - Give feedback to stakeholders
   - Make adjustments, if necessary

Characterisation & Analysis Tools

- GIS
- Databases
- Statistical packages
- Numerical models
- Flow estimations
- Load estimations
- Monitoring

River Basin Management Plan

[3] This table is adapted from USEPA (2008)

Establish a Sense of Urgency
Progress in the immediate future is essential if the beneficial objectives of *FH2020* and the 2021 WFD objectives are to be achieved.

Build Partnerships
This requires identifying key stakeholders, both in relevant public bodies (such as local authorities, IFI, Teagasc) and local communities, awareness campaigns, public outreach, identifying issues of concern to local communities, and getting views on solutions, i.e., it needs to be a two-way process. Account must be taken of all views – the implementation process cannot be an EPA and local authority remit alone.

Characterise the Catchment
This involves gathering existing data, identifying data gaps, collecting additional data if needed, analysing data, estimating pollution loads, identifying causes and sources of pollution. Information is needed on the following:

Catchment Physical Setting
- Topography
- Rainfall
- River Flow
- Soils
- Geology
  - Subsoil
  - Bedrock
- Aquifers
- Groundwater recharge
- Groundwater vulnerability, including subsoil permeability
- Surface water susceptibility, e.g., inadequate percolation
- Interactions between surface water and groundwater

Receptors (water bodies) and Related Environmental Standards
- The groundwater receptor
- The river receptor
- The lake receptor
- The estuary receptor
- Groundwater dependent ecosystems (GWDTEs)
- Surface water dependent ecosystems
- Protected areas
- High status sites

Drinking Water Sources and Related Drinking Water Standards
- Zones of contribution of sources

Pressures
- Agriculture (diffuse and point)
- Discharges from WWTPs
- DWWTSs
- Forestry
- Peat cutting
- Overgrazing
- Landfills and Old Dumps
- Mines and Quarries
- Contaminated Land

- Urban Areas
- Water abstractions
- Heavy rainfall, resulting in floods
- Droughts

Pathways
- Atmospheric deposition
- Overland flow
- Shallow subsoil flow (interflow)
- Shallow bedrock flow
- Deep bedrock flow
- Groundwater contribution to surface water
- River in-stream transport and delivery to lakes/estuaries

Impacts
- Groundwater/river/lake/estuary water chemistry
  - N
  - P
  - Sediment
  - Pathogens
  - Hazardous substances
- Biological quality of river/lake/estuary
- Status of water bodies
- Changes in water quality
  - Spatial trends
  - Temporal trends

Risk Assessments
- Based on the combination of pressures, pathways and impacts on receptors.

This stage can be undertaken using existing information and knowledge.

Undertake Further Characterisation of Catchment
This involves location of critical source areas (CSAs) (see Appendix 1), catchment walks focussed on CSAs and investigative monitoring to enable detailed analysis and identification of the causes, sources (including location) of impacts that need to be controlled.

Finalise Goals
As the WFD is an overarching Directive that encompasses, for instance, the Floods and Nitrates Directives, the policy objectives of the WFD, with associated standards, should be adopted as the key policy objectives for ICM. In addition, the requirements of the Drinking Water Directive must be achieved. Relevant water indicators to measure performance and realistic targets are then developed, together with estimation of required pollutant load reductions. The resilience of water bodies to absorb stresses while continuing to function in the desired way must be taken into account.

Identify and Evaluate Possible Management Strategies
The effectiveness of existing management approaches need to be assessed and the lessons learned recorded. New practical and pragmatic solutions, which build on relevant existing processes and take account of ‘water value’ and ecosystem services, would then be developed. These involve consideration of:
- CSAs;
- experience with existing approaches;
- recent research findings;

- best management practices (BMPs) for both diffuse and point pollution sources, based on recent knowledge and experience, e.g., Teagasc research;
- statutory requirements;
- the sensitivity of water receptors;
- the value of water;
- risk-based targeting of measures; and
- the cost of the potential solutions.

A ranking of options is then undertaken. Account should be taken of the benefits from options that will create short term 'wins' as a means of showing progress and encouraging the process, as well as solutions that lead to longer term improvements.

Design an Implementation Programme and Complete the Catchment (River Basin) Management Plan

Account is taken of each 'tool' in the 'toolkit' given in Table 1, with a focus on the required environmental outcomes rather than the processes. Using the ranked and agreed options, and the information collected in the earlier steps, detailed management strategies are selected, which take account of the goals that have been set and involve the stakeholders, including local communities. An implementation schedule is established and the catchment (river basin) management plan is then prepared; the plan will need to be accessible to the different relevant audiences.

Implement the Programme

The implementation will require all the 'tools' listed in Table 1 to be used in an integrated, interconnected manner.

Clearly a good plan without effective implementation is pointless (if not worse as resources will have been wasted in producing the plan). Some elements of a successful implementation process are as follows:

- Making organisational structures compatible with the vision.
- Ensuring that necessary expertise and skills are available.
    - Undertaking a skills gap analysis in deciding on team membership.
    - Taking care that the personality/character of staff involved in undertaking ICM is suitable, as an open, collaborative working style will be needed in most instances.
    - Employing appropriate staff with the range of skills and expertise required.
- Preparing a work plan, with short-term and long-term outcomes.
- Deciding on metrics as a means of tracking progress.
- Undertaking the work plan.
- Continued promotion of the process, for instance, using short-term wins' to achieve this.
- Continued emphasis on communication and on achieving 'behavioural change' in parallel with the catchment science elements of the work.
- Achieving successful ICM will be complex and difficult; 'adaptive change' and 'cultural change' processes will need to be maintained, in part at least by continued promotion of the process.

Measure Progress and Make Adjustments

This requires tracking progress with implementation:

- Analysing water quality and trends.
- Getting feedback from stakeholders, particularly local communities.
- Re-examining the environmental goals, if necessary, on the basis of reviews of progress.
- Making adjustments, if necessary.

Conclusions and recommendations

1 Successful protection and restoration of our waters will not be achieved by using the current approaches.
2 In the view of this author, **an Integrated Catchment Management (ICM) approach is the only feasible means of achieving WFD and *FH2020* objectives**, and also the objectives of other relevant Directives such as Habitats, Drinking Water, Floods, etc.
3 The ICM approach is an evolving process; it has made limited progress to-date world-wide, except in Australia.
4 This paper outlines a process that is suitable for Ireland and that is achievable, provided that there is 'buy-in' and it is given a sufficiently high priority and adequate resources.
5 A vision of a '**healthy, resilient, productive and valued water resource, that supports vibrant communities**', is proposed, branded as a '**healthy catchments programme'**.

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This paper is influenced by discussions with colleagues within (particularly in the Hydrometric & Groundwater Section) and outside the EPA; USEPA and Australian reports on ICM; outcomes from the pilot catchment programme undertaken in England and Wales 2011-2013; the work of the EPA STRIVE 'Pathways' Project team; the work of the Teagasc Agricultural Catchments Programme team; and the County Kilkenny *FH2020* technical group.

APPENDIX 1

THE CRITICAL SOURCE AREAS APPROACH TO CATCHMENT MANAGEMENT

General Concept

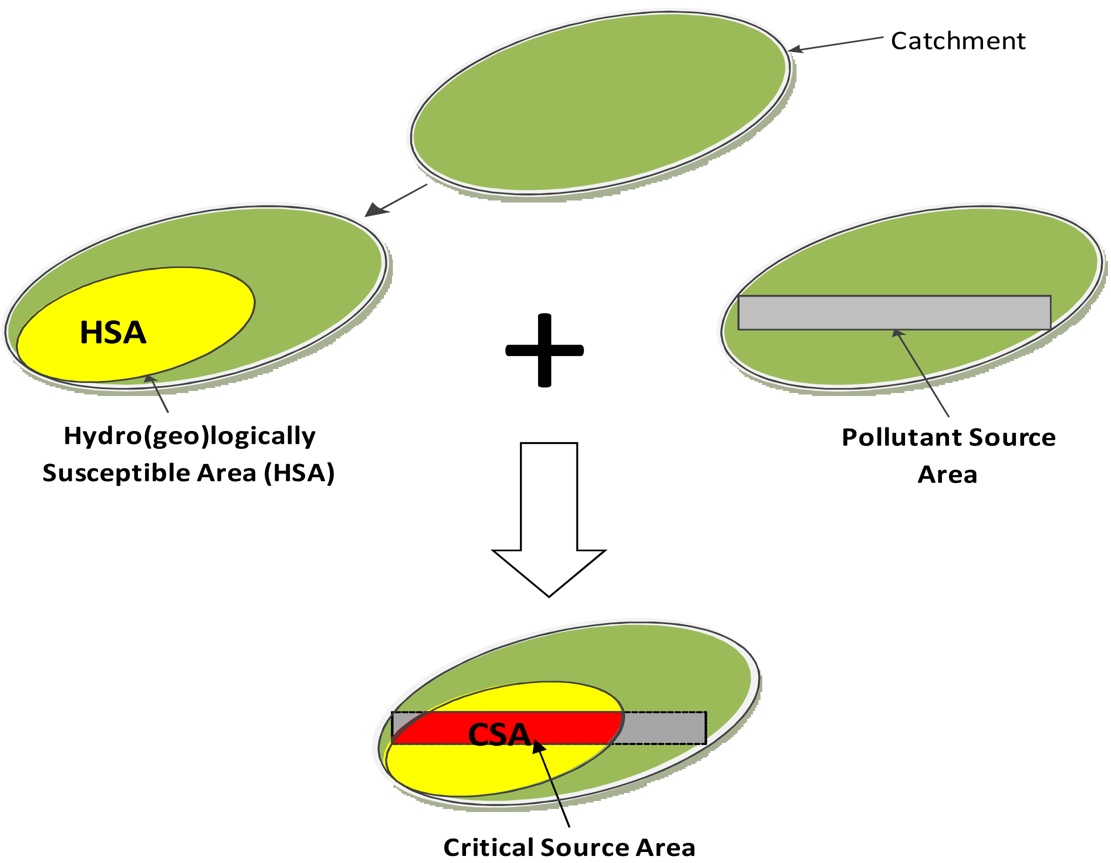
Critical source areas (CSAs) are areas within a catchment that contribute more pollutants than other portions of a catchment. Research findings show that small areas of a catchment (5-20%) generate a disproportionately large amount of pollutants; location of these areas enables the focusing of awareness raising, investigative monitoring, catchment walks, and planning and enforcement resources in areas which will yield the most benefit.

The CSAs approach fits within the source-pathway-receptor model (SPR) for environmental management.

The 'pathway susceptibility' (which in some papers is called 'transport factors') defines the hydraulic connectivity between the pollution source and the receptor. There are two main pathways – surface and subsurface.

The potential pollution 'source' will vary geographically depending on the intensity of agriculture, housing density, etc.

CSAs are the intersection of hydrologically/hydrogeologically (hydro(geo)logically) susceptible areas and pollutant sources in specified areas, such as catchments – see diagram.



Application of the CSA Approach

The application of the approach requires the following:

- Use of GIS.

- Information layers on the pollution sources in a catchment, e.g. DWWTSs.
- Location of hydro(geo)logically susceptible areas; the relevant pathway layers defining the hydraulic connectivity will depend on the pollutant (N, P, sediment, microbial pathogens) and on the receptor being considered.
- Evaluation of, and agreement, on the boundaries between prioritisation categories.

The CSA concept was used as the basis for the DWWTSs National Inspection Plan (EPA, 2013(a) & (b))

IS CATCHMENT MANAGEMENT FEASIBILE FOR IMPROVING QUALITY OF PUBLIC GROUNDWATER SUPPLIES?

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ABSTRACT

This paper presents the outcome of the study of 44 catchments to public groundwater supply boreholes in the Midlands and North West of England. Land use and nitrate loading to each catchment was characterised and a trend model was fitted to concentration data. Predictions of concentrations in 25 years' time were used to inform the feasibility of catchment management to improve abstracted groundwater quality. In many of the catchments, measures would not be required because a better understanding of the system demonstrated that drinking water quality is not at risk. In many others, concentrations are too high to be controlled effectively by catchment management measures. In the remainder, a spectrum of different levels of stewardship would be required to achieve desired outcomes. Catchment management is most suited to achieving marginal (<20%) reductions in nitrate concentrations in these catchments. At this level of loading reduction, some land use change would be required. Where the reduction in concentration required is 8% or less measures may be cost beneficial for the farmer and may not need incentivisation for their adoption.

INTRODUCTION

At the last five-yearly price review the UK's water industry regulator, Ofwat, allowed water companies to include elements of catchment management activity in their Asset Management Plans to reduce diffuse water pollution. Ofwat signed off £60M of stewardship activity, which despite the large figure, represented a small proportion of budget assigned to water quality programmes overall.

For the next price review targeted catchment management will take a far more prominent role in water companies' proposals for 2015 and beyond. In December 2011, Defra published a White Paper which outlined a commitment to a new 'catchment-based approach' to water quality and diffuse pollution control (Defra, 2011a). A couple of months earlier, Ofwat published 'Catchment to Customer' (Ofwat, 2011), which highlighted a National Audit Office finding that diffuse water pollution from agriculture is one of the biggest challenges to improving water quality. Water utilities are now seriously reviewing targeted agricultural land stewardship as an alternative to treatment and blending.

Water companies, however, still face a simple reality: catchment management has to be at least as cost-effective as industrial treatment solutions or else Ofwat will not approve their water quality plans for funding. There can also be resistance from farmers to adopt required new practices because of cost, reduced profitability or the extra workload that new methods place on their businesses. Therefore the challenge for water companies is to provide compelling evidence that interventions work, that they are cost-effective (for water companies and for farmers) and that they are sustainable. Most evidence to date arises from schemes that improve surface water quality, there has been some success with limiting nutrient (ADAS, 2011; Wessex Water, 2011) and pesticide (Wessex Water, 2011) concentrations in groundwater catchments.

This paper discusses the findings of a review of the feasibility of catchment management in about 44 catchments to groundwater abstractions in the English Midlands and North West (Figure 1). All of these catchments were put forward for detailed assessment because nitrate concentrations are rising towards critical target concentrations. Target concentrations vary depending on installed capacity for downstream treatment or blending. Based on simple linear fits to recent data it appeared that abstraction concentrations would exceed targets within about twenty years. Catchment management was to be considered as an option to limit concentrations to below the target, or at least to slow the rate of rise and therefore extend the lifespan of the current arrangements. Feasibility studies reported here were used to assess which of the 44 catchments were likely to respond positively to nitrate reduction measures.

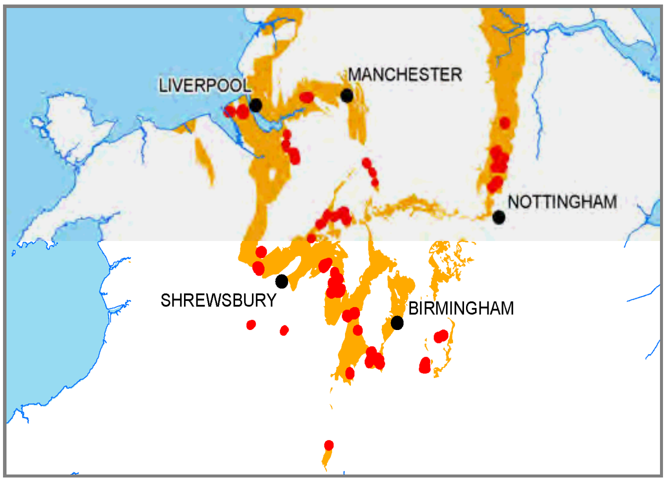

Figure 1. Catchment locations (red) on the Midlands and North West England Permo-Triassic sandstone outcrop (orange).

PREDICTIVE MODELLING

Linear trends, used in the initial screening of the sites, are too pessimistic for prediction and have no conceptual justification or physical relationship with historical nitrogen inputs. A conceptually informed model, for predicting nitrate concentrations, was therefore developed and calibrated to:

- demonstrate that the conceptual understanding of the hydrogeological system and assumptions about land use were robust; and if not, to identify when concentrations deviate from the expected trend, to help identify unanticipated hydrogeological mechanisms or land use change; and,
- to predict what concentrations would be without intervention (the do-nothing scenario), and the timing of any peaks in concentration; and to predict future concentrations and likely timescales for scenarios with reduced future N loading.

CATCHMENT DELINEATION

Land use within the historical catchment area – where the recharge came from, and therefore where the diffuse nitrate pollution came from – is a key input to the models. Accurate delineation of catchments is important in obtaining representative land use parameters and it is essential to identify where measures are to be implemented – otherwise any scheme would have limited credibility and may not work as intended.

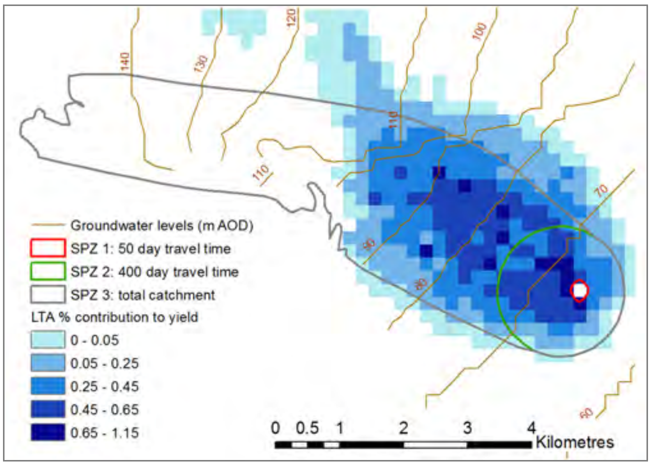

Figure 2. Comparison of two methods for groundwater catchment delineation. Source Protection Zones are derived from particle tracking using the maximum (licensed) annual abstraction rate. Distributed historical contribution of borehole yield from each cell (using FlowSource post-processing software) is shown as a blue colour gradient.

Catchments to public water supply boreholes are delineated in England and Wales as part of defining Source Protection Zones (SPZ). The total catchment, or SPZ3, is the estimated area within which recharge contributes to the licensed maximum borehole yield, but abstractions are seldom operated at their licensed rate, so this is larger than the catchment that will have contributed yield historically. Historical catchments may be derived manually by scaling SPZ catchments, by using existing SPZ delineation models or, lately, groundwater model post-processing tools have become available to define catchments (Whiteman, 2013). FlowSource, for example, uses results from transient groundwater model runs to compute the amount of historical yield contributed by each model cell. Figure 2 shows a comparison of the SPZ and FlowSource outputs for a typical groundwater catchment in the Nottinghamshire Permo-Triassic sandstone aquifer. Historically, abstraction has been at about 50% of the licensed rate, which is clear from the extent of the modelled catchment. These results also make it clear that the greatest contribution of abstraction yield comes from closer to the borehole, so it is obvious where nitrate mitigation measures should be focused.

SOURCE TERM

All of the groundwater catchments in these studies comprised >50% agricultural land, whilst only 14 had >10% urban land. The National Environment and Agricultural Pollution Nitrate (NEAP-N) dataset (Lord and Anthony, 2000) is a national scale tool for predicting concentration of nitrate in leachate from agricultural land. Crop and animal data in the model are obtained from parish-scale census data. NEAP-N assumes that nitrogen is applied at the correct rate for the crops given in the agricultural census. It does not include the effects of non-compliance with official fertiliser recommendations, good agricultural practice or Nitrate Vulnerable Zone (NVZ) limits; nor sludge spreading, or point sources, all of which may contribute excess N to the catchments. NEAP-N data, from the 1980 and 2010 datasets, therefore gives two well-constrained snapshots of diffuse agricultural nitrate loading in the catchments. National fertiliser use (Defra, 2011b) and county scale livestock numbers (Defra, 2013) were used to interpolate between the two NEAP-N snapshots of 1980 and 2010, and to hindcast pre-1980 loading. Loadings were turned to soil leachate concentrations by dilution from annual recharge (estimated from regional rainfall data at *data.gov.uk*) to output concentrations. Urban loading was estimated (as a constant input) using parameters from Wakida and Lerner (2005).

SUB-SURFACE TRANSPORT

Water and nitrate move slowly through the hydrogeological system so the soil zone inputs are subject to significant delay before they reach the abstraction. Conservative solute transport rates may be estimated using generic data on unsaturated zone velocity, and Darcy's Law for the saturated zone. But heterogeneity in the subsurface such as marl bands and bypass flow, and order-of-magnitude uncertainty in hydraulic parameters, makes it difficult to estimate travel times with confidence. In the trending model a combined unsaturated and groundwater travel time is estimated by fitting a modelled trend to the data. Hydrodynamic dispersion is not simulated in the model at present. In the unconfined Permo-Triassic aquifers of the English Midlands, nitrate is not subject to retardation or biodegradation (Rivett *et al.*, 2007).

IN-BOREHOLE DILUTION AND MIXING

Additional processes that affect abstracted concentrations occur near to, or within, the abstraction boreholes. Each is simply accounted for in the model to fit the data, by defining a concentration and a percentage of abstraction yield contributed. Deep, unpolluted, groundwater entering at the bottom of deep boreholes dilutes concentrations from the near-surface polluted layers of aquifers. Ingress of surface water from rivers passing close to the borehole may dilute or increase concentrations in the abstracted water, depending on the relative concentrations. Point sources of pollution close to the borehole, such as manure heaps, leaking slurry pits, septic tanks, etc. can provide additional sources of pollution. Finally, blending with water from other sources at treatment works or in service reservoirs is used to operationally lower concentrations to public water supply.

MODELLING METHODOLOGY

Catchment land use, nitrate loading and rainfall determine the results from the soil zone model. Delay, dilution and mixing processes modify the soil zone model results into the results from the groundwater trend model. Model parameters are calibrated within reasonable limits, informed by the conceptual understanding, and to achieve the best fit to concentration data. A typical example of the quality of fit to data, for a catchment in the Cheshire Permo-Triassic sandstone aquifer, is shown in Figure 3. There are two boreholes close together: BH3 is 91 m deep, BH 4 is 244 m deep. The model trend line (solid black) for the catchment is fitted closer to the BH 4 data because that is the borehole that provides most yield. This model suggests a 35 year travel time and suggests that concentrations may not peak for another 10-20 years or so.

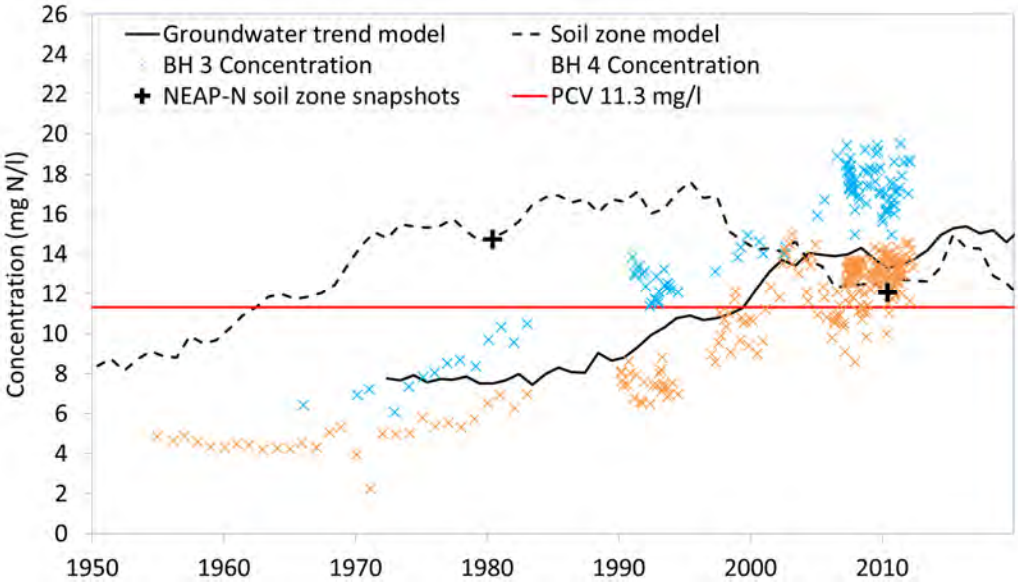

Figure 3. Soil zone model and groundwater trend model for a dominantly dairy farming area of Cheshire.

INSIGHTS

Catchments, land use and hydrogeology of 44 public water supply groundwater abstractions were modelled and the trends compared with data to assess deviations from the expected trend. These deviations were examined and conceptual justification was sought, to demonstrate that the model was robust. All but three catchments are in the unconfined Permo-Triassic sandstone aquifer. Based on these analyses the following insights were gained.

- **Typical transport times, from the base of the soil zone to the abstraction, are in the range 15 to 35 years.** Without reviewing correlations in detail, modelled delay time seems to relate most strongly to:
  a) **Presence/absence of marl layers.** The Nottinghamshire Permo-Triassic sandstone aquifer is mostly free of marl bands unlike the sandstone aquifers further west. This is believed to be the reason that in most of the Nottinghamshire abstractions, concentrations have remained relatively stable at elevated concentrations since the 1990s. Concentrations further west are still increasing, or have been stable for only five years. This is despite lower recharge rates, and therefore slower rates of movement in the unsaturated zone, in east England.
  b) **Thickness of the unsaturated zone.** Where similar sized catchments are compared, in aquifers with similar development of marl bands, those with the thickest unsaturated zones have the longest apparent travel times. This is not a surprise, of course, but highlights that the lithology of the aquifer (above) is more significant than the overall distance travelled.
  c) **Area of the catchment zone / time of travel within groundwater.** Of the Cheshire sources, all are constructed within a similar aquifer and have a similar unsaturated zone thickness. While larger catchments have longer travel times, these are not in proportion to the area.

Delay times imply a consistent unsaturated zone travel time about 24 years, across c. 50 m of aquifer, or c. 2 m/year. Travel velocities in the saturated zone are around 0.5 km/year.

- **Travel times of 15 to 35 years imply that the 1980s peak N loading has passed**, or is passing imminently, in Permo-Triassic sandstone aquifers. A relatively stable trend is often seen in the latest five years' data. Seen in isolation any of these might be assumed to be fluctuation on a general rising trend. However, the weight of evidence from calibrated model results, and the combined review of 44 sets of data, gives confidence that many trends are levelling out. Except for the few catchments in which nitrate loading has increased over the last thirty years, further risk of a significant increase in nitrate concentrations therefore appears small.
- **There is stratification of concentration with depth below the water table.** Where there are multiple boreholes on site of significantly different depths the deepest borehole consistently shows a lower concentration (e.g. the catchment in Figure 3: BH 3 is 91 m deep; BH4 is 243 m deep). This stratification is also observed in many single boreholes where, when abstraction rates and therefore drawdowns increase, then concentrations decrease. Exceptions are noted where there are multiple boreholes connected by adits, which have complex water quality responses to drawdown.
- **Interaction with nearby rivers is important in many unconfined catchments.** Smaller river catchments normally have similar land use to the groundwater catchment. In this instance surface water has a similar concentration to soil leachate and may not affect borehole concentrations. Larger rivers may have upland catchments, resulting in lower nitrate concentrations to dilute concentrations in the borehole. But also these larger rivers may have significant N loading from upstream sewage treatment works, so may act as a source of excess N.
- **Point sources, that significantly increase concentrations above those predicted by the soil zone model, appear uncommon**. Where this has been seen, field surveys have identified varied potential sources (none have yet been investigated and verified as causing an issue): open water with significant wildfowl activity, poorly constructed slurry stores, poorly managed farm runoff, and dense cropping of particularly leaky crops (e.g. potatoes and salads) near the boreholes.
- **Ploughing-up permanent pasture has occurred in some catchments and has caused considerable spikes in nitrate concentration,** sometimes increasing the concentration at the borehole by 5 mg N/l, for more than a decade. This is seen particularly clearly in data from smaller Cheshire catchments. In the early 1980s the local dairy industry was restructured, with a reduction in the number of dairy farms and an increase in the size of the remaining farms. There was then greater reliance on housing animals with a consequent increase in the requirement for fodder; in part supplied by maize, hence replacement of pasture by arable land.
- **Catchments with significant amounts of urban area are characterised by very flat trends**, sometimes with a minor rise from outlying agricultural loading. Trends could not be fitted well in any of the urban catchments and it is thought that Wakida and Lerner (2005) underestimate nitrate loading from urban areas, and/or the numerical models used in assessing recharge inputs may underestimate urban recharge.

FEASIBILITY OF CATCHMENT MANAGEMENT

Models were parameterised that best fitted historical data. Future concentrations were forecast to predict how abstraction concentrations are likely to change up to 2037. A 25-year planning horizon was chosen as this is, firstly, a requirement for long term planning from OFWAT, and secondly, a time at which catchment management interventions starting now might be significantly realised.

Uncertainty analysis was undertaken on model parameterisation to identify more pessimistic predictions, albeit with the model still being a reasonable fit to historical data. Scenario analysis was also undertaken to test the potential risk posed by climate change, or by changing agricultural practice. Predictive model scenarios were used with 20% less recharge (a reasonably pessimistic case for the English Midlands from UKCP09 modelling – Christierson *et al.*, 2012) and 20% higher N loading.

MODELLING RESULTS

Results from all 44 sites are tabulated in Figure 4. This table shows the predicted annual peak concentration in 2037 (accounting for parameter uncertainty) compared with water company targets (which take into account blending and treatment to provide a potable supply at customers' taps). Headroom is presented as a percentage change needed to comply with the target (negative headroom means that groundwater concentrations would need to be reduced to meet the target). Vulnerability to climate change or land use change (scenario uncertainty) is also presented as a percentage of the target concentration. Terms used for the "assessment of feasibility" are explained in the next sub-section.

		Best estimate + parameter uncertainty		Best estimate + parameter uncertainty + scenario uncertainty		
Source ID	Peak target mg N/l	Peak concentration in 2037 (mg N/l)	Headroom	Peak concentration in 2037 (mg N/l)	Headroom	Assessment of feasibility
1	8.5	15.6	-46%	17.4	-51%	Feasible with considerable land use change
2	8.5	15.5	-45%	17.6	-52%	Feasible with considerable land use change
3	8.5	15.5	-45%	17.4	-51%	Feasible with considerable land use change
4	9.5	16.1	-41%	17.8	-47%	Feasible with considerable land use change
5	8.5	14.1	-40%	16.2	-48%	Feasible with considerable land use change
6	8.5	14.0	-39%	17.0	-50%	Feasible with considerable land use change
7	13.5	20.5	-34%	23.4	-42%	Feasible with considerable land use change
8	6.5	9.7	-32%	12.6	-48%	Feasible with considerable land use change
9	8.5	12.0	-29%	14.0	-39%	Feasible with considerable land use change
10	8.5	10.9	-22%	12.7	-33%	Feasible with considerable land use change
11	9.5	11.8	-20%	13.8	-31%	Feasible with considerable land use change
12	10.2	12.6	-19%	14.4	-29%	Feasible with limited land use change
13	12.4	15.2	-19%	18.0	-31%	Feasible with limited land use change
14	7.9	9.3	-15%	10.4	-24%	Feasible with limited land use change
15	9.5	10.8	-12%	12.3	-23%	Feasible with limited land use change
16	13.5	14.6	-7%	16.7	-19%	Feasible with light touch measures
17	11.3	12.0	-6%	13.7	-17%	Feasible with light touch measures
18	9.5	9.7	-2%	11.2	-15%	Feasible with light touch measures
19	11.6	11.7	-1%	12.7	-9%	Unfeasible (urban catchment)
20	8.5	8.4	1%	9.9	-14%	Feasible with light touch measures
21	16.3	16.1	1%	17.8	-9%	Feasible with light touch measures
22	8.5	7.7	10%	8.8	-4%	Probably robust, ensure no deterioration
23	16.5	14.9	10%	16.4	1%	Probably robust, ensure no deterioration
24	14.7	13.1	12%	15.8	-7%	Probably robust, ensure no deterioration
25	15.8	14.0	13%	15.7	1%	Probably robust, ensure no deterioration
26	8.5	7.3	16%	8.1	5%	Probably robust, ensure no deterioration
27	17.6	15.0	17%	16.7	6%	Probably robust (urban catchment)
28	14.9	12.7	17%	14.3	4%	Probably robust, ensure no deterioration
29	17.6	14.8	19%	18.6	-5%	Probably robust, ensure no deterioration
30	14.0	11.1	26%	12.2	14%	Probably robust, ensure no deterioration
31	20.3	14.5	40%	16.6	23%	Probably robust
32	19.0	13.2	44%	16.0	18%	Probably robust, ensure no deterioration
33	22.6	15.6	45%	17.9	26%	Probably robust
34	13.3	9.1	47%	10.8	23%	Probably robust
35	8.5	5.5	54%	6.0	41%	Probably robust
36	14.0	8.7	60%	10.2	37%	Probably robust (urban catchment)
37	14.9	9.3	61%	11.7	28%	Probably robust
38	20.3	12.5	62%	14.5	40%	Probably robust
39	12.6	7.8	63%	8.7	45%	Probably robust
40	24.8	15.2	63%	19.3	29%	Probably robust
41	27.1	16.5	64%	19.2	41%	Probably robust
42	8.5	5.1	66%	5.7	49%	Probably robust (urban catchment)
43	8.5	5.1	66%	5.9	44%	Probably robust
44	17.4	7.5	131%	8.3	110%	Probably robust

Figure 4. Assessment of catchment management feasibility.

MEASURES TO REDUCE CATCHMENT NITRATE LOADING

Diffuse pollution mitigation measures aimed at mitigating leaching of nitrate to groundwater are identified in Newell-Price *et al.* (2011). While precise selection of measures to implement in a catchment requires individual assessments of the local farm-scale context, some generic mitigation strategies were considered. Light touch measures, or those that require no fundamental change to farming operations, are preferred as farmers' business models would not be substantially affected.

- For arable-dominated land, light touch measures might include: use of cover crops before spring cereals; use of a fertiliser recommendation system; and integration of fertiliser and manure nutrient supply. In combination, these may achieve a reduction in nitrate losses to groundwater of up to 8%. Where outdoor pigs are part of the rotation, low N and P foods can be used to reduce nitrate loading by 10% to fields where manure is applied.
- For pasture-dominated land, light touch measures might include: reduction of field stocking rates when fields are wet; avoiding spreading manufactured fertiliser at high risk times; use of clover in place of fertiliser N; use of a fertiliser recommendation system; and integration of fertiliser and manure nutrient supply. In combination, these may achieve a reduction in nitrate losses to groundwater of up to 10%. Where dairy cattle are farmed, low N and P foods can also be used to reduce nitrate loading by 10% to fields where manure is applied.

Some of these measures proposed above are cost beneficial for the farmer, and others are required for farms in an NVZ – so they may be current practice in the catchment and the anticipated reduction may not be achieved. On the other hand, if they are not practised, then the changes will lead to more profitable farm businesses and therefore there should be little resistance to change.

More significant changes to the farming systems might be required to achieve reductions in N loading of more than about 8%. These might include: undersowing of spring crops (c. 10% reduction in the catchment); reduction in stocking densities; or reversion of some or all arable land to extensive grazing (c. 80% reduction on land reverted) or woodland (up to a 95% reduction). However losses of income incurred would need compensation, and schemes would inevitably meet with some resistance.

FEASIBILITY OF CATCHMENT MANAGEMENT

Based on the likely effectiveness of mitigation measures presented above, the following statements of catchment management feasibility can be made:

- **Light touch measures** are recommended in the first instance for catchments with predicted headroom between, say, -8% and +5%. Perhaps, however, many of the measures are in current practice, and a judgement would have to be made whether to encourage more significant change. If the measures have been recently adopted then it is likely that there will be some improvement in concentrations anyway.
- **Limited land use change** would be recommended if headroom is between, say, -20% and -8%. Reversion to extensive grazing of, perhaps, the 10% of land in the catchment nearest the borehole(s) would be beneficial both because of an additional 8% reduction of nitrate loading, but also it would tend to reduce the magnitude of variability in monitored concentrations at the abstraction. Since abstraction yield is mostly obtained from areas closest to the borehole(s) (Figure 2) there is a disproportionate gain in water quality if inputs in this area are controlled.
- **Considerable land use change** would be at the scale of reversion of arable land use on the scale of whole farms or catchments. While this often still appears to be cost effective compared to construction of a nitrate treatment plant, it is likely to meet considerable resistance, and other high-level pressures begin to become significant (such as local jobs, and food security). It is expected that this level of land use change could not be widely achieved in the UK.
- **Ensuring no deterioration of water quality** is recommended for catchments where the headroom is insufficient to cope with additional inputs of N from changing crop types, say +5% to +20%. In these catchments it is recommended that some of the light touch measures might be encouraged (where they are cost beneficial to the farmer) and contact be maintained to ensure that the water company has early warning of, for example, ploughing up permanent pasture, or an increase in the amount of maize or potatoes grown.

From Figure 4 it is clear that, of the 44 sources in the studies, it would not be possible to achieve targets without considerable land use change in 11 catchments (25%), and in 13 catchments (30%) the headroom is sufficient that there is little risk of drinking water quality being compromised. In four catchments (9%) the nitrate inputs are dominated by urban influences, for which effective measures are not yet defined. Of the remaining 16 catchments (36%) some level of stewardship is recommended and catchment management should be a feasible solution to protecting drinking water quality.

CONCLUSIONS

Compelling evidence for the effectiveness of catchment management needs support from catchment-specific data sets and modelling. Calibrating a predictive model to historical data, in which upward trends are the result of historical increased nitrate loading, provides confidence that the model can predict the effects of reduced nitrate loading. Use of a nationally-validated soil zone model (NEAP-N) in a nitrate trending model removes further uncertainty. Review of data, conceptualisation and modelling of nitrate trends in 44 catchments from the English Midlands and North West provides insights into the nature of catchment-scale nitrate transport and near-borehole effects. With a few exceptions, deviations from expected soil zone concentrations can be explained by a few hydrogeological influences.

Predictions of future nitrate concentration, when compared with water company targets, can be used to assess feasibility of catchment management. In many of the catchments studied, measures would not be required because a better understanding of the system demonstrates that drinking water quality is not at risk. In many others, concentrations are too high to be managed effectively. In the remainder, a spectrum of stewardship schemes would be required to achieve desired reductions in nitrate loading. Catchment management is most suited to achieving marginal (<20%) reductions in nitrate concentrations in the catchments studied. At this level of loading reduction, some land use change would be required. Where the reduction in concentration required is 8% or less measures may be cost beneficial for the farmer and may not need incentivisation for their adoption.

Calibrated and conceptually-justifiable models can provide compelling evidence that can be used to design mitigation strategies and to persuade stakeholders of the effectiveness of proposed measures. With this evidence, practical interventions needed to reduce pollutants entering groundwater are far more likely to be adopted, maintained and assimilated into everyday farming practice. This is crucial to maintain the long-term sustainability of catchment management programmes and will provide the value for money sought by both water companies and Ofwat.

ACKNOWLEDGEMENTS

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GROUNDWATER MODELLING TOOLS USED IN CATCHMENT MANAGEMENT

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ABSTRACT

The Environment Agency uses a range of groundwater resources modelling tools for catchment management, taking a tiered, risk-based approach to regulation. These tools have been used for assessment of available groundwater resources for abstraction, assessment of groundwater impacts upon surface water bodies and groundwater-dependent terrestrial ecosystems, and in groundwater protection for definition of source protection zones and safeguard zones. The EU Water Framework Directive (WFD) has required a more integrated approach to catchment management of groundwater and surface water quantity and quality to protect ecological receptors. Modelling tools aid the development of conceptual understanding and support decision-making, for example investigating measures to mitigate groundwater abstraction or chemical impacts. These tools are being used by a wider range of users, including private Water Companies, who may use them for investigation of groundwater quality and land use impacts, and delineation of source protection zones. Although groundwater modelling tools can inform many of these issues, they are only part of a broader picture combined with surface water, ecology, economics and geomorphology.

In secondary aquifers, numerical models are not always appropriate and the skill of the hydrogeologist (ideally working as part of a multidisciplinary team) in the development of a good conceptual understanding at a catchment scale becomes vital to effective catchment risk assessment and management. Both in the UK and Ireland, public finances are tight, so it is important to focus resource on smarter use of hydrogeological conceptual understanding and decision-making. A range of modelling and visualization tools are available to the Environment Agency which help in this work including simple analytical tools, geological models, GIS-based data visualization tools, spreadsheet tools and impact models.

INTRODUCTION

This paper describes the range of groundwater resources modelling tools developed by the Environment Agency, and discusses their use in catchment management. Integrated management of land and water requires that we consider the integration of data, understanding and decision making so that adopted remedial measures in one sector (such as risk) do not have negative effects in other sectors (such as fisheries)(Farrell & Whiteman, 2008). The UK Government is moving towards an ecosystems approach [Defra 2007] to conserving, managing and enhancing the natural environment in England. This is about adopting a new way of thinking and working, by:

- Shifting the focus of our policy-making and delivery away from looking at natural environment policies in separate 'silos' – e.g. air, water, soil, biodiversity – and towards a more holistic or integrated approach based on whole ecosystems; and
- Seeking to ensure that the value of ecosystem services is fully reflected in policy- and decision-making across Government at all levels.

The modelling of the major aquifers of England and Wales represents a significant investment for the Environment Agency. Catchment scale models, as they attempt to model a large part of the water cycle in some detail, tend to have potential benefits for a much broader cross section of the organisation's work than might at first be considered. The Environment Agency has a national, regulator-led programme of numerical groundwater models covering the principal aquifers of England & Wales (Whiteman et al 2012). The Environment Agency takes a tiered, risk-based approach to hydrogeological impact assessment (Boak & Johnson, 2007). Tiered tools for groundwater resource assessment ranging from simple to complex are described by Farrell & Whiteman (2008).

This paper focuses on recent developments in the use of groundwater modelling tools for catchment management. Over the last 10 years, the Environment Agency has undertaken an extensive national regulator-led programme of groundwater resource assessment and modelling of the principal aquifers of England and Wales (Hulme et al, 2002; Whiteman et al, 2012; Figure 1a). Conceptual models have been developed, and where pressures on groundwater resources justify it, for example in South East England, numerical models have been constructed. Numerical groundwater models are valuable tools for development and testing of conceptual hydrogeological understanding, and also attribution of impacts from groundwater abstractions upon receptors such as rivers and wetlands. However, a quick glance at the geological map of England & Wales reveals that a large part of the country is not underlain by principal aquifers (Figure 1b).

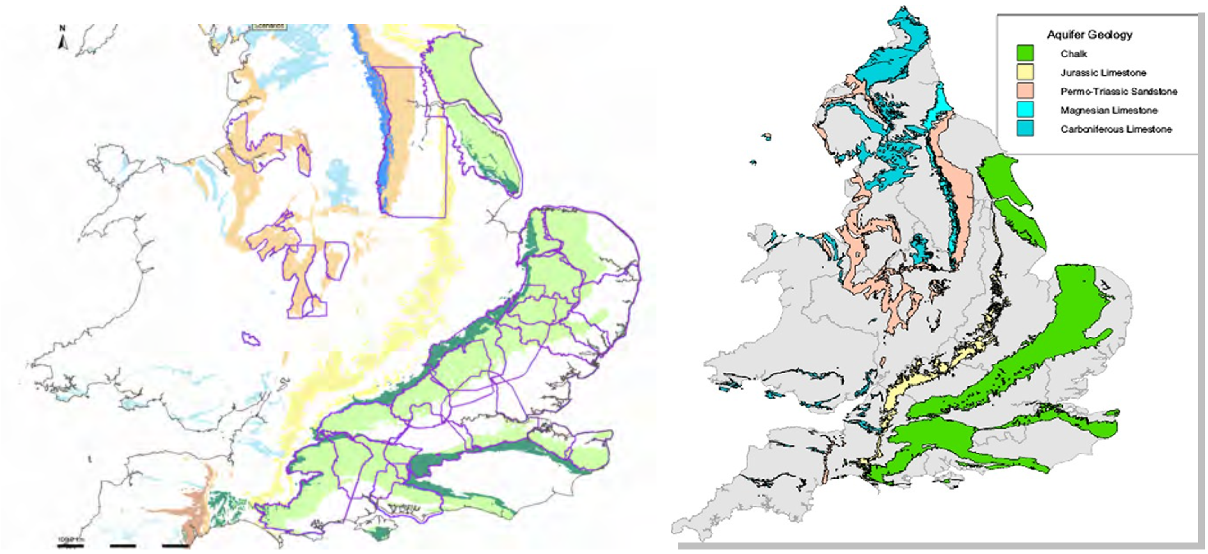

Figure 1: (a) location of regional numerical groundwater models (purple outlines) in relation to principal aquifers in England & Wales; (b) Principal aquifers of England & Wales

For these secondary aquifer areas, often characterised by complex, faulted geological sequences in local structural basins, regional numerical groundwater models are not an appropriate tool for groundwater resources management, being disproportionately costly and time-consuming to apply in such settings. In Ireland this is likely to also be the situation, with large areas underlain by relatively impermeable Palaeozoic basement sequences, and thick quaternary cover deposits. In secondary aquifers, the skill of the hydrogeologist (ideally working as part of a multidisciplinary team) in the development of a good conceptual understanding at a catchment scale becomes vital to effective catchment risk assessment and management. Both in the UK and Ireland, public finances are tight, so it is important to focus resource on being smart with our hydrogeological conceptual understanding and decision-making. A range of modelling and visualization tools are available to the Environment Agency which help in this work (Table 1):

- Simple analytical tools;
- Geological models;
- GIS-based data visualization tools;
- Spreadsheet tools;
- 'impact' models.

Each of these methods will be discussed in turn briefly below.

Complexity/cost	Water Resources	Groundwater Contamination
Simple	Conceptual modelling Guidance (Environment Agency, 2002)	Conceptual modelling (Environment Agency, 2001b)
	Simple risk screening tools e.g. Water Resources GIS risk engine	Groundwater vulnerability maps (Environment Agency, 1999, 2004)
Complex	Simple/analytical (deterministic) models e.g. IGARF (Environment Agency, 2001a)	Analytical (deterministic) models e.g. Remedial Targets Method (Environment Agency, 2006)
	Analytical (probabilistic) code (rarely used)	Analytical (probabilistic) code e.g. ConSim
	Numerical models e.g. MODFLOW-VKD (Environment Agency, 2003)	Numerical models (rarely used) e.g. MODFLOW+MT3D

Table 1: Tiered modelling tools for groundwater resources and contaminant modelling components of integrated catchment management (modified after Farrell & Whiteman, 2008).

SIMPLE ANALYTICAL TOOLS

A suite of analytical solutions have been packaged into spreadsheet tools by the Environment Agency, for example IGARF (Fig.2) which permits rapid assessment of groundwater impacts upon river flows (Environment Agency, 2001a; http://www.environment-agency.gov.uk/business/topics/water/135979.aspx), and analytical solutions for use in modelling the impacts of quarry dewatering. These tools use standard analytical textbook solutions such as those developed by Theis, Hantush and Hunt for different types of aquifer.

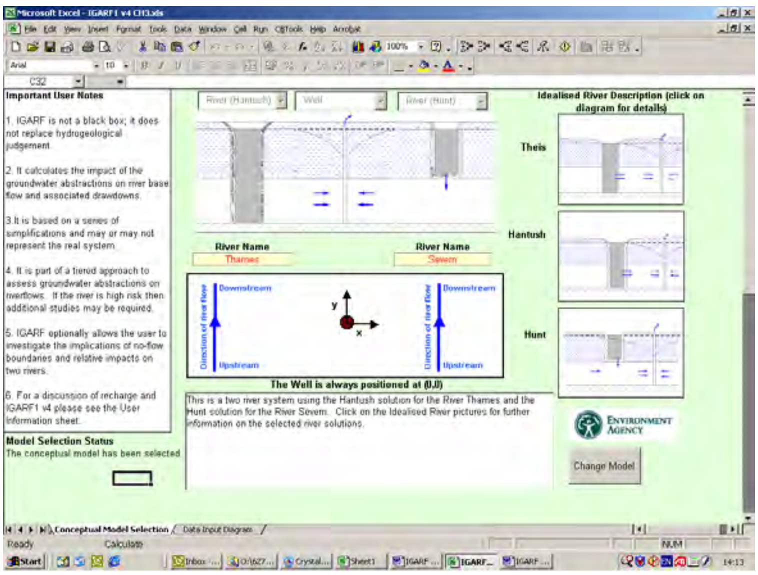

Figure 2: The IGARF (Interaction of Groundwater And River Flows) analytical tool, in this example representing a pumping well located between two rivers.

These analytical solutions are used by hydrogeologists with simple estimates for hydraulic parameters obtained from literature (e.g. Aquifer Properties Manual) or pumping tests, and can be valuable in testing conceptual understanding of hydrogeological processes operating in a catchment.

GEOLOGICAL MODELS

A series of detailed, local 3D geological models have been commissioned by the Environment Agency and produced by the British Geological Survey as part of the national programme of groundwater resource assessment and modelling. These are valuable where a numerical model requires a good understanding of the geological structure from which to make a hydrogeological interpretation. However, such models can be expensive and time consuming to construct. Recent collaborative development work between BGS and the Environment Agency (BGS, 2010) has led to the development of a more skeletal network of geological 'fence diagrams' for England and Wales (Figure 3). These have the advantage of providing a large-scale overview which can help build the framework of conceptual understanding. It is important to use these as an aid for the hydrogeologist to delve down to the catchment scale using local information and their conceptual understanding and skills.

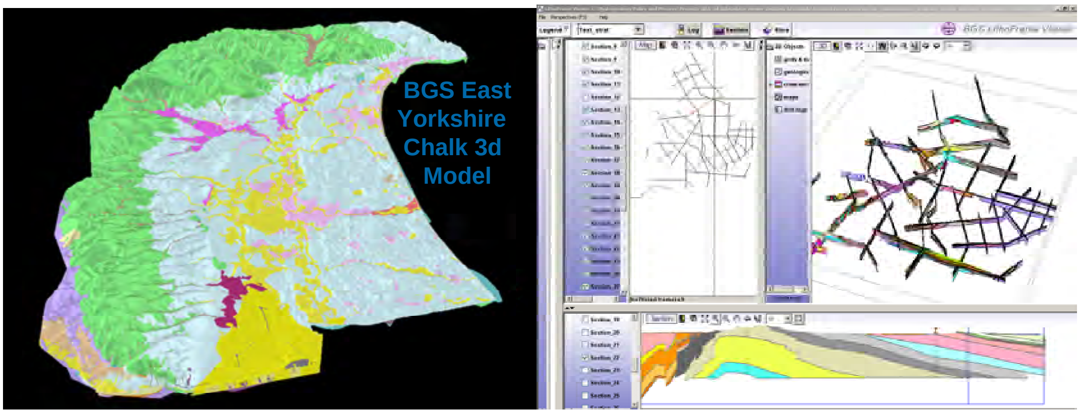

Figure 3: (a) BGS 3D Lithoframe geological model for East Yorkshire Chalk; (b) Geological fence diagram for England and Wales.

GIS-BASED DATA VISUALIZATION TOOLS

In recent years there has been a rapid expansion of the use of GIS to overlay hydrogeological datasets including model inputs such as recharge and aquifer parameters, and outputs such as groundwater heads, river-aquifer interactions, streamflows and groundwater flow vectors. GIS tools such as 'Modelmap' developed by AMEC Environment & Infrastructure (UK) for the Environment Agency, are valuable to hydrogeologists as they help with rapid development of conceptual understanding. Modelmap displays the outputs of the regional numerical groundwater models in ArcGIS, and has been adapted to assist with issues such as source protection zone delineation, impacts of groundwater abstractions on receptors including rivers and other protected water features such as wetlands (Fig.4a).

Fundamental to the Environment Agency's role in managing water resources at a catchment and national scale is our 'Water Resources GIS' (Fig. 4b). This has been developed to provide a 'front-end' for our abstraction 'accounting tool', the CAMS ledgers (see below), and to permit automated processing of impacts from abstractions upon surface water bodies. The GIS combines data including the geographic extent of water bodies, land use, and flow statistics, along with artificial influences including abstractions and discharges.

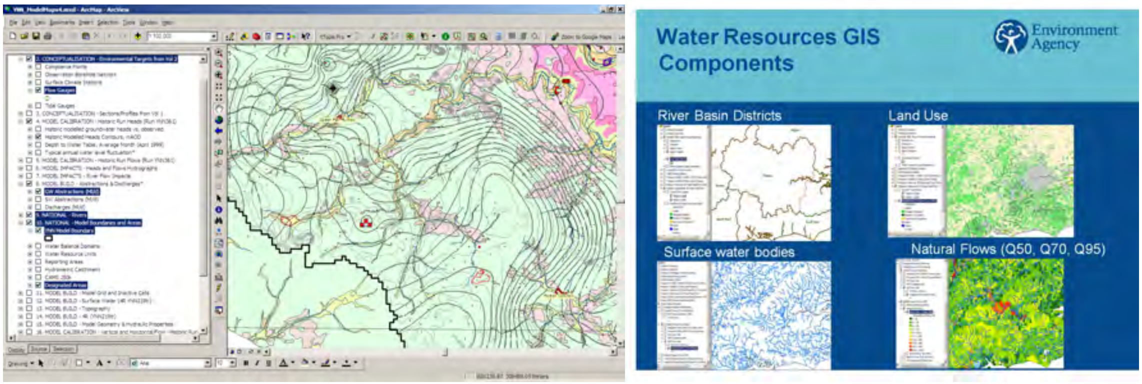

Figure 4: (a) Example of Modelmap GIS showing modelled groundwater head contours in the Chalk, solid geology, groundwater abstractions, flow gauges, environmental compliance points; (b) Components of the Water Resources GIS.

The WFD classification tool has also been developed to aid assessment and reporting. It includes a GIS front end which enables hydrogeologists to find the results of the groundwater quantity and quality status tests for each groundwater body (Figure 5a), including overall groundwater balance, impact of groundwater upon dependent surface water bodies, saline intrusion and groundwater dependent terrestrial ecosystems (Figure 5b). The chemical tests displayed include overall chemical status, trends and specific pollutants. Of specific interest in terms of catchment management is the dependent surface water test, which obtains data from the Water Resources GIS to calculate the proportion of impact from individual groundwater abstractions upon each WFD surface water body.

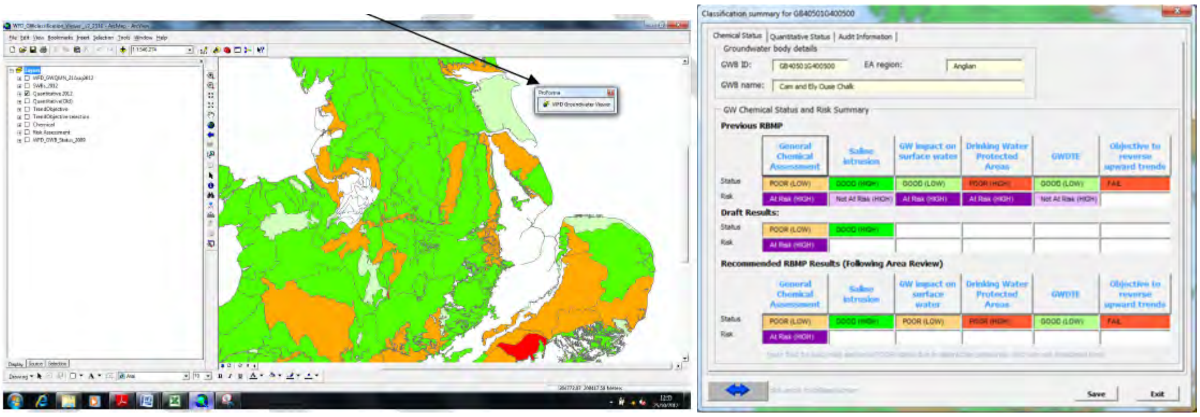

Figure 5: WFD Classification tool (a) GIS front end to enable rapid search for results by WFD groundwater body; (b) summary of groundwater classification test results for an individual water body.

CATCHMENT SPREADSHEET TOOLS

Catchment Abstraction Management Strategies (CAMS; Environment Agency, 2013) are one of the main water resource management tools used by the Environment Agency, both to assist with regulation of abstraction licences, and resource planning. The CAMS ledgers are water balance spreadsheets which contain a summary of all groundwater abstractions within a catchment, including the impact of each abstraction upon surface water bodies. CAMS ledgers are increasingly relied upon to undertake the groundwater status tests for WFD, and to provide information to National Permitting Service (see below). Importantly, the ledgers represent all parts of the hydrological cycle in the catchment, including surface water flows, and complex impacts including reservoir releases and river augmentation and inter-basin transfers not usually represented in numerical groundwater models.

Several modelling utilities have been developed recently to make it easier to use the data and conceptual understanding contained in groundwater models to 'wise up' the CAMS ledger by comparing/improving:

- flow duration curves & time-series flows and improving 'natural' flows;
- artificial influences;
- groundwater abstraction association with aquifers, GW bodies (& groundwater management units);
- groundwater abstraction impacts on surface water bodies;
- recharge.

A 'Risk screening tool' for impacts of licensed groundwater abstractions has also been developed, which takes data from the Water Resources GIS (based on the CAMS ledgers). This is used by the Environment Agency's National Permitting Service to inform licence applicants about the potential for impacts, although it's limitations are recognised, with all complex or high risk applications being passed to technical specialists within local Groundwater & Contaminated Land teams for detailed evaluation. Another useful spreadsheet tool is the recharge calculator developed in partnership with the Scottish Environment Protection Agency (SNIFFER, 2003), which permits recharge estimation for any catchment in the United Kingdom.

MODELLING TOOLS FOR GROUNDWATER PROTECTION

In a recent review of the Environment Agency's source protection zone methodology (Entec, 2010), a suite of modelling tools was recommended, including the US EPA wellhead analytical element tool (WHAEM; US Environment Protection Agency, 2007) which is suitable for situations where a regional numerical groundwater model does not exist. Where a numerical model is available, Modflow output can be processed directly by programs such as Modpath (USGS, 2003) or MODALL (Potter *et al*. 2008). More recently, the Environment Agency, along with Water Companies in the UK have begun to make use of the regional numerical groundwater models using a programme called Flowsource, developed by Groundwater Science Ltd. (Figure 6), which produces comparable results to MODALL, but is computationally more efficient. During 2012, a methodology was developed (AMEC, 2012) using a combination of Modpath and Flowsource to delineate protection zones. Figure 6 shows an example, run using the National Groundwater Modelling System (NGMS), where the fractional flow through each model cell arriving at a source X is calculated with all sources within the model switched on (Fig.6a), then an individual source Y is switched off in a scenario run to examine the effect of that source on the fractional flow to source X (Fig.6b).

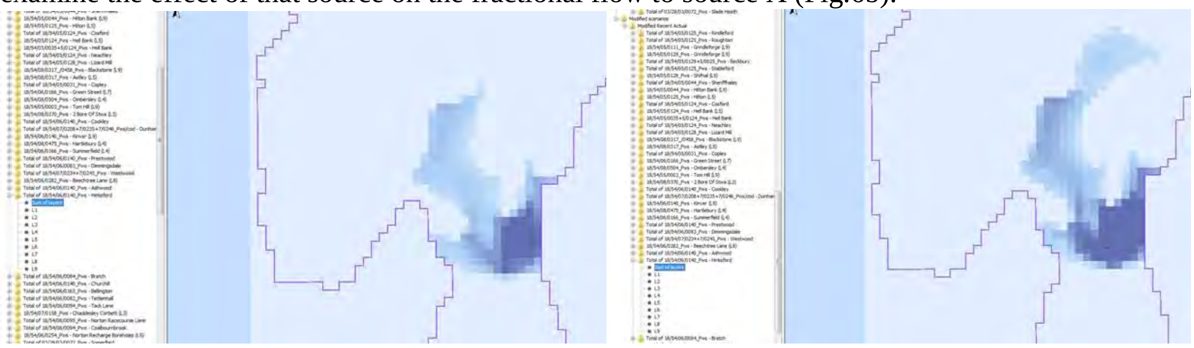

Figure 6: (a) Fractional flow to Source X; (b) Fractional flow to Source X with source Y switched off In both cases the plots show the combined flow contributions of all individual model layers.

Buss (this conference) gives further examples of the use of source protection zone models, including Flowsource, in catchment management to understand the interaction of groundwater sources in a wellfield with changing abstraction rates through time, and interactions with rivers. These tools are a powerful aid to conceptual understanding for the hydrogeologist.

HOW CAN THESE TOOLS BE USED IN CATCHMENT MANAGEMENT?

Hulme *et al.* (2012) describe the development of a simple impact model which can be used to rapidly estimate the impacts of groundwater abstraction where a regional numerical model is not available. Such an approach gives a better representation of impacts than simple analytical tools but takes days/weeks to develop rather than the months/years required for a regional groundwater model. The approach used an impact version of the BGS 'ZoomQ3D' groundwater model. Hulme *et al.* (2012) describe how an impact model can be used to estimate whether abstraction impacts upon river flows are acceptable for specific ecological receptors, in this case fish species in the River Eden. Further work in the Eden catchment, undertaken by the Environment Agency's Science team, examined the potential for building up a 'weight of evidence' for diffuse pollution impacts by combining different existing spatial datasets. This type of 'weight of evidence' approach has also been used to help identify groundwater-dependent terrestrial ecosystems at risk of 'significant damage' from groundwater abstraction and chemical impacts for the WFD 'wetland' test (Whiteman et al, 2010).

The National Groundwater Modelling System (NGMS) has been developed by the Environment Agency as a scenario tool for the numerical groundwater models (Whiteman et al, 2012b). This has proven to be valuable in catchment management by enabling hydrogeologists (not just modelling specialists) from the Environment Agency and Water Companies to undertake abstraction impact scenarios in support of WFD investigations where a groundwater body has failed one of the status tests. Scenarios have also been used to assist Water Companies who are investigating the impacts of groundwater abstractions upon rivers/wetlands as part of the National Environment Programme of capital investment in water supply infrastructure (Figure 7).

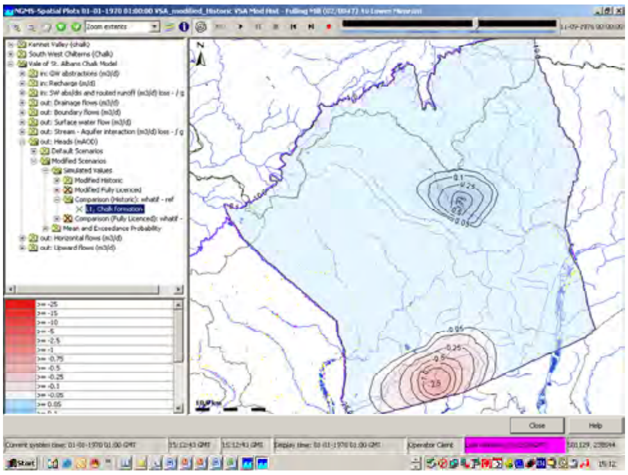

Figure 7: National Groundwater Modelling System (NGMS) - Groundwater head difference plot modelling potential impacts from relocating a groundwater abstractions source to a different location.

In all of these examples, it is important to stress that groundwater is only one component of the problem being evaluated. Finding a successful solution, where the issue involves impacts upon ecology, for example, requires hydrogeologists to work as a team with surface water hydrologists, catchment planners, ecologists, water resource managers and economists. The skill of the hydrogeologist is crucial, however, in understanding conceptually how the system works and communicating this to the other actors (Brassington & Younger, 2010).

Modelling tools are also increasingly being required to undertake scenario analysis for hydrological extremes, such as groundwater flooding, drought and climate change. The UK Government is also currently assessing options for reform of the abstraction licensing system and the role of modelling tools within the proposed new system.

CONCLUSIONS

A tiered suite of groundwater modelling tools have been developed over the last 10 years by the Environment Agency, which can be applied not only in those areas covered by principal aquifers, but also in the large areas of complex geology and secondary aquifers. These tools are important in helping hydrogeologists to conceptualize and communicate the groundwater flow system and impacts upon receptors to a wider audience, as part of the decision-support process. In their own right, the models cannot provide the answers to questions relating to catchment management (Whiteman et al, 2012). They are part of a wider picture including surface water, economics, ecology and hydromorphology. Increasingly, hydrogeologists must work as part of a wider team with specialists from other disciplines and managers to ensure effective measures are put in place, such as those required to restore groundwater bodies to good status, and by tackling ecological impacts or managing land use to reduce diffuse pollution. A detailed numerical model of the groundwater system is often not available or necessary to make robust catchment management decisions, especially in complex secondary aquifers and/or where abstraction pressures are low. Much can be gained by sharing conceptual understanding, and the use of visualisation tools such as GIS.

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STUDENT POSTER PRESENTATIONS

MULTI-DISCIPLINARY INVESTIGATION OF IRISH WARM SPRINGS AND THEIR POTENTIAL FOR GEOTHERMAL ENERGY PROVISION

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ABSTRACT

Irish warm springs are one of a set of several target types that will be assessed for their geothermal energy potential during the course of the IRETHERM project.

There are 42 recorded warm springs in Ireland that can be grouped into two distinct clusters, in East Leinster and North Cork. Water temperatures measured in these springs (approximately 12°C to 25°C) are elevated with respect to average Irish groundwater temperatures. This study will focus on the Leinster warm springs. Geophysical methods (controlled source electromagnetics (CSEM) and audio-magnetotellurics (AMT)) will be utilised in conjunction with hydrochemical analysis to determine the source of the heated waters at depth and the nature of the conduit systems that deliver the warm waters to the surface. This will provide the basis for an assessment of these spring occurrences for geothermal energy provision.

This poster presents our current assessment of existing and available hydrochemical data, and preliminary subsurface models derived from new geophysical data collected by IRETHERM during 2012. High-resolution AMT surveys at Kilbrook spring, Co. Kildare, and St. Edmundsbury spring, Lucan, Co. Dublin consist of a grid of 40 soundings recorded at roughly 200 m intervals centered on each spring. A CSEM survey (25 sounding localities with 100 m spacings along 2 profiles) was also carried out at St. Edmundsbury spring. These surveys aim to image directly any (electrically conductive) fluid conduit systems that may be associated with the springs and provide an understanding of the observed association of the springs with major structural lineaments such as the Iapetus Suture Zone.

Future work will include detailed hydrochemical analysis of several key warm springs in Leinster. The groundwater sampling and analysis will be carried out over six seasons. A further AMT survey is planned for St. Gorman's spring near Enfield, Co. Meath, in 2013.

UPDATING/EXTENDING THE WATER BALANCE FOR THE POLLARDSTOWN FEN 2010 TO 2011

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ABSTRACT

A constant supply of calcium-rich groundwater from the surrounding gravel aquifer helps sustain the habitat of the whorl Snail Vertigo geyeri at the Fen margin. The snail's habitat is protected under the EU Habitat's Directive, and the snail is used as an indicator species to assess the health of the habitat. Dewatering of the aquifer took place from 2001 to 2003 to facilitate construction of a bypass road. A combination of dewatering and below average rainfall in subsequent years lowered the aquifer groundwater level below the critical level required to sustain the habitat. This investigation aimed to identify any continuing impact from dewatering on the aquifer groundwater level and to establish if groundwater levels have recovered following dewatering.

A catchment water balance was used to estimate the 2010/11 fen catchment area, and this result compared favourably with an estimate based on groundwater head data. Both found that previous research had overestimated the catchment area by 11%. The location of the seasonal low groundwater divide from 1997 to 2010 was plotted and the resulting catchment areas calculated. A time-series plot of these areas indicated a reduction in catchment size in the 2002/03 hydrological year, possibly related to dewatering. Groundwater levels were impacted by dewatering from 2000/01 to 2002/03 and a residual impact continued to the 2005/06 seasonal low. Above average rainfall in 2006/07 recharged the aquifer enabling recovery of the groundwater level. A strongly positive linear relationship between the change in groundwater head with effective rainfall over the hydrological year was established for aquifer monitoring wells (R^2 of 0.953, sig. < 0.001). This relationship indicates that annual effective rainfall of 325 mm to 350 mm is required to maintain equilibrium. This study has increased the understanding of the aquifer dynamics, and the relationship between head change and effective rainfall will be a useful tool to manage the groundwater resource.

NITROGEN ATTENUATION ALONG DELIVERY PATHWAYS IN AGRICULTURAL CATCHMENTS

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ABSTRACT

Nitrate is regarded as one of the dominant contaminants affecting surface water and groundwater quality worldwide. With the enactment of the EU Nitrates Directive (1991) into Irish law, the risks to water quality associated with farmland activities must be reduced while also maintaining agricultural productivity. The Agricultural Catchments Programme (ACP) aims to provide a scientific evaluation of the effectiveness, or possible need for modification, of the National Action Programme measures under the Nitrates Directive. These measures are implemented through the Good Agricultural Practice for Protection of Waters Regulations (2010). In order to facilitate this objective, a detailed conceptual understanding of the fate of agriculturally derived nitrogen as it travels through the subsurface is required. This research project is being undertaken from 2012 to 2016 in two intensively managed catchments in Co. Wexford and Co. Cork. Both catchments are dominated by well drained soils and relatively permeable geology but have contrasting prevailing land-use: tillage in Co. Wexford and dairy grassland in Co. Cork. The focus of this work is to quantify the flux of nitrogen through the saturated zone, from the top of an intensively monitored hillslope transect, to its base where it intersects with the stream hyporheic zone. Each hillslope borehole consists of three piezometers all equipped with an instrument recording and logging groundwater piezometric level. This information, in conjunction with monthly low flow groundwater sampling and analysis, will provide a nitrogen flux dataset with a high degree of temporal accuracy. In addition, the nitrogen assimilatory capacity of both the aquifer system and hyporheic zone will be quantified. This will be achieved by undertaking dissolved gas sampling and also isotopic tracer analysis on the boreholes and also, potentially, within the hyporheic zone.

ANALYSIS OF FAULTS AND FRACTURE SYSTEMS AND THEIR IMPACT ON GROUNDWATER FLOW IN IRISH BEDROCK AQUIFERS

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ABSTRACT

Fault and fracture systems are the most important store and pathway for groundwater in Ireland's bedrock aquifers either directly as conductive flow structures or indirectly as the locus for the development of dolomitised limestone and karst. Through the quantitative analysis of fault and fracture systems in the broad range of Irish bedrock types, this project is designed to develop generic conceptual models for different fault/fracture systems in different lithologies and at different depths, linking them to observed groundwater behaviour. In this poster, we briefly describe the geometrical characteristics of the full range of post-base Carboniferous fault/fracture systems controlling groundwater flow in different Irish bedrock types from field observations at more than 60 outcrop, quarry and mine localities. The structures range from Lower Carboniferous normal faults through to Variscan-related faults and veins, with the most recent structures including Tertiary strike-slip faults and ubiquitous uplift-related joint systems. A variety of attributes are described, including fracture orientations, densities, spacing/clustering, sizes (e.g. aperture/thickness), scaling, connectivity and depth, all of which are critical determinants of the flow behaviour of such systems: differences in attributes within certain lithological sequences are attributed to mechanical controls. The geometrical characteristics of different fault/fracture systems combined with observations of groundwater behaviour in both quarry and mine localities, can be linked to general flow and transport conceptualisations of Irish fractured bedrocks, but most importantly they also provide a basis for relating groundwater flow to particular fault/fracture systems and their expression with depth. Although uplift-related joints always contribute to flow and storage, Variscan faults and veins and Tertiary strike-slip faults, in particular, are often the most permissive Carboniferous or younger structures.

SESSION II

PHOSPHORUS ATTENUATION POTENTIAL ALONG THE NUTRIENT TRANSFER CONTINUUM IN A KARST SPRING ZONE OF CONTRIBUTION

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ABSTRACT

This study applied concepts of specific phosphorus (P) vulnerability to develop intrinsic groundwater vulnerability risk assessments in a 32 km^2 karst spring zone of contribution in a relatively intensive agricultural landscape in western Ireland. To explain why emergent spring water was below an ecological risk threshold, concepts of P attenuation potential were investigated along the nutrient transfer continuum based on soil P buffering, depth to bedrock and retention within the aquifer. New techniques of high temporal resolution monitoring of P loads in the emergent spring made it possible to estimate P transfer pathways and retention within the aquifer and indicated small-medium fissure flows to be the dominant pathway. A revised groundwater vulnerability assessment was used to produce a specific P vulnerability map and, using this and soil P data, the definition of critical source areas in karst landscapes was demonstrated. Following material is part of a manuscript currently under peer review.

INTRODUCTION

Nutrient delivery to groundwater-fed surface waters is determined by the transfer of nutrients through the soil-aquifer continuum (*e.g.* Fenton *et al*., 2011) and is a major concern where diffuse pollution from agricultural sources is a significant and widespread pressure (Haygarth *et al*., 2005). Karst aquifers are seen as particularly vulnerable to contamination and in need of special protection as they are important for groundwater-fed surface water ecosystems (Goldscheider, 2005) and also important drinking water resources (Mimi *et al*., 2012). In Ireland, where approximately 19% of the landscape is underlain by karst (Daly and Drew, 1999), there is a concern that P in groundwater from karst aquifers may contribute to poor ecology of adjacent surface waters (Kilroy and Coxon, 2005). Groundwater in Ireland is considered to be at *"poor status"* when an Environmental Quality Standard (EQS) of an annual mean concentration of 0.035 mg l^{-1} of total (molybdate) reactive P is exceeded and when the hydraulic load from that groundwater body exceeds 50% of a receiving surface water body that is at less than "*good status*".

Specific groundwater vulnerability concepts were developed within the European Union for land use planning and groundwater protection (Zwahlen, 2004) and are transferrable to other regions of karst landscape. In contrast to intrinsic vulnerability, specific vulnerability classification takes both the properties of the contaminant and the intrinsic vulnerability of the area into account but is constrained by the nature and depth of data related to the contaminant. This specific classification is useful, for example, when dichotomies arise in terms of intrinsic vulnerability classification and observed water quality (*eg.* Mellander *et al*., 2012a).

EXPERIMENTAL SITE

The investigated 32 km^2 spring ZoC is in Cregduff, Co. Mayo, western Ireland. The geology consists of a medium to thick bedded pure Carboniferous calcarenite limestone overlain by relatively thin glacial deposits (0 – 5 m) which thin-out towards the west (Drew and Daly, 1993). The topography is gently undulating and characterised by numerous karst features such as springs, sink holes, ephemeral streams, losing streams, dolines (enclosed depressions of varying morphology and the most frequent feature), epikarst windows (exposed epikarst), superficial solution features and turlough areas (seasonal groundwater-fed lakes). Soils in the area are dominated by shallow Brown Earths (Cambisols) and Rendzinas (Leptosols) with Gleys (Gleysols) and Peats (Histosols) in more poorly drained areas.

METHODS

1. Catchment soils were sampled to assess the soil P status and depth.
2. Phosphorus attenuation potential was characterised for dolines (the most prevalent karst feature) by a detailed field survey.
3. Spring water discharge and P concentration was monitored on a sub-hourly basis in the main emerging spring.

RESULTS AND DISCUSSION

During 2.5 years of monitoring the Environmental Quality Standard (EQS) for P was only exceeded on four occasions (Fig 1).

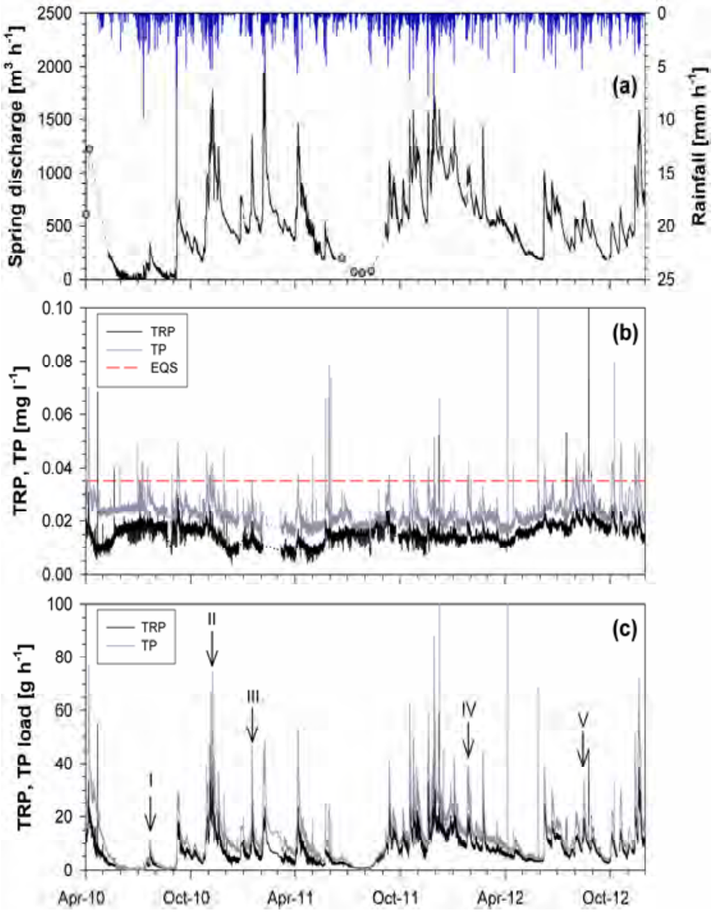

Figure 1: Hourly hydrochemistry in the main spring zone of contribution. EQS = 0.035 mg TRP l^{-1} is marked with red horizontal line. Arrows highlights five analysed flow events.

Annual total P delivery to the main emerging spring was 92.7 and 138.4 kg total P (and 52.4 kg and 91.3 kg as total reactive P) for two monitored years, respectively.

Thin soils (< 1 m) apparently provided substantial buffering against P leaching loss, despite a high vulnerability to vertical water movement.

90 % of 1327 dolines had sediment floors with a buffering capacity against P leaching loss.

Small-medium fissure flows dominated the P transfer pathway, delivering 52-90 % of P loads during storm events (Fig. 2).

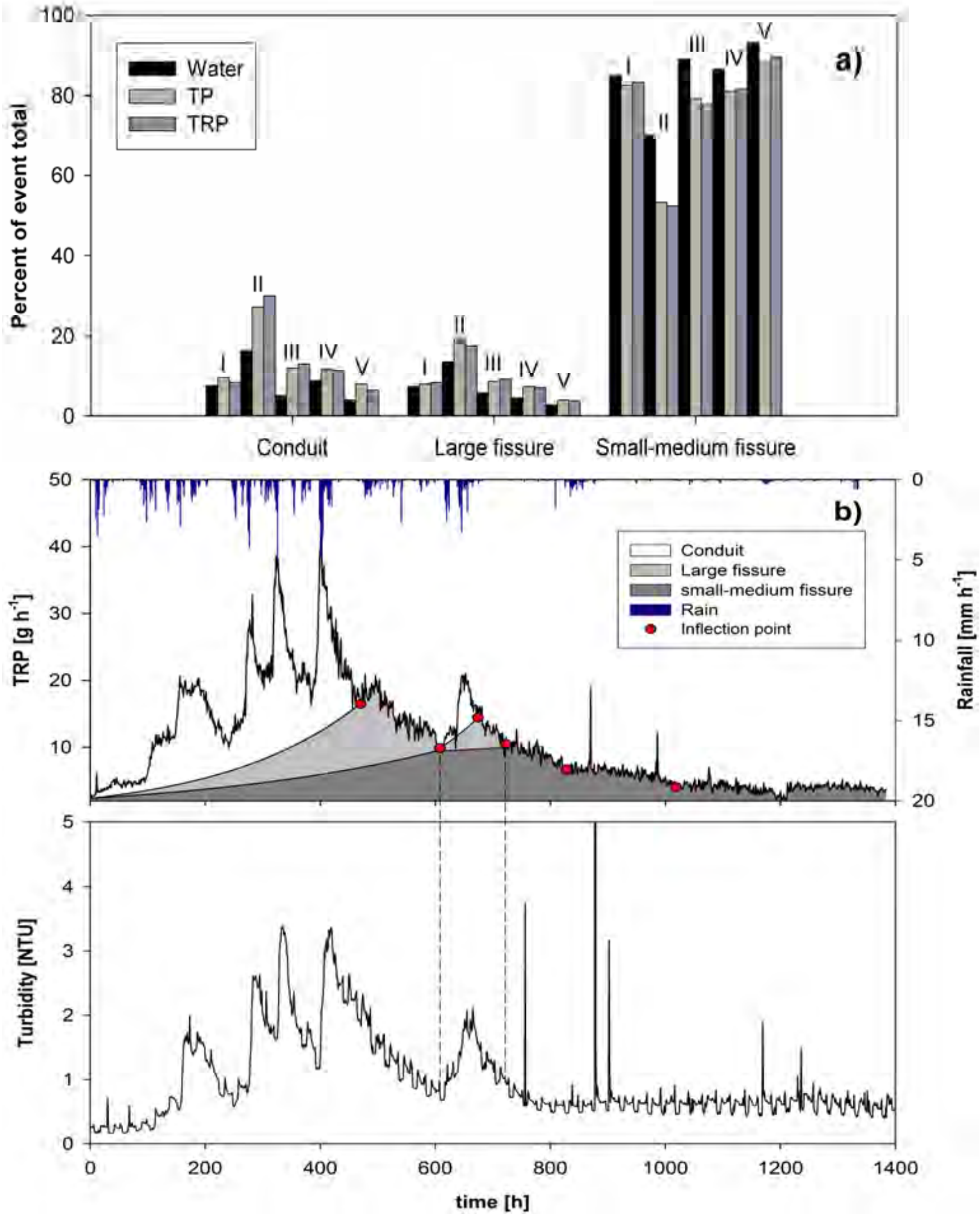

Figure 2: Proportion of water and P transfer pathways for five flow events. Water and P transfer pathways were estimated using *hydrograph separation* and *Loadograph Recession Analysis (*Mellander *et al*., 2012b*)*

A revised groundwater vulnerability assessment *(*Mellander *et al.*, 2012a*)* was used to produce a *specific P vulnerability* map. Only 14% of the spring zone of contribution was classified as being highly vulnerable to P transfer to groundwater (data not shown).

The proposed type of *specific groundwater P vulnerability* map could be used to identify critical source areas (CSA) by combining this with soil P status. This CSA map highlights areas of high risk for P transfer to the aquifer and suggests where measures could be targeted for greater effect. Across the spring ZoC, this CSA approach identified 2% of the sampled farmed land at high risk and 4% at moderate risk (data not shown).

CONCLUSIONS

The proposed *specific P vulnerability* classification uses simple categories of risk assessment based on conceptual models of nutrient loss and attenuation processes in a karst landscape combined with (at least) data on source pressures; at the catchment or contributing area scale, this is only validated by the magnitude of catchment exports. Importantly, however, the assessment includes components of the P transfer continuum from source to delivery and can be used to modify expectations of risk and focus management efforts in karst landscapes sensitive to nutrient loss and eutrophication.

ACKNOWLEDGEMENTS

This study is a part of the Agricultural Catchments Programme funded by the Irish Department of Agriculture, Food and the Marine. We thank the Irish Department of Environment, Community and Local Government for additional support with mapping and tracing work. We acknowledge farmers for cooperation and access to their land. We thank Mr Donal Daly from the Irish Environmental Protection Agency for valuable discussion and suggestions regarding the specific P vulnerability map. Discharge data were provided by Environmental Protection Agency hydrometric staff.

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DEVELOPING GROUNDWATER CONCEPTUAL MODELS FOR THE UK DEMONSTRATION TEST CATCHMENTS

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British Geological Survey

ABSTRACT

The Demonstration Test Catchment project in the UK is studying diffuse agricultural pollution, and which on-farm mitigation measures are most effective at reducing it. The British Geological Survey (BGS), principally funded by NERC and Defra, is involved in all three of the DTC study areas providing geological and hydrogeological expertise and contributing to the conceptual models of the groundwater systems. This paper describes some of the work and results to date.

INTRODUCTION

Agricultural diffuse pollution, particularly from nitrate and phosphate, is a significant problem in the UK (e.g. Carpenter *et al*., 1998; Jarvie *et al*., 2005; Collins and Antony 2008; Kay *et al*., 2008) and is the focus of the national Demonstration Test Catchments (DTC) programme (http://www.demonstratingcatchmentmanagement.net) - a UK Government initiative. One of the objectives of the DTC programme is to test the hypothesis that it is possible to cost effectively reduce the impact of agricultural diffuse water pollution on ecological function while maintaining food security through the implementation of multiple on-farm measures. This will involve studying how such measures affect pollutant concentrations in so-called receptors, such as the streams which drain the catchments (e.g. Zhang *et al*., 2012). To evaluate a measure it is therefore important to understand the nature of the surface and subsurface pathways between where a measure is applied and the stream draining the catchment. These may be complex and include a combination of surface, shallow subsurface and deeper subsurface routes. In particular, knowledge of flow timescales is important in order to interpret the monitoring data.

source	→	**pathway**	→	**receptor**
Measures applied to reduce diffuse pollution		Overland flow Interflow through soils Shallow groundwater Deeper groundwater		Instream monitoring at catchment outlet

Test catchments have been identified in three different areas and monitoring equipment installed in them. The catchments cover both upland and lowland areas of England with different agricultural and farm management systems. They are underlain by different rocks with a range of hydrogeological properties and hence variations exist in the interaction between surface water and groundwater. It is therefore important to investigate how water moves from the land surface to the receptors and in particular to quantify the amounts and timescales which are involved for the different water flow routes.

Methods that can be used to study the pathways include:

- Geological modelling
- Hydrogeological assessments
- Flow accretion measurements, as rivers do not gain flow uniformly
- Age indicators
- Numerical modelling to test hypotheses
- Natural groundwater quality, eg phosphate may not all be coming from pollution.

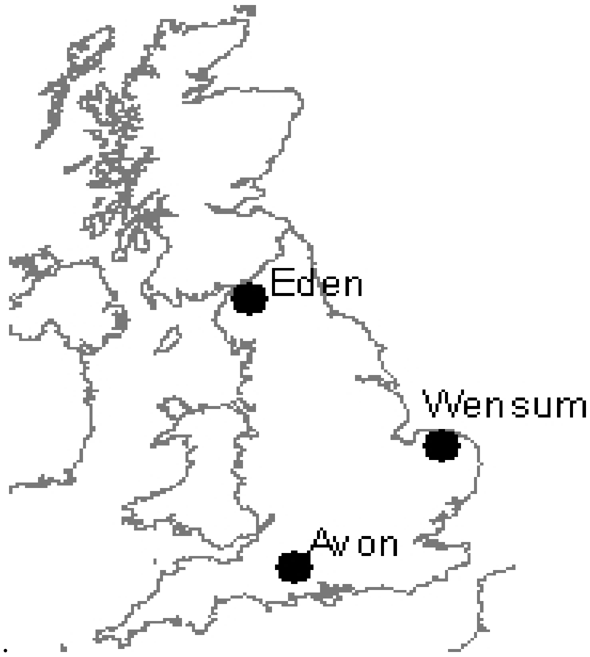

Figure 1 Location of Demonstration Test Catchments

The DTC catchments chosen were the Eden in Cumbria, the Avon in Hampshire and the Wensum in Norfolk (Figure 1). Groundwater flow comprises a significant component of main river flow in all of these catchments, ranging in overall terms from around 50% of river flow in the Eden to 90% in the Avon (Table 1). It is therefore important that robust conceptual models of the groundwater flow systems of the catchments - and in particular of the monitored sub-catchments - are developed.

Table 1 Baseflow indices (BFI) for the DTC catchments

Catchment	**General BFI range (%)**
Eden	26-50
Wensum	60-83*
Avon	72-94

Source: NERC Hydrological data UK, 2003

*Includes data from adjacent rivers

The different geological and agricultural characteristics of the catchments are shown in Table 2.

Table 2 Characteristics of DTC catchments

DTC	Superficial deposits	Bedrock geology	Main farm type
Eden	Glacial deposits, locally	1. Palaeozoic volcanics and conglomerates 2. Carboniferous sediments 3.Triassic sandstones	Arable and livestock
Wensum	Glacial deposits	Chalk	Arable
Avon	Alluvial deposits, locally	U Jurassic sediments, UGS and Chalk	Arable and livestock

Background monitoring data have been collected for over a year, and now the on-farm mitigation measures are being applied. These include buffer strips, fencing of streams to avoid poaching of banks, ensuring yards are properly drained, washing down of equipment on hard standing, etc.

EDEN DTC

In the Eden DTC, the high rainfall and runoff means that pollutants are likely to be somewhat diluted. The study catchments cover a variety of bedrock types and, where present, the nature of the glacial deposits (till) can have a significant effect on groundwater flow routes to streams. Drilling in one of the DTC sub-catchments has shown that while the till sequence mainly consists of clay it also contains layers of sand and gravel. These sands are likely to be permeable and are known to provide subsurface drainage pathways to a stream (Figure 2). The Morland subcatchment contains fractured limestones where underground flow can emerge at specific points as springs or upwellings of water in the stream bed.

Figure 2 Drainage from a sand horizon in the till to a stream

WENSUM DTC

In the monitored Blackwater subcatchments, the Chalk aquifer (locally in hydraulic continuity with the overlying Crag) is overlain and confined by a thick and complex sequence of Quaternary deposits, deposited by the interaction of two ice sheets. The associated sediments comprise tills (with different compositions and properties) interbedded with, and probably glacially tectonically emplaced, glaciofluvial sands and gravels and glaciolacustrine sands and silts. Groundwater movement is mainly through, and stored in, the sands and gravels, with some flow through the more permeable tills. In the western subcatchments, the uppermost deposits have low permeability, and surface runoff predominates with water moving rapidly from the land surface into watercourses, often via field drains. Further east, where more permeable material is present at the surface, pollutants reach the watercourses more slowly by following a variety of shallow and deeper flow paths.

Two cored boreholes were drilled, in conjunction with the University of East Anglia, and the pore water extracted by centrifuging the sands and squeezing the clays. These pore waters were analysed for major and minor ions as well as stable isotopes. Analysis of the pore waters in borehole F (**Figure 3**) shows a redox boundary and indicates in combination with the piezometry that little groundwater infiltrating in this part of the catchment will reach the underlying, and regionally important Chalk aquifer. At each site other boreholes were completed at varying depths to sample the groundwater from different horizons and aquifers. The pumped water from all these holes and a nearby pumping station were analysed (for the same determinands as the pore waters, as well as for age indicators (CFC and SF_6) and stygobytes) to provide information on the age and origin of the groundwaters. This has provided information on the processes occurring in these deposits, assisting in the understanding of groundwater movement through the sequence above the Chalk aquifer.

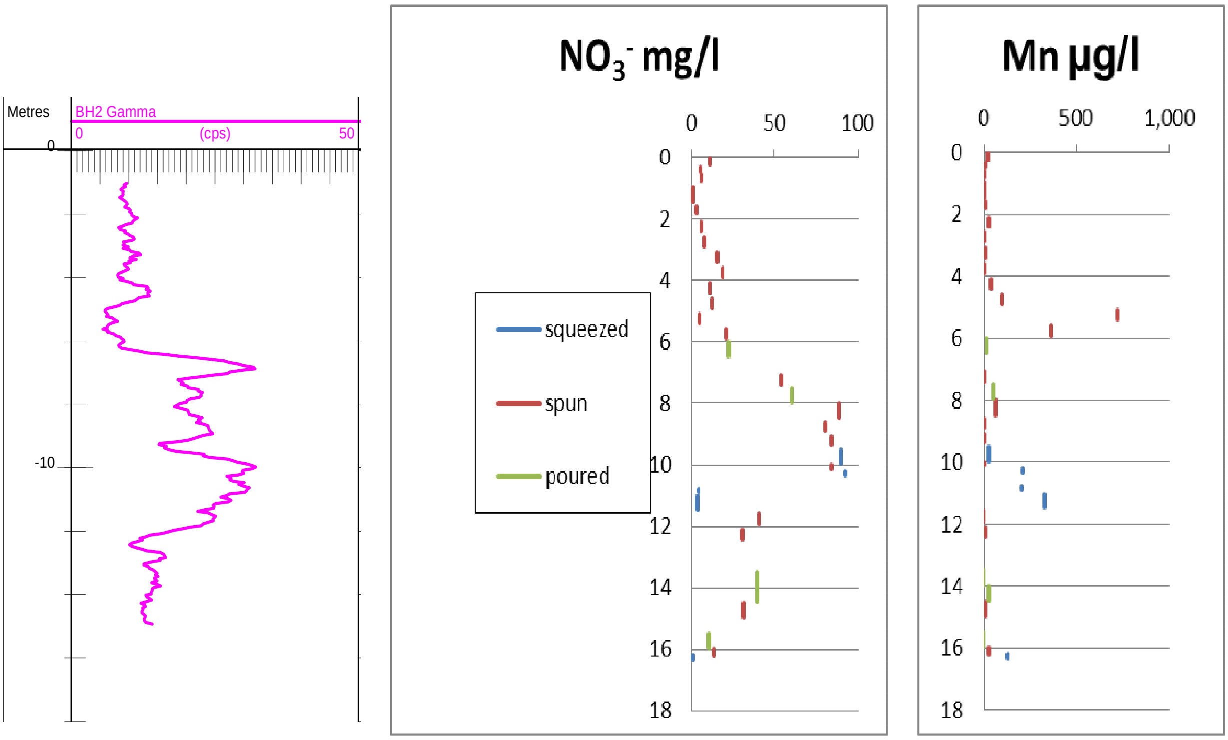

Figure 3 **Gamma log and porewater profiles from borehole in Blackwater subcatchment F**

AVON DTC

Geological variations in the Avon DTC have a significant effect on how stream flows change along a river's course. For example, in the Wylye sub-catchment around 90% of river flow is derived from groundwater as the catchment is dominated by the Chalk and Upper Greensand aquifers. In contrast the Sem (Priors Farm) sub-catchment is underlain by clays, with water generally moving rapidly to the watercourses. Variations in the aquifer properties result in complex groundwater systems, with the Wylye, supported by springs whose locations are strongly controlled by the geology (Figure 4), containing both gaining and losing sections. It is likely that the groundwaters feeding the river will have followed a variety of subsurface flow routes and have a range of residence times, which will affect the nature of pollutant loads.

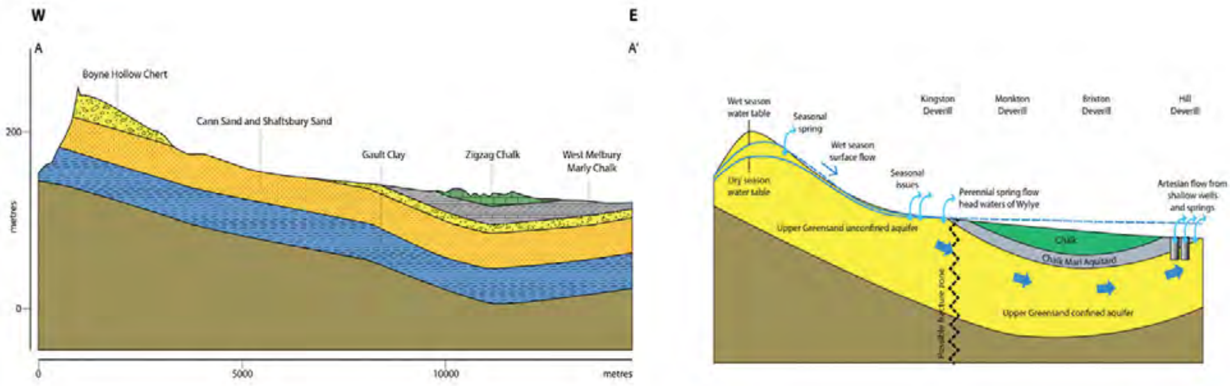

Figure 4 **Conceptualisation of geological controls on groundwater flow in the upper River Wylye**

CONCLUSION

Groundwater is significant in many of the sub-catchments and as a result of geological variations, the subsurface flow systems are commonly complex, with a spectrum of travel times (minutes/hours to tens of decades) from rapid surface runoff to slow, deep groundwater flow systems. In addition the geometries of the flow systems can be complex, for example discrete inputs to river flows occur via springs. It is evident that to interpret the monitoring data correctly, so that the effectiveness of the different measures can be determined and for proper understanding of both pollutant behaviour and catchment management, good conceptual groundwater flow models are essential, as groundwater flow systems can strongly influence both the degree and the timing of the impact of on-farm mitigation measures on river receptor pollution.

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HYDROGEOLOGICAL PATHWAYS IN TWO CONTRASTING CATCHMENTS - IMPLICATIONS FOR MANAGEMENT

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ABSTRACT

Diffuse contaminants on the land surface can make their way into rivers via a number of different pathways through the landscape, including overland flow, interflow, shallow groundwater flow and deep groundwater flow. Identification of the key pathways that deliver contaminants to a receptor of interest is important for implementing successful water management strategies. Research into characterising and modelling the hydro(geo)logical pathways in Irish conditions has found that in a regionally important karst catchment with Extreme to High vulnerability, the key pathway for nitrate delivery is the network of diffuse fractures in the limestones. For phosphate, the highest risk areas hydro(geo)logically are the sub-catchments of the Namurian surface water streams that sink at the limestone/shale boundary, and any point recharge locations within the limestone areas where the nutrients can gain direct access to groundwater. In a contrasting poorly productive aquifer setting, the key hydrogeologically sensitive areas for nitrate are places where the depth to rock is shallow and where land drains are present. For phosphate, the hydrologically sensitive areas are places closer to the stream, where the slopes are relatively steep such that the contribution of overland flow to the stream is high. The field perimeter ditch network is also important. These hydrologically sensitive areas can then be integrated with a map of the landuse pressures in the catchment to define the Critical Source Areas. These are the areas within which programmes of measures and the management effort should be focussed to achieve the best environmental outcomes.

INTRODUCTION

Management of water quality issues arising from diffuse sources of contamination is a major challenge for European countries in their efforts to reach Good Status targets under the Water Framework Directive. In a largely rural landscape dominated by agriculture and one-off housing, such as we have in Ireland, diffuse sources of nutrients in particular, are ubiquitous. A risk based approach is therefore necessary to focus the management effort so that targeted, efficient, and cost effective mitigation measures can be implemented.

The Source-Pathways-Receptor model provides a useful environmental risk management framework. The sources are the contaminants arising from a range of land use activities such as septic tanks, land spreading, fertilizer use, etc. The receptors are the resources that require protection from the contaminants, such as drinking water wells, surface water streams and groundwater dependent wetlands. The pathways are the hydro(geo)logical connections that link the two and therefore are responsible for delivering the contaminants to the receptors. Identifying the key pathways, and the attenuation processes that take place along them, is an important step in identifying the highest risk areas, known as Critical Source Areas. Contaminant sources without a hydrological link to a receptor pose a relatively low risk; whilst the Critical Source Areas are places where contaminants potentially have an easily accessible hydrological pathway to an aquatic receptor are located. Critical Source Areas are defined by Daly (this volume) as 'the intersection of hydrologically/hydrogeologically susceptible areas and pollutant sources in catchments' and they are further described in his paper.

A major research project characterising and modelling the hydro(geo)logical pathways in Irish conditions is currently underway. The *Contaminant Movement along Pathways Project* ("The Pathways Project") is funded by the Environmental Protection Agency (EPA) and is being carried out by a consortium of researchers from Queen's University of Belfast (QUB), Trinity College Dublin (TCD) and University College Dublin (UCD). The aim of the project is to integrate knowledge of hydro(geo)logical processes and water-borne contaminant fate and transport along each of the different pathways. These findings are being used to develop and populate a catchment management tool (CMT) which will be used by the EPA, and potentially by River Basin District managers, to assist them in implementing the programmes of measures required under the Water Framework Directive (Archbold *et al.*, 2010). Further information on the CMT is available in the paper by Mockler *et al.* in this volume.

PATHWAYS

The pathways being investigated are based on a conceptual model developed by Daly and Hunter-Williams (as reported in RPS, 2008) which is shown in Fig. 1. These are overland flow, interflow and shallow and deep groundwater which are defined as follows:

Overland flow — Overland flow is sheet flow occurring on the land surface (Shaw, 1994). In Ireland, it commonly occurs only after the soil becomes saturated, i.e. saturation-excess overland flow (Nash *et al*., 2002). It is sometimes termed surface runoff or direct runoff and it produces a rapid response in a stream hydrograph.

Interflow — There are variable definitions in the literature for interflow but it is generally any lateral subsurface flow that occurs between the ground surface and the water table (Dingman, 2002; Nash *et al*., 2002; Chin, 2006). It can occur in both the topsoil and subsoil, and may include unsaturated matrix flow, bypass or macropore flow, saturated flow (from locally perched water tables) and potentially artificial field drainage (Archbold *et al*., 2009).

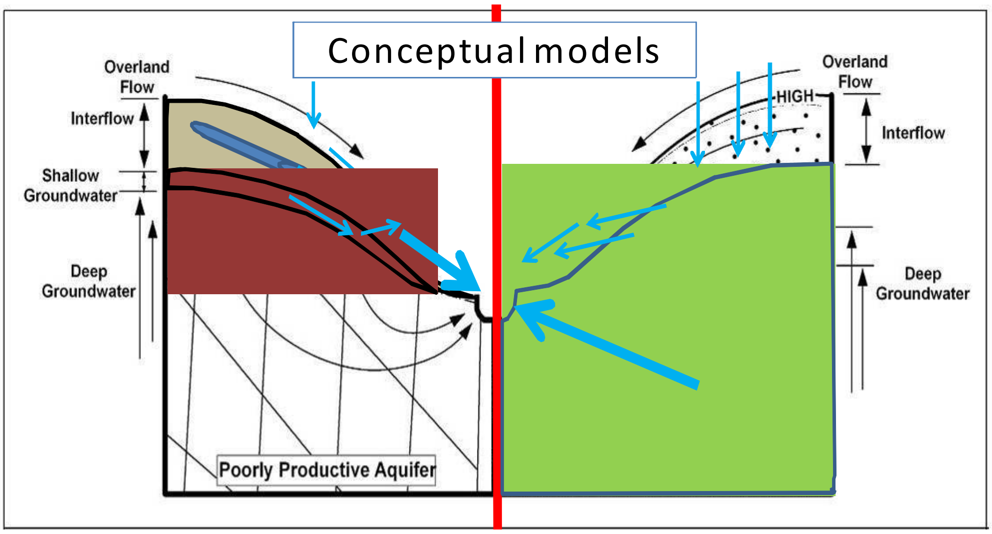

Fig. 1. Dominant components of flow contributing to a stream in poorly productive (left), and productive (right) bedrock aquifer settings. Low or high permeability subsoil may overlie either bedrock aquifer type (modified from a sketch by Daly and Hunter Williams, as reported in RPS, 2008).

Shallow groundwater Shallow groundwater occurs within the top few metres of weathered and fractured bedrock and it is considered to be the main groundwater pathway in poorly productive bedrock aquifers.

Deep groundwater Deep groundwater occurs in the main body of the bedrock aquifer. It is of greater importance in productive (especially regionally important) aquifers and is equivalent to the long-term sustainable yield of a groundwater flow system.

This paper compares and contrasts the research findings from two of the study catchments in the *Pathways* project: the Nuenna catchment near Freshford in Co. Kilkenny, and the Mattock catchment at Collon, on the border of Counties Meath and Louth.

THE NUENNA CATCHMENT

The Nuenna catchment (36 km^2) in Co. Kilkenny is a tributary of the River Nore. The catchment is largely underlain by a highly productive, permeable karstified limestone aquifer (Dinantian Pure Bedded Limestone) which is classified by the Geological Survey of Ireland as a Regionally Important Karstified Aquifer dominated by Diffuse Karst (Rk_d). In the higher parts of the catchment, the limestones are overlain by low permeability Namurian sandstones and shales which are classified as a Poor Aquifer which is Generally Unproductive except for Local Zones (Pl). High permeability sands and gravels with low permeability clay horizons are present in the floor of the valley in the lower half of the catchment, mainly on the northern side of the river, whilst on the southern side, there are thin moderate permeability limestone tills overlying the karst. Much of the catchment has Extreme Vulnerability.

The landuse in the area is 73% pasture (dairy and sheep) and 19% arable for cereals. There is one known piggery and landspreading of organic waste takes place within the catchment. The population of approximately 600 is rural and is serviced by private wells, group water schemes and septic tank systems. Preliminary analysis using a catchment loadings tool (Entec, 2010) suggests that organic and inorganic fertilizers are the most important sources of N and P in the catchment, and that the catchment nutrient loads in soil drainage[1] are of the order of 62 kg/ha/year of nitrogen and 6 kg/ha/year of phosphorus.

The median flow at the study catchment outlet (Monument Weir) between 2010 and 2012 was 0.5 m^3/s and the river hydrograph recessions are long and slow (Fig. 2), indicating that there is a large contribution of groundwater to the river. Longitudinal chemistry and flow surveys and regular monitoring have shown that three large karst springs dominate the flow (and nutrient delivery) in the river, particularly at low flow, and that the remainder of the flow is from the smaller springs and the gravels (Fig. 3). The groundwater and surface water resources are therefore highly interconnected. The average nitrate concentration in the river is 25 mg/l as NO_3 which is above background levels. The nitrate concentrations are diluted in wet weather but the load or flux increases overall. The average Total Phosphorus concentration at baseflow conditions is very low at 0.009 mg/l as PO_4 but in wet weather both the concentrations and the load increase significantly.

A fourth karst spring further downstream was found to contribute higher levels of total phosphorus than elsewhere (>0.200 mg/l as PO_4). Tracing studies have linked this spring to two sinking streams that originate in the upper catchment on the low permeability Namurian sandstones and shales (Walsh, 2011). Management of P in the catchment areas to these sinks is therefore an important priority.

[1] Soil drainage refers to the amount of N or P leaching from the base of the soil zone. In other words the N or P present after attenuation processes in the soil taken place, but before any attenuation that may occur in the unsaturated and saturated subsoils and bedrock, as the latter is more difficult to estimate.

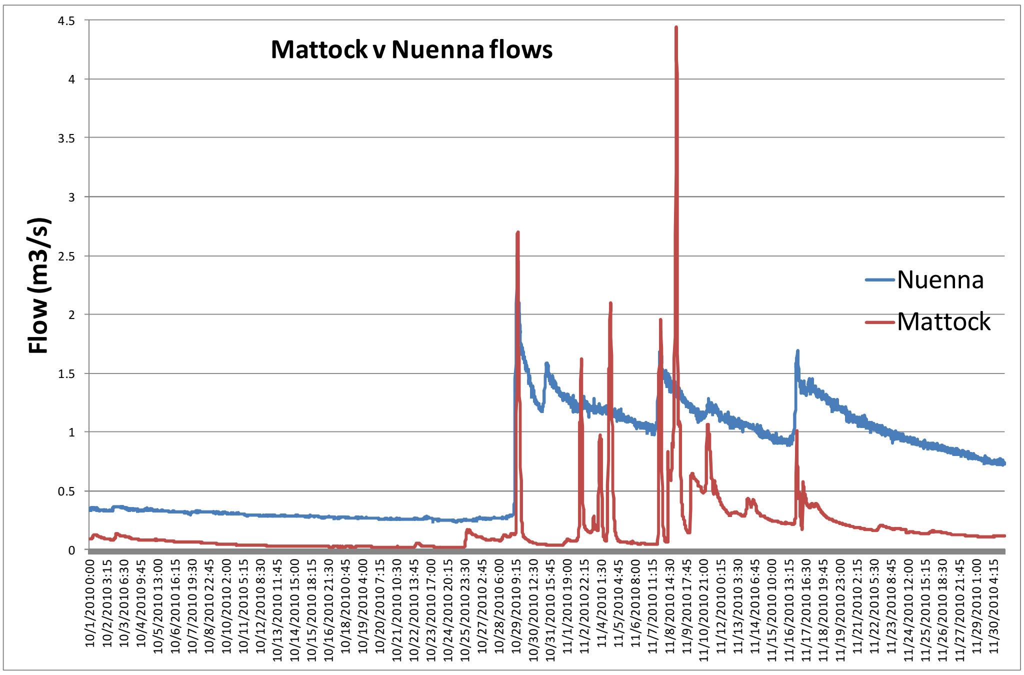

Fig. 2 Comparison of flows in the Mattock and Nuenna between Oct 2010 and Jan 2011

Spatial and event sampling in the catchment has allowed mixing models to be generated of the pathways delivering water to the stream, using the hydrochemistry of the various components of flow as natural tracers. Groundwater flow in the limestone bedrock is the dominant hydro(geo)logical pathway in the catchment. Stream flow is a mixture of quickflow from karst conduits which discharges via springs, and flow through the more diffuse limestone fracture network which is interconnected, and becomes dominant at low flows. Surface water derived from the upper parts of the catchment underlain by the Namurian rocks is an important source of water for flow discharging at the springs, particularly at high flows (Fig. 4). Nutrient mixing models show that the nitrate is delivered via both the diffuse and conduit networks. Phosphate is not present in the diffuse limestone groundwater but is present in the springs, and in the surface waters that drain the Namurian strata and enter the limestone aquifer via sinkholes near the contact.

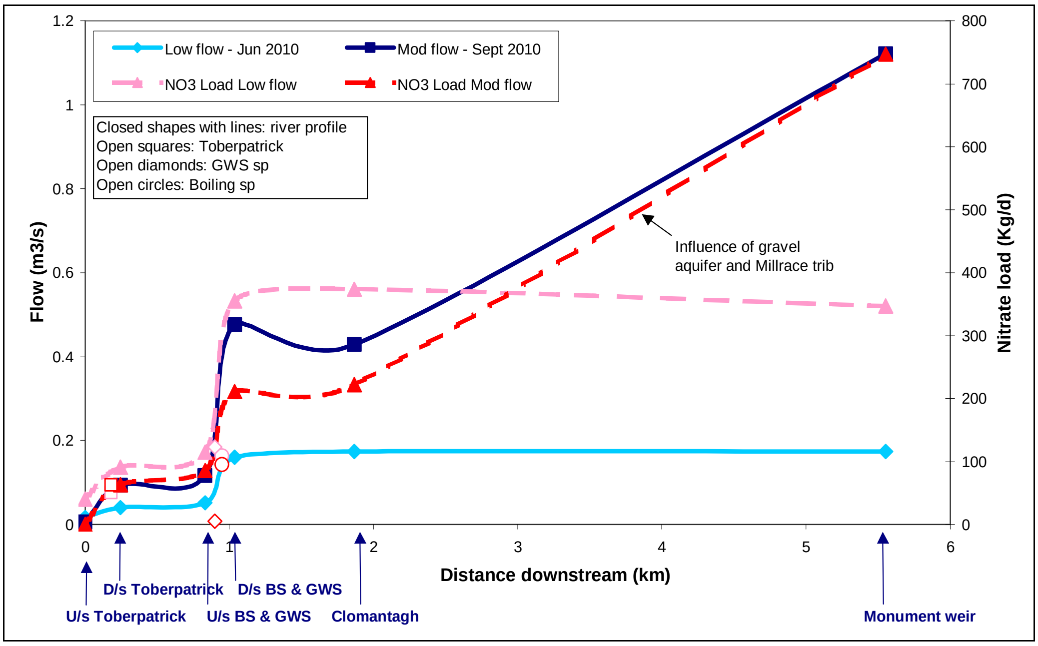

Fig. 3. Change in nitrate load with distance downstream in the Nuenna at low and moderately high flows.

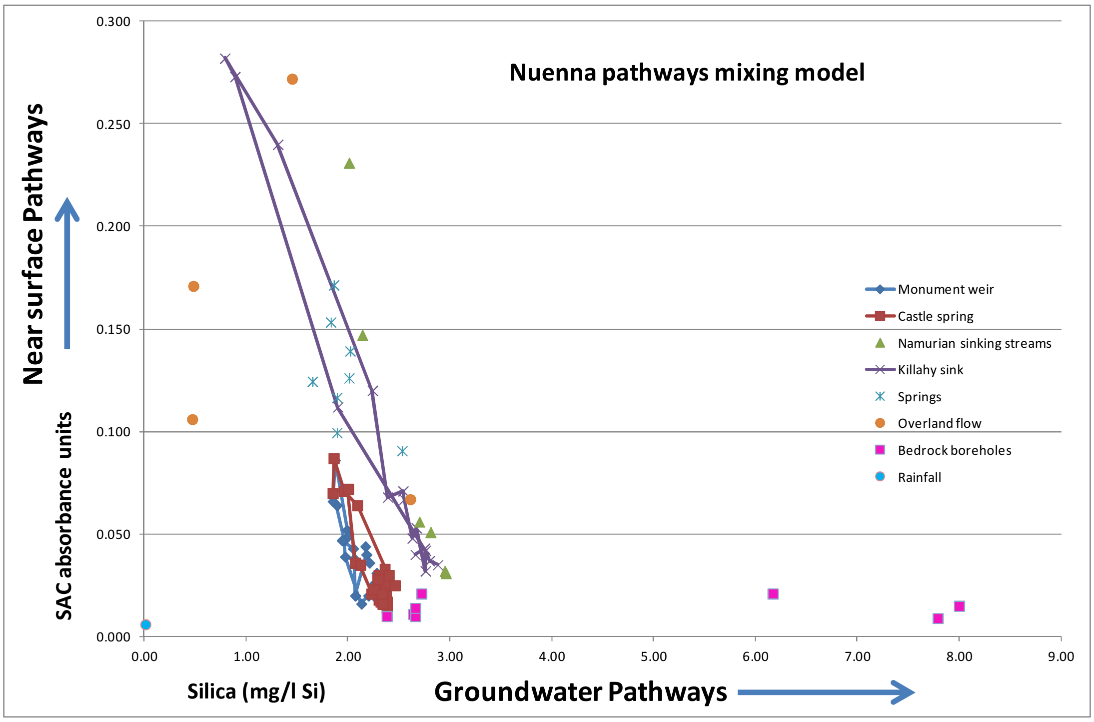

Fig. 4. Mixing model showing changes in stream and spring flow concentrations of two selected tracers during the course of a rainfall event in Winter 2012. Silica is used to represent groundwater contributions and specific absorbance capacity at 254 nm is used as a proxy for dissolved organic carbon and is taken to represent a near surface contribution.

THE MATTOCK CATCHMENT

The Mattock river catchment (17 km^2) on the Co. Meath/Louth border is a tributary of the River Boyne. The bedrock geology comprises calcareous Silurian mudstones, siltstones and greywackes, and Ordovician volcanics and metasediments, both of which are considered to be poorly productive aquifers. The subsoils in the catchment are mainly low permeability tills derived from Lower Paleozoic rocks which vary in thickness from less than 1 m on the higher ground, to more than 10 m in the base of the river valley and between the hills to the north. The Vulnerability of these areas ranges from Extreme to Low depending on the thickness of the subsoils. There are also some units of high permeability sands and gravels in places along the river channel, some of which are permeable enough to provide the public drinking water supply for the town of Collon.

The land use is similar to the Nuenna catchment with slightly more pasture (83%; dairy, cattle, sheep) and less arable (7%; cereals and maize), with the remainder a mixture of woodland, scrub, urban and other categories. Landspreading of organic waste takes place and inorganic fertilizers are also applied. The population is approximately 1850, just over half of which is located in or around the town of Collon. The town has a modern waste water treatment plant (WWTP) which discharges into the river downstream of the Collon weir. The remainder of the population is rural and is serviced by private wells and septic tank systems. Preliminary analysis using the catchment loadings tool suggests that organic and inorganic fertilizers are the most important sources of N and P in the catchment, and that the catchment nutrient loads in soil drainage are of the order of 15 kg/ha/year of nitrogen and 3.4 kg/ha/year of phosphorus. It has been observed however, in the field sampling campaigns that there are issues with farm yard runoff and septic tanks discharging into the surface water network in places. While on a catchment scale P from these sources may amount to relatively small loads, the loads do have an impact at the local scale.

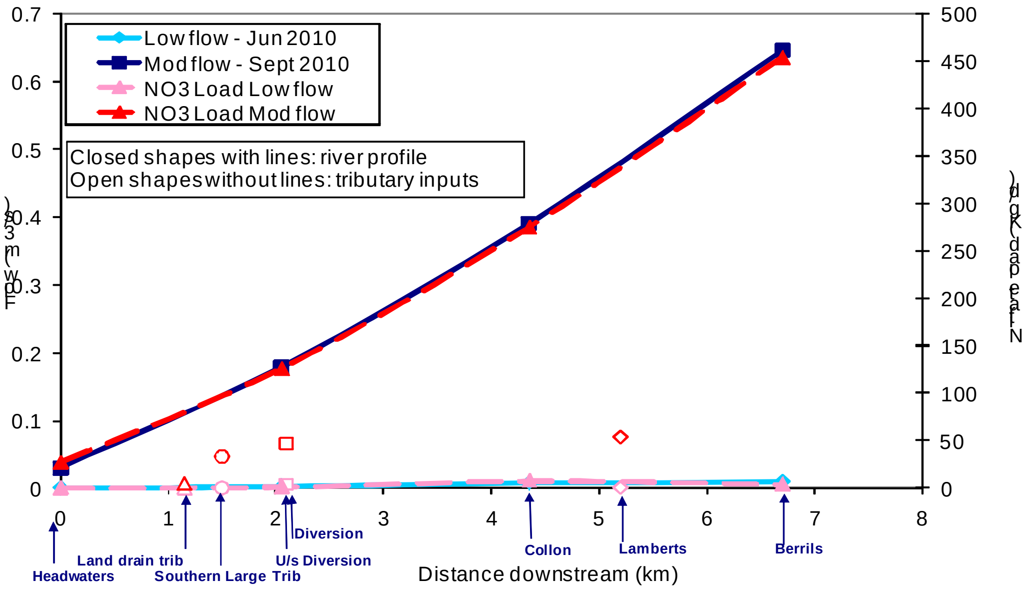

Fig. 5. Change in nitrate load with distance downstream in the Mattock at low and moderately high flows.

The median flow between 2010 and 2012 in the Mattock catchment was much less than in the Nuenna at 0.1 m^3/s. The catchment is also more flashy and baseflows are much lower as the groundwater contribution is smaller from the Poorly Productive rocks (Fig. 2). The average TP concentration at the catchment outlet is 0.113 mg/l as PO4 which is much higher than the Nuenna, but the average nitrate is lower at 11 mg/l as NO_3. In wet weather, the loads of N and P entering the stream increase significantly. Longitudinal chemistry profiles show that the nitrate load is quite uniformly spread throughout the catchment suggesting there is a diffuse origin (Fig. 5). The phosphate load is similar in the upper catchment but there appears to be a disproportionately large load entering the stream in the mid to lower catchment which is suspected to reflect the influence of the Collon WWTP.

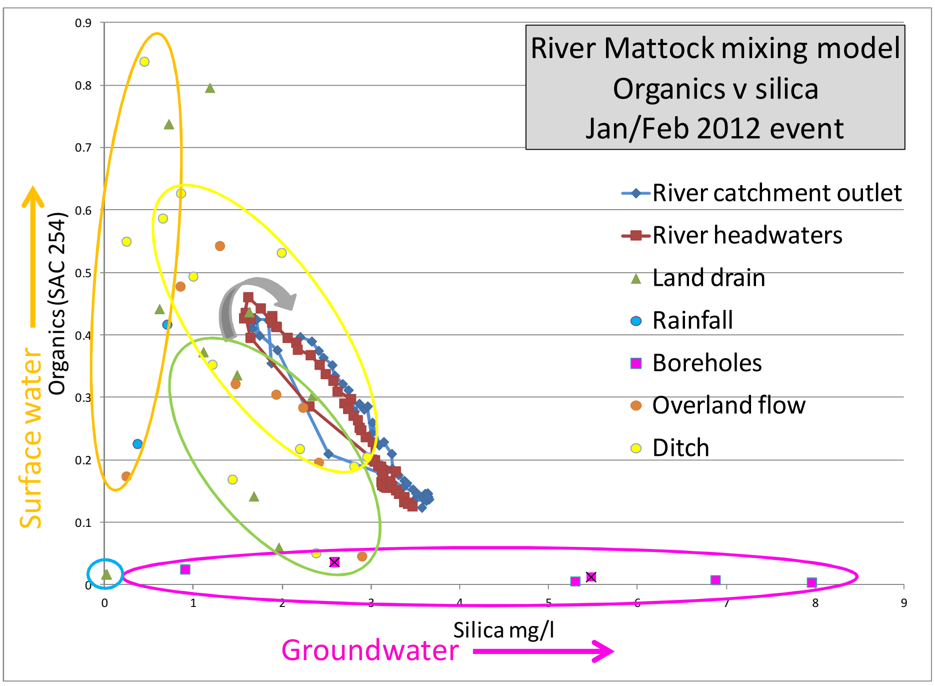

Fig. 6. Mixing model showing changes in concentrations of two selected tracers in various pathways and in stream, during the course of a rainfall event in early 2012. Silica represents the groundwater contributions and specific absorbance capacity at 254 nm is used as a proxy for dissolved organic carbon and is taken to represent a near surface contribution.

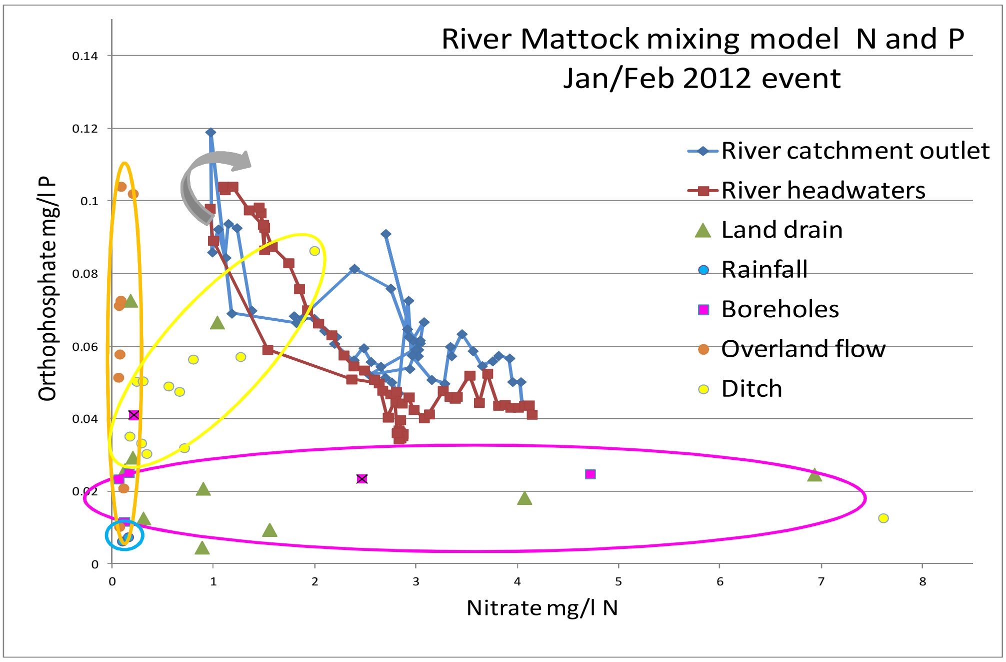

Fig. 7. N and P mixing model. Results show that N is delivered primarily via groundwater and land drains, whilst P is more associated with overland flow. Ditches transport more dilute quantities of both N and P. Results also highlight some anomalies, e.g. a ditch high in N and low in P, highlighting that it may be groundwater fed.

The mixing models show that stream flow in the Mattock is dominated by overland flow and flow through artificial land drains and ditches, while the contribution from deep groundwater is relatively small (Fig. 6), as would be expected from the poorly productive aquifer classification. The shallow groundwater pathway along the weathered zone at the interface between the soils/subsoils and bedrock (the transition zone) also play a significant role, especially where it discharges via the artificial drainage network. The land drains (and probably the transition zone/shallow groundwater pathway) deliver a lot of the nitrate to the stream, while the P is more typically associated with overland flow (Fig. 7). Field perimeter ditches are an important source of both N and P, particularly where they are located next to a local source of contamination such as a farm yard or septic tank.

CONCLUSIONS AND MANAGEMENT IMPLICATIONS

In the Nuenna catchment, the key hydrologically sensitive areas for nitrate are those parts of the catchment which are underlain by limestones with Extreme and High Vulnerability, i.e. places where the nitrate can readily infiltrate into the diffuse fracture network with rainfall. The hydrologically sensitive areas for phosphate are the catchments of the Namurian surface waters that sink at the limestone boundary, and areas contributing to any point recharge locations within the limestone areas where the nutrients can gain direct access to groundwater.

In the Mattock catchment, the river receptor is most at risk due to the presence of the low permeability glacial tills that serve to protect groundwater. The key hydrologically sensitive areas for nitrate are places where the depth to bedrock is shallow so that contaminants can reach the weathered transition zone and move laterally as shallow groundwater. Land which has been artificially drained is also high risk. For phosphate, the hydrologically sensitive areas are places closer to the stream, where the slopes are relatively steep and display strong hydraulic connectivity such that the contribution of overland flow to the stream is high. The field perimeter ditch network is also important. There is generally much less risk to groundwater from P because of the presence of the low permeability soils and subsoils.

These hydrologically sensitive areas can then be integrated with a map of the landuse pressures in the catchment to present the Critical Source Areas. The Critical Source Areas are the areas within which programmes of measures and the management effort should be focussed to achieve the best environmental outcomes.

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"…AND THEN IT GOES TO THE SEA": THE ECOLOGICAL APPROACH TO UNDERSTANDING COASTAL CATCHMENTS

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ABSTRACT

The Griffiths Biogeoscience Group at NUIG has been working along the south Galway Bay coast on the interaction of the marine and terrestrial environments. The on-going work of the group is presented and the importance of a multidisciplinary approach is stressed. In catchment science and management it is critical to take what has been called an ecological approach to better understand the complexity of the interactions and interrelationships between variables at many scales across catchments.

INTRODUCTION

The Griffiths Biogeoscience Group at NUIG has been working on a number of Irish coastal catchments since 2008. The initial focus of the group was along the south coast of Galway Bay dealing with the coastal karst aquifer systems and the group has now expanded its work to include coastal zones in Clew Bay and in north Louth, the latter of which will integrate Griffiths and TELLUS work. This paper presents an overview of the work in the context of the coastal science theme and focuses on the work in Galway Bay. Four PhD students funded by the Griffiths awards are working on the various aspects of this project: Aisling Smith, Marie Perriquet, Yvonne O'Connell and Enda McRory; and they are supervised by Rachel Cave, Tiernan Henry, Eve Daly and Liam Morrison.

The work in this area hinges around the coastline: the studies have approached the area from the seaward and the landward side and have incorporated both terrestrial and marine geophysical investigations.

SOUTH GALWAY BAY

STUDY LOCATION

The main coastal karst aquifer discharging to Galway Bay drains a catchment area of approximately 500km^2 (EPA, 2011). The catchment is largely made up of Carboniferous pure bedded limestones (forming the extensive low lying topography between the coast and Gort and Loughrea) and Devonian Old Red Sandstones (ORS) which make up the core of the Slieve Aughty mountains, which lie to the east and south east. Rainfall amounts vary across the catchment from approximately 1100mm/year in the coastal zone to more than 1300mm/yr in the Slieve Aughty mountains. The aquifer classification is Rkc for most the limestones in the area, while the ORS is classed as Pl (with the bordering impure limestones classed as Ll). This aquifer classification reflects the surface drainage patterns too: a well-developed surface drainage is found on the Slieve Aughty mountains, while surface drainage features are largely absent from the lower lying pure bedded limestones. In this latter region the drainage is dominated by epikarst and conduit flows, with discharge along the coastal zone through a series of coastal springs (from Kinvarra in the east to Bell Harbour in the west) and submarine springs in the various bays and inlets and, probably, in Galway Bay.

A number of studies have been carried out in the area over recent years, with the work of David Drew and Donal Daly most prominent. More recently researchers from TCD have been working on various aspects of the groundwater movement through the limestone lowlands, modelling flows and flow

patterns. This work is led by Laurence Gill, Paul Johnston, and Carlos Rocha and their research students.
The work of the Griffiths group at NUIG focuses on Kinvarra Bay and Bell Harbour and on the potential zones of groundwater/sea water interaction in the coastal zones.

RESULTS

OVERVIEW
The outcomes and some of the results of the on-going work are presented here.

Aisling Smith's work focused on understanding the chemical interactions in the marine waters that were affected by the inflows from the catchment. Her work focused on a number of estuarine settings along the west coast of Ireland, but the results presented here relate specifically to her work along the south coast of Galway Bay, and in Kinvarra and Aughinish bays in particular.

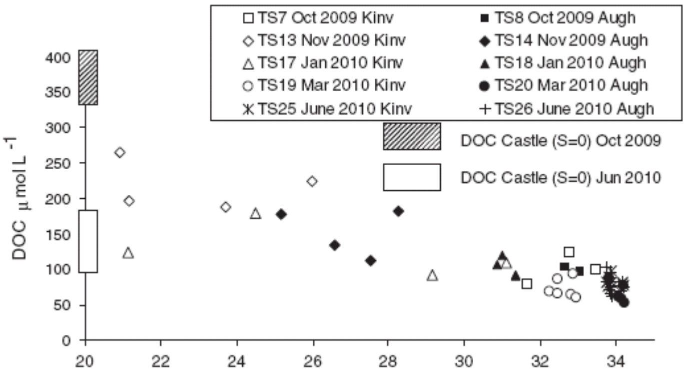

Figure No 1: DOC and salinity values Kinvarra and Aughinish bays

These two adjacent bays which host shellfish aquaculture sites were studied to establish the influence of fresh water inputs on nutrients and dissolved organic carbon (DOC) (Fig 1). There are no surface drainage features discharging to either bay and discharge is through both intertidal and submarine groundwater discharge. Water and suspended matter samples were collected half hourly over 13h tidal cycles over several seasons. Water samples were analysed for nutrients and DOC, while suspended matter was analysed for organic/inorganic content. Temperature and salinity measurements were recorded during each tidal station by SBE 37 MicroCAT conductivity/temperature sensors. Long-term mooring data were used to track freshwater input for Kinvara and Aughinish Bays and compare it with rainfall data.

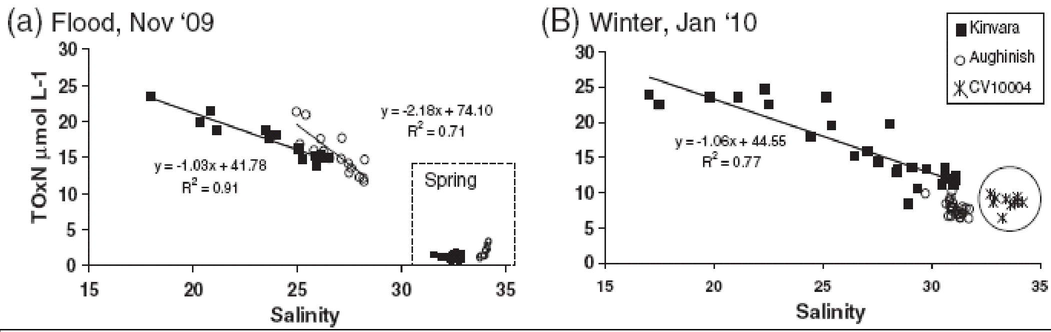

Figure No 2: Nitrate and salinity values Kinvarra and Aughinish bays (a) November 2009 (b) January 2010

Results show that Kinvara Bay is much more heavily influenced by fresh water input than Aughinish Bay, and this is a strong source of fixed nitrogen to Kinvarra Bay (Fig 2). Only during flood events is there a significant input of inorganic nitrogen from fresh water to Aughinish Bay, such as in late November 2009. Fresh water input does not appear to be a significant source of dissolved inorganic phosphate (DIP) to either bay, but is a source of DOC to both bays. Freshwater is a source of DOC in the studied bays.

The relationship between discharge and salinity in Kinvarra bay is shown in Figure 3 for the period between June 2009 and January 2010. In November 2009 a significant rainfall event occurred with rainfall amounts between 250-300% of the 6190 average recorded across the area. Twenty five days of rainfall in November were followed by an extended dry period and there was significant flooding in the limestone lowlands between Gort/Loughrea and Kinvarra as the inputs of water were significantly greater than the outputs through the karst. It is worth noting in Figure 3 that salinities in Kinvarra bay dropped significantly with the onset of the rainfall (at the start of November 2009). Rainfall stopped on November 25 but the salinities had not fully recovered until mid-January 2010, indicating that groundwater discharge from the catchment continued to dominate the system.

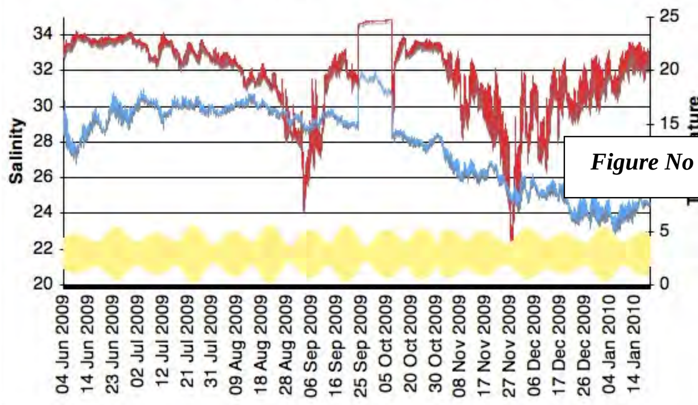

Figure No 3: Salinity, temperature and tides in Kinvarra Bay

Marie Perriquet is working on the groundwater inputs to Bell Harbour and her work shows that there is a tidal influence in some near coastal wells and that other wells show no influence from the tides. Flow in the Bell Harbour catchment is focused in conduits and in a mapped fault structure and discharges to the bay are through inter-tidal springs and submarine discharge points in the bay (Fig 4).

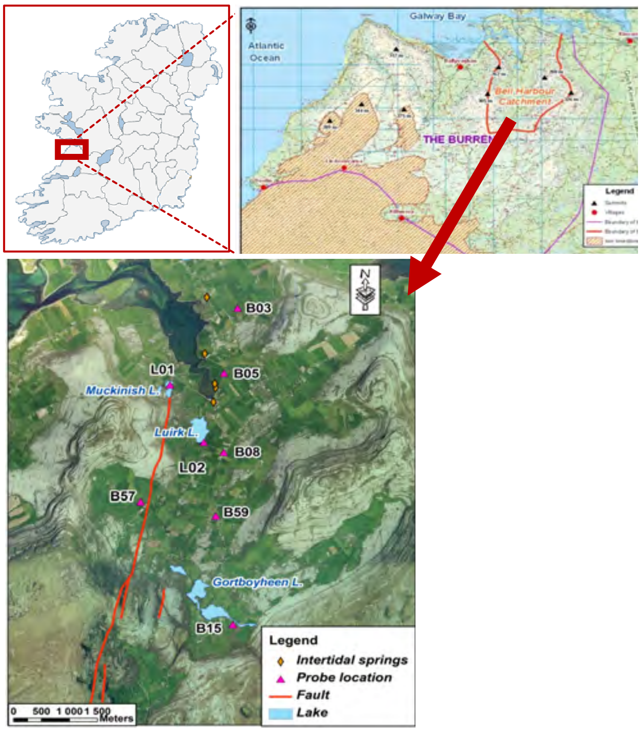

Figure No 4: Bell Harbour Catchment

She has been recording water level, conductivity/salinity and temperature data from six wells, five springs, two turloughs and from two locations in Bell Harbour bay since 2010. Rainfall data is also collected in the catchment from a dedicated rain gauge installed in 2011.

Her results show that diffusivity values indicate that the aquifer is heterogeneous, with the greatest values associated with wells adjacent to the mapped fault structure along the western side of the catchment. There is significant variation in the hydraulic gradient throughout the catchment depending on the outflow of fresh water and the tidal height. Marie is still trying to best determine the total inflows of water to the bay from the catchment and to resolve the differences in estimation of inputs from the terrestrial side (using rainfall data) and from the marine side (using a tidal prism estimation).

One of the areas that Marie is now focused on better understanding is the potential extension of the mapped fault into the bay and the possible submarine discharges associated with that extension.

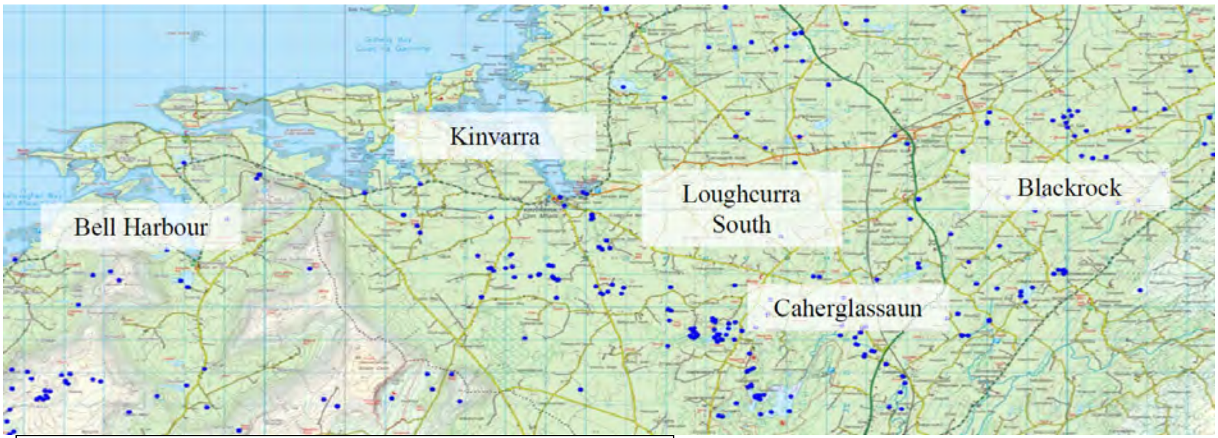

Figure No 5: Geophysical Survey Locations

Yvonne O'Connell has been using electrical resistivity and seismic methods to collect and analyse data in these coastal karst systems to establish pathways connecting coastal aquifers with transitional waters. She has completed detailed surveys at the two turloughs at Blackrock and Caherglassaun, and at Loughcurra south, Kinvarra bay and Bell Harbour (Fig 5).

Most recently Yvonne has been focused on assessing the nature of the mapped fault to the west of the Bell Harbour catchment and its association with submarine groundwater discharges in Bell Harbour bay (Fig 6). This work shows the likely extension of the fault under the bay and the probable linkage between the fault as a conduit and the submarine springs in Bell Harbour (Fig 6).

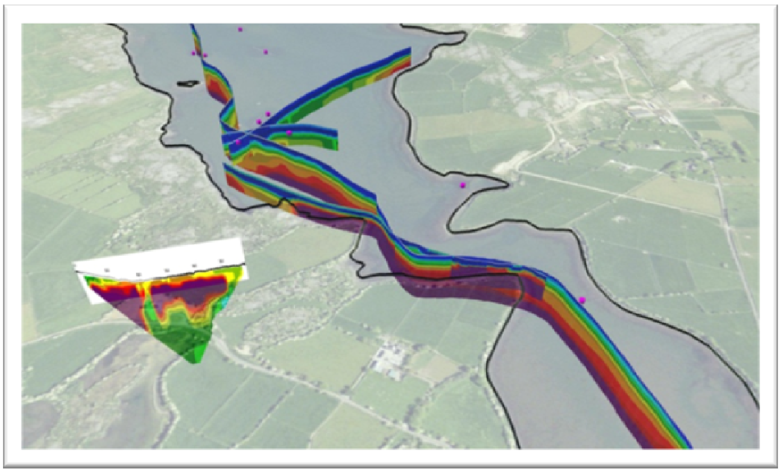

Figure No 6: Geophysical Survey Location in Bell Harbour

The work undertaken by these three researchers had initial different starting points, but has been converging as the work progressed. One of the key outputs of these research topics has been to show how inter-related and how inter-reliant they are on each other.

CONCLUSIONS

The title of this talk is "… And then it goes to the sea". This was the typical wrap up comment of hydrogeology field trips that tracked water movement and the changing landscape from the Slieve Aughty mountains across the low lying limestones to Kinvarra Bay. Yet this only tells half the story. The marine component of this is not simply the end point; rather it offers an insight into the nature and the magnitude of the flows of freshwater leaving catchments and discharging to the marine environment and it also allows us to look at the impact of landuse practice on marine water chemistry (and therefore on marine use). In this coastal karst area there is a grey area of interaction between the marine and the terrestrial environment. There is no hard and fast line that can be drawn on a map indicating the extent of sea water intrusion or the extent of mixed or transitional water. However, this work being undertaken as part of the Griffiths funded research highlights the importance of understanding the nature and character of catchments and understanding the complexity of relationships that exist between the meteorology, geology, hydrogeology and marine components of the systems.

In instrumenting a catchment it is important to understand the range of relationships present to ensure that there is not under or over representation of variables. Some wells in this study close to the shore show no interaction with or any effect of changes in sea water levels, while others have much closer relationships. The use of geophysical methods can prove extremely useful is characterising the physical makeup of the underlying bedrock and coupled with hydrogeological methods can prove extremely useful in better understanding the nature of the system. In coastal zones assessment of the marine water chemistry and fluxes can illuminate terrestrial impacts and can be useful in stressing the continuity of the water – that it doesn’t change at the coastal interface.

In social science theory Uri Bronfenbrenner suggested a way of assessing all of the influences on human behaviour based on what he called the ecological approach, which looks at all aspects from interpersonal to community to legislation. In catchment science and in catchment management such an approach may prove useful. Management has to be within a legislative and structural framework, but it must also be informed by the various physical and chemical relationships throughout the catchment – how geology and water interact and how both are modified by each other, and how inputs to better understanding how a catchment functions can be drawn from a range of various disciplines and studies.

SESSION III

PATHWAYS CATCHMENT MANAGEMENT TOOL – INVESTIGATING CRITICAL SOURCE AREAS WITH HYDRO(GEO)LOGICAL KNOWLEDGE

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ABSTRACT

The Pathways Catchment Management Toolbox (CMT) is being developed as a management tool for a broad, technically aware user group, interested in water quality modelling and its environmental consequences. The CMT is a Geographical Information System (GIS) based application that helps decision makers manage water at catchment scale by predicting fluxes of water and contaminants and identifying critical source areas (CSAs). This management tool effectively combines national datasets, GIS tools and a hydrological model to dynamically simulate fluxes of water, sediment, nutrients and contaminants entering a river along various flow paths. As user-friendliness is a high priority, three levels of user interaction are facilitated in the interface. In Level 1 of the tool, users can view national data sets, delineate a catchment of interest and generate reports summarising the data. Level 2 involves the generation of static Critical Source Area (CSA) maps using the intersection of spatial loadings and susceptibility datasets for the contaminant under investigation. The third level of interaction allows investigation of dynamic CSAs by modelling hydrological flow paths and the associated transport and attenuation of pollutants in catchments. The CMT tool can assist environmental managers in identifying CSAs for contaminants, evaluating alternative strategies for land use and their impacts on aquatic ecosystems, and targeting areas for enforcement of regulations.

INTRODUCTION

Catchment management aims to balance the objectives of facilitating economic growth while maintaining environmental quality. Both operational management, which has direct impact on the catchment by means of regulation, and planning in the form of River Basin Management Plans (RBMP) can be supported by data analysis. The Pathways Catchment Management Tool (CMT) is a GIS-based platform for environmental managers interested in water quality modelling and its environmental consequences. The Source-Pathway-Receptor model is commonly used to describe the transport and attenuation of contaminants through our environment, and is used in the CMT to identify critical source areas (CSAs). These are areas which contribute a disproportionally higher amount of contaminant to the receptor, and will vary for each combination of contaminant and receptor investigated. The Pathways CMT can identify CSAs for a particular receptor by combining loadings information representing the source of a particular contaminant with knowledge of transport and attenuation along the likely pathways to the receptor, referred to as the pathway susceptibility.

The fieldwork component of the Pathways project is investigating how subsurface flow paths in the complex geology of Ireland contribute to nutrient and contaminant export from our catchments. Investigations included detailed monitoring at 4 study catchments across the country, with instrumentation for meteorological data, flow and water quality in groundwater borehole clusters, subsoil and in-stream. This research, combined with previous studies, is used to inform the development of the CMT, in particular the partitioning of effective rainfall between conceptual hydrological flow paths.

River Basins are the unit of management under the Water Framework Directive, which promotes Integrated Water Resources Management (IWRM) to protect and improve our aquatic environment while implementing sustainable water use. A catchment or river basin is a geographical area that defines the surface hydrological system, often taken as the natural topographical surface water boundary. This is not always fully accurate, as catchment boundaries may be ambiguous in flat topographies, may not align to the groundwater body particularly in karst regions, and may have anthropogenic transfers with adjacent water bodies. Even taking these shortcomings into consideration, the river basin is de-facto the chosen catchment management unit, and as such the EPA River Sub Basin GIS layer is the base unit for the Pathways CMT.

VERTICAL AND HORIZONTAL PATHWAYS

Critical Source Area identification is a key tool for environmental managers using a risk-based approach to decision making, as these are locations where a relatively high proportion of the total pollution exported from the catchment originates. For each contaminant and potential pathways, susceptibility matrices based on national spatial datasets are combined with seasonal or annual averages of loadings to spatially display associated CSAs for the receptor under investigation. This is particularly suitable where the pathway is vertical through the soil column to a groundwater receptor, and where pollutant transport occurs at a relatively consistent rate, so that temporal averaging does not have a masking effect on the magnitude of pollutant delivered.

Where the pathway is horizontal in the Source-Pathway-Receptor model, initial contributions to surface pathways can be assessed using GIS layers, but overlaying layers, by itself, can only give a limited representation of transport and attenuation mechanisms. This is also true for transport of contaminants driven by the timing and intensity of rainfall, where the pollutant load may be increased by several orders of magnitude during a single event. Seasonal averages in this case may hide short-term, high impact pollution events and associated environmental impacts. For in-depth analysis of these situations, hydrological modelling is required to capture the dynamics of the catchment.

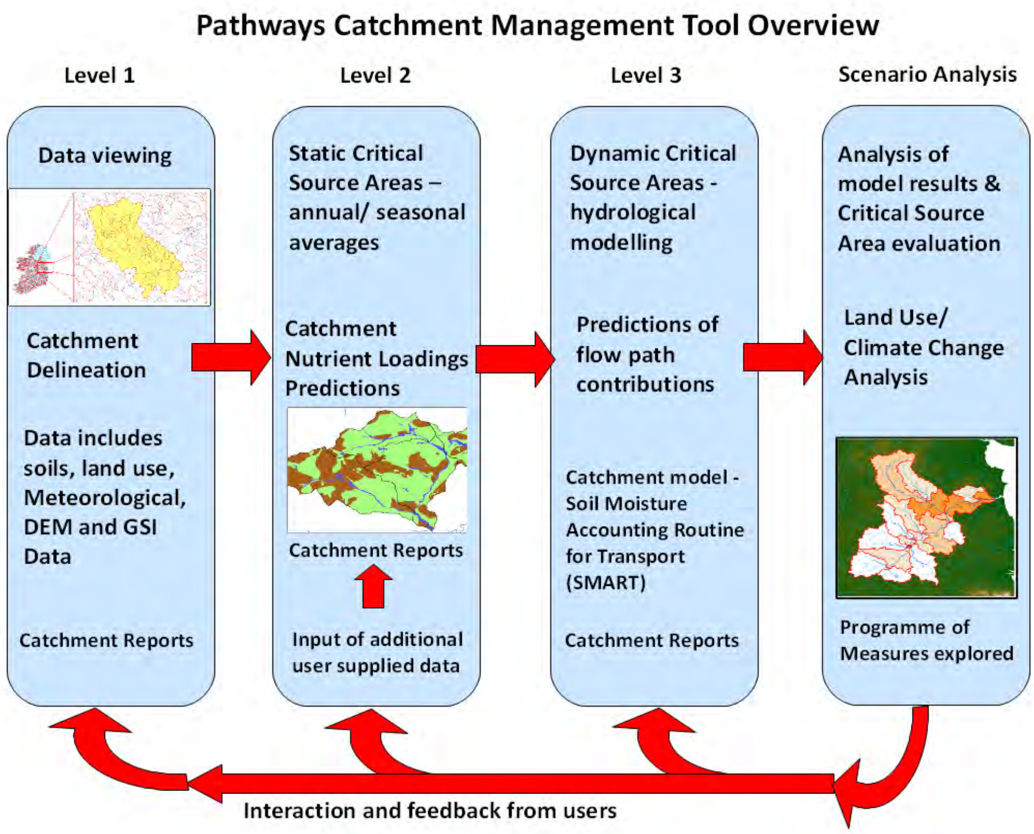

Figure 1. Levels of interaction with the Pathways Catchment Management Tool

PATHWAYS CATCHMENT MANAGEMENT TOOL

LEVELS OF INTERACTION

A range of end-user interests and prior knowledge is accommodated through the multiple levels of user's interaction with the system, taking account of their level of experience and of the information and analysis required. The 3 tiered structure of the Pathways CMT allows the user to balance the time-cost of the catchment analysis with the level of detail required, while allowing projects to be saved and re-visited. In this manner, catchment analysis can be shared among environmental managers, improving communication and ultimately understanding of our environment. The system has three levels, (Figure 1).

Level 1 – Data exploration

A user can, after selecting the catchment of interest, explore the various relevant data sets, e.g. hydrological, geological, soils, land-use, population, pollution sources, etc. for that catchment. Very little training is required and the system compiles summary reports of the information available. This may be sufficient information for some user's purpose. Otherwise, more detailed analysis is possible in the next levels.

Level 2 – Static CSAs

Static analysis of data in Level 2 can produce annual/seasonal average mapping of nutrient application or estimated nutrient loading to groundwater. The system will produce a map of the critical source areas in the selected catchment for a selected contaminant, generally useful for loadings to groundwater or for preliminary surface pathway studies.

Level 3 – Dynamic CSA

Level 3 incorporates the more complex processes of lateral transport and attenuation, e.g. in overland flow, interflow and lateral groundwater movement. A hydrological rainfall runoff model, specifically designed for this project to model individually the conceptual flow pathways, is linked to the user interface. The CMT can visually identify CSAs for selected contaminants dynamically, using the hydrological model for investigating the transport and attenuation of pollution. Use of this level requires specific user training.

Scenario Analysis

Land use and climate change scenarios can be explored with both Level 2 and 3 of the CMT, by altering the spatial loadings or meteorological input data respectively. This can be used to explore alternative programme of measures and assess future risks in our river basins.

FRAMEWORK FOR KNOWLEDGE EXCHANGE

A broad range of expert opinion is combined with national datasets to inform the delineation of CSAs in the CMT within the Source-Pathways-Receptor model. For example, susceptibility matrices for inadequate percolation for single house treatment systems (EPA, 2013) are integrated into the system. Previous research studies, results from the study catchments, and expert opinion are being combined to inform the pathways susceptibility matrices that describe the linkage between the source and receptor. Theses matrices will be available within the Pathways CMT framework for future testing, development and refining of the risk categories.

BACKGROUND TO DEVELOPMENT OF TOOL

With the increasing need for more detailed hydrological and hydro-chemical information to satisfy the demands of the EU Water Framework Directive (WFD), the Irish Environmental Protection Agency (EPA) initiated the development of the CMT in 2007. An extensive review of catchment management tools and hydrological models was carried out in the first year of the project (Bedri & Bruen, 2012). This concluded that available systems could be adapted for use as a management tool in Ireland, but none of the existing tools had the flexibility to incorporate new research findings specific to Irish conditions, as the models reviewed were all fixed structures. Although flexible modelling systems have become available which have capacity to alter the hydrologic connectivity, these systems did not fulfil an important requirement of the stakeholder: user-friendliness of the management tool. This is because existing systems cannot easily be tailored to Irish catchments and data, and requires varying degrees of experience from the modeller. It was therefore decided to develop a new GIS-based application linked with a flexible hydrological model for investigating the movement of pollution through our river basins and identifying the potential sources of contaminants. In Ireland, this is complicated by extreme heterogeneity in geology and soils and land-use (Archbold et al., 2010).

DATA EXPLORATION

CMT GRAPHICAL USER INTERFACE

The graphical user interface (GUI) of the CMT uses the Quantum GIS software to view data stored in the PostGIS (PostgreSQL) database. A plugin written in the Python language provides interaction with the user to load the required data and view statistics about the data. When the CMT plugin is started, a map of the river water bodies of Ireland is shown along with other data to orient the user. After selecting a river of choice, the catchment that serves this water body will be generated by the software relating to the river sub-basins defined by the EPA.

LEVEL 1: SOURCE LAYERS

The first level of interaction allows the user to view the source layers of underlying soil and geological information present in the selected catchment (see Figure 2). These layers are mostly those existing in the EPA WFD database plus some maps provided by the Geological Survey of Ireland (GSI). Maps included are soil and subsoil characteristics, bedrock aquifers, gravels, vulnerability data and CORINE categories. Point datasets can also be viewed to appreciate the presence of local pressures in the region, such as waste water treatment plants, CSOs, Landfills and other licensed facilities. As seen in Figure 2, selection of information is controlled in the top right panel of the CMT and summary information is displayed below this. The map is seen in the centre of the display and the colour legend is shown on the left hand side.

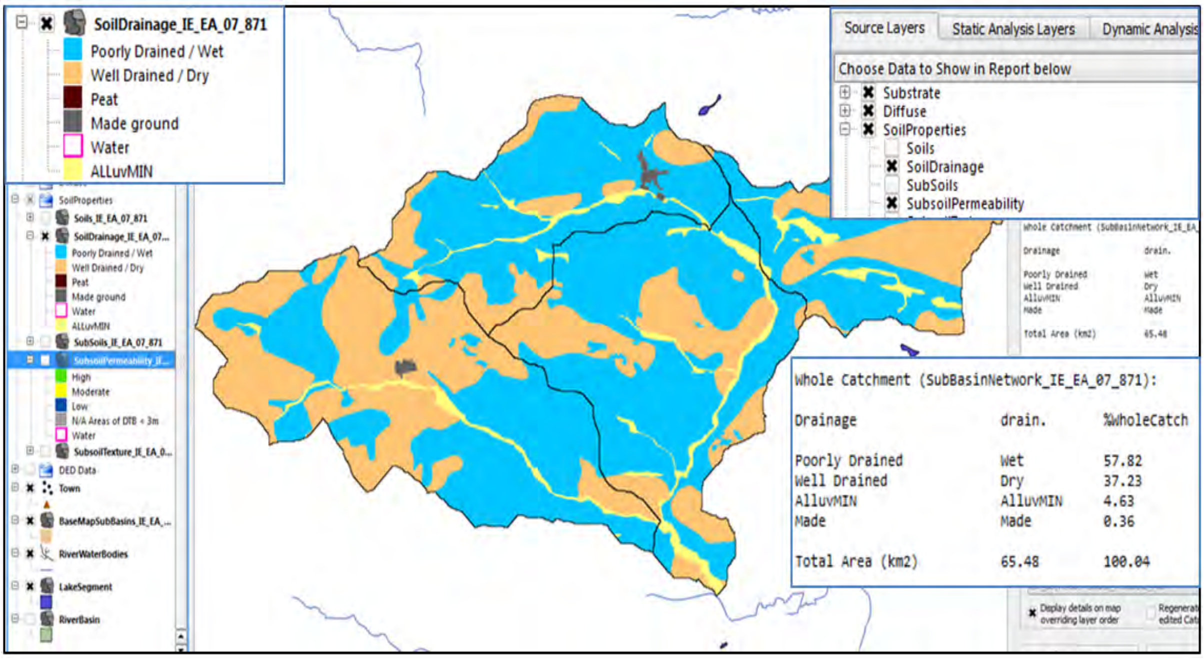

Figure 2. Soil drainage GIS layer for Mattock catchment.

LEVEL 2: STATIC CRITICAL SOURCE AREAS

The second level of interaction in the CMT is the Static Analysis Layers that combines information from other layers to show the Loadings in the area and subsequently the related Critical Source Areas. Loadings are calculated following the Entec loadings tool methodology (Entec 2010) adapted for Irish conditions by the EPA. However, the spatial data available allows for a more detailed representation of nutrient loadings to the catchment and therefore an evaluation of static critical source areas is possible.

The Loadings Tool uses available public data to estimate the amount of Nitrogen and Phosphorous loadings applied to Rural and Urban areas. Data sources include the Central Statistics Office of Ireland (CSO 2006) for human population information, Teagasc for Fertiliser application (Lalor et al. 2010) and the Department of Agriculture, Fisheries and Food (DAFM) for crop usage and animal population figures (CSO 2000). The latter information is also provided by the CSO broken down by District Electoral Divisions (DED). Using the Entec method, the proportion of relevant data (such as number of dairy cows or area of pasture) under each intersecting DED is divided over the catchment in question and then summed to provide a single figure for the catchment. In the CMT, these proportions are retained so that different amounts of loadings can be queried and visualised.

For example, in Figure 3 the concentration of Nitrogen in soil drainage to the extended Mattock (subcatchment of the River Boyne) catchment are shown. The Entec methodology was used, but the various attributes of the underlying GIS layers are combined to provide the varying amounts. The organic fertiliser input varies by DED, the inorganic fertiliser input is driven by the average county inputs due to its Agronomic Zone (Lalor et al. 2010). Because the catchment crosses two counties and thus different Agronomic Zones, the bottom left of the catchment receives larger fertiliser input. The N is leached from the soil following the NCycle_IRL (del Prado et al. 2006) calculation using the Soil Drainage map. Effective rainfall provided by the GSI Recharge map (Hunter Williams et al. 2011) is used to convert the input to concentration in mg/l.

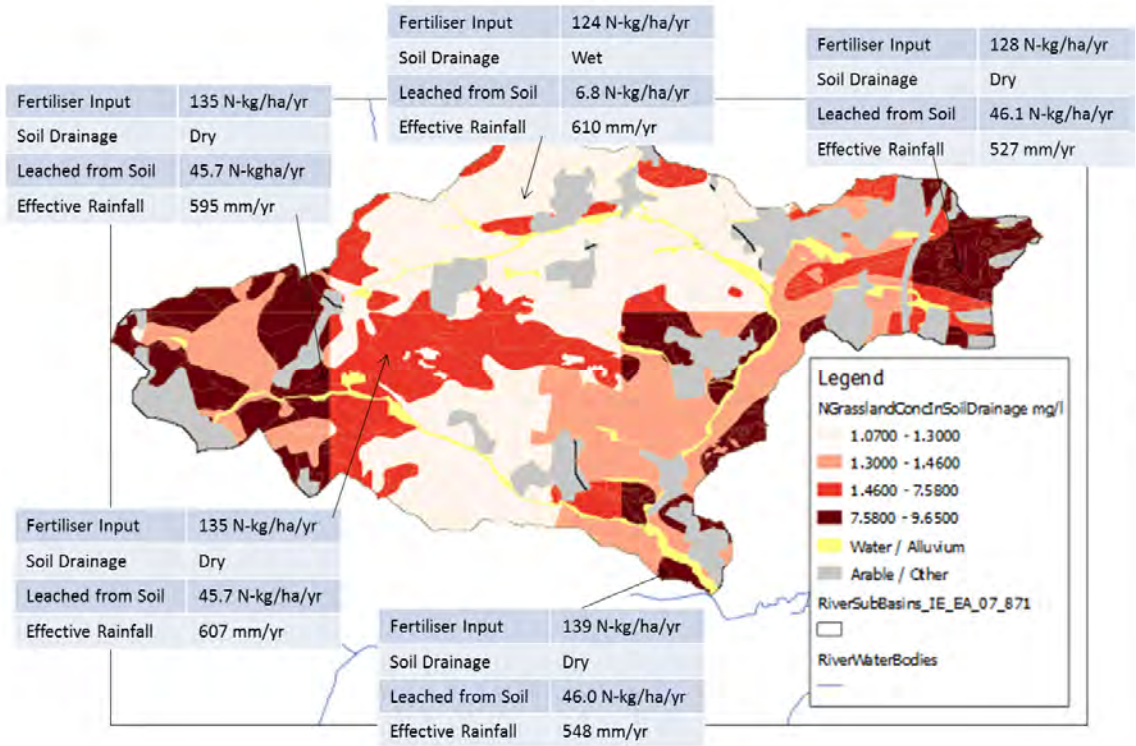

Figure 3. Example of Critical Source Areas for Nitrogen (mg/l) in soil drainage from grassland to groundwater for Mattock catchment.

In order to model the amount of nutrient that reaches groundwater, the spatially (not temporally) varying recharge coefficient from the Irish Recharge Map is used, improving on the single value used by Entec. In addition some attenuation factors were introduced to simulate attenuation through the subsoil (Permeability Map) and thickness (Depth to Bedrock). These were combined to produce the map in Figure 4, no attenuation of Nitrogen in bedrock is assumed. This CSA map indicates the areas of concern within the catchment with respect to diffuse loading of N to the groundwater receptor. When combined with point pressures, a full evaluation of the risks can be made.

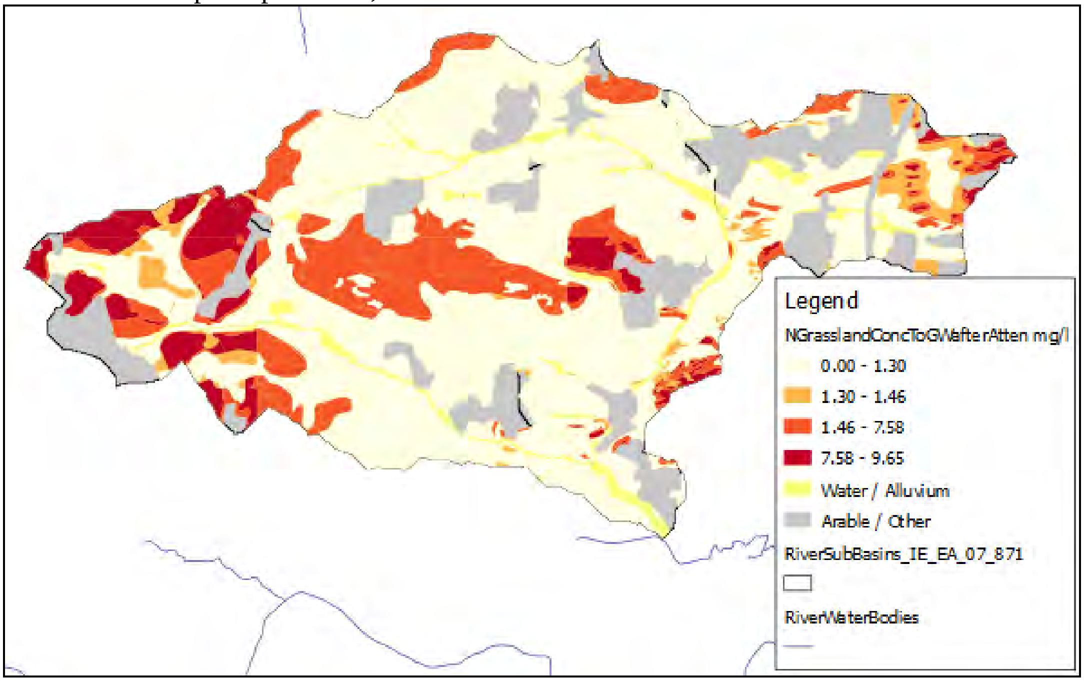

Figure 4. Attenuation included to produce a final Critical Source Areas for Nitrogen (mg/l) from grassland to groundwater for Mattock catchment.

LEVEL 3: DYNAMIC CRITICAL SOURCE AREAS

CONCEPTUAL HYDROLOGICAL FLOW PATHS

Hydrological modelling can give a complete picture of the transfer of pollution from the land surface via both surface and sub-surface pathways to our water courses. Modelling of water flow paths within a catchment, rather than overall response, is needed to investigate the physical and chemical transport of matter through the various elements of the hydrological cycle. The main conceptual hydrological flow paths that excess rainfall can take to contribute to stream flow are identified as (1) overland flow, (2) Interflow, (3) shallow groundwater flow, and (4) deep groundwater flow. Drain flow is also incorporated as a sub-path of interflow within the hydrological model, thereby accommodating separate transport and attenuation equations adapted to simulate field drains (Figure 5).

Overland flow is the precipitation in a catchment that runs off over the landscape, sometimes called sheet flow, producing a quick response in the hydrograph of the receiving water body. In temperate climates, it mostly occurs when the soil is at capacity, referred to as saturation excess overland flow. Hortonian flow occurs when the intensity of rainfall exceeds the maximum infiltration capacity of the soil, and is a dominant process for overland flow generation in arid regions. In this study, overland flow refers mainly to sheet flow and flow in the upper few millimetres of topsoil. Interflow is defined as the lateral movement of water in soils and subsoil, occurring in both saturated and unsaturated conditions. Shallow groundwater flow occurs in the high permeability zone at the top of the bedrock aquifer, and includes the transition zone. This is generally the top fractured and weathered zone of the bedrock. Deep groundwater flow is below the weathered bedrock, and is of greater importance in productive aquifers.

SMART CATCHMENT MODEL

Developed from an earlier hydrological model, SMAR (Tan & O'Connor, 1996), from NUI Galway, the Soil Moisture Accounting Routine for Transport (SMART) model is used in the Pathways Computational Engine (PACE) Framework to simulate the movement of flows and contaminants both vertically and horizontally through our river basins. The CMT acts as a user-friendly interface to the model to aid environmental managers in identifying critical source areas for contaminants, particularly where dynamic simulation of hydrological processes is required to evaluate CSAs. The SMART model simulates 4 hydrological pathways with 8 parameters which are populated with values related to GIS layers from the CMT, informed by a national regionalisation study. These include 5 soil moisture accounting parameters and 3 routing parameters (shown in square brackets, Figure 5).

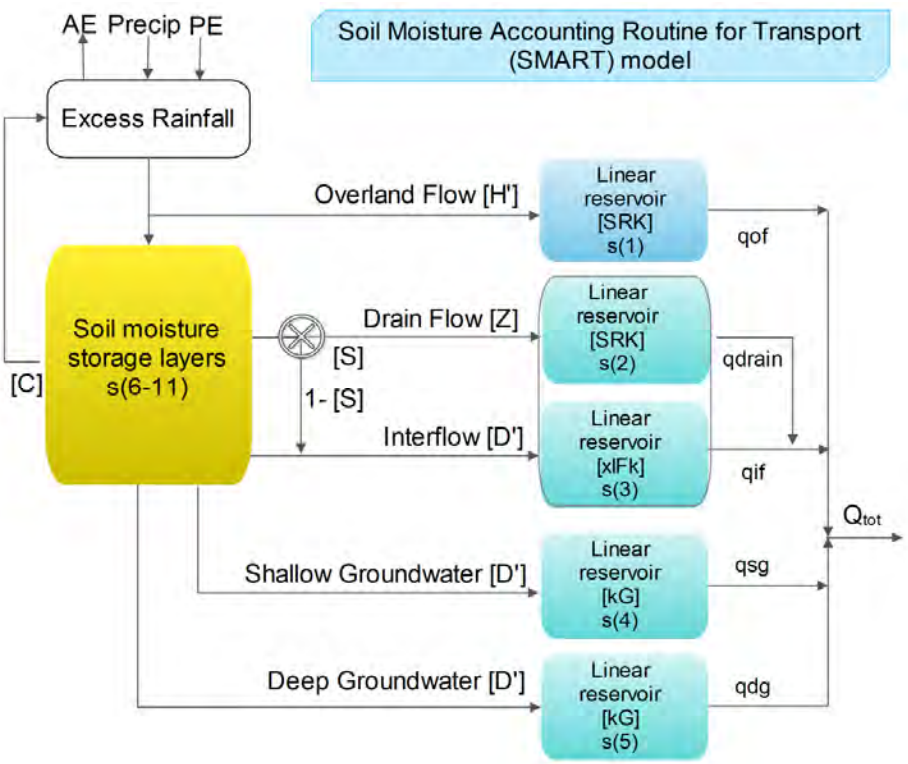

Figure 5. Schematic of conceptual flow paths of SMART catchment model.

The Pathways CMT can assist users in modelling Irish catchments with the SMART model by generating the required input files from national datasets. Semi-distributed models for the selected catchment are generated by the tool based on Irish EPA defined River Sub-Basins which have a mean area of 10km^2. The model network structure of each sub-catchment is initially determined from GIS data including aquifer type and soil thickness. An advanced user will be able to further adjust connections within the model network to test hypotheses on hydraulic connectivity.

WATER QUALITY SIMULATIONS

Hydrology is the driver of contaminants in the SMART model. Time series of rainfall and potential evapotranspiration are used as inputs to the hydrological model, typically in the range of sub-hourly to daily as availability allows. Daily values of these time series are included in the CMT's database for a range of stations across Ireland as default inputs when local data is not supplied by the user. The CMT defines initial parameter values linked to geological, soils and vegetation information to determine the distribution of flows along surface and groundwater pathways. Actual evaporation and flows are produced as outputs from the model at the same time step as the temporal input data.

Diffuse loadings calculated in Level 2 are used as a basis for the pollutant source data, and combined with available point source data in the catchment. Equations describe the transformations of this source along each conceptual pathway within the sub-catchment, with parameters of the water quality components of the model linked to spatial GIS data when appropriate. Water quality equations for the SMART model are informed by existing state-of-the-art models, including the INCA-N model (Wade et al., 2002), and are being reviewed and refined for Irish conditions.

CONCLUSIONS

The Pathways CMT assists in pollution risk assessment in river basins, and can inform decision making in catchment management. The source-pathway-receptor model is used to identify and quantify the linkages between pollutant sources, hydro(geo)logical pathways and receptors to evaluate the presence of a risk of contamination. Combining multi-disciplinary knowledge and national data sets with a user-friendly interface, the Pathway CMT can present informative risk maps of CSAs to environmental managers, to assist in risk assessment, mitigation, monitoring and review of contaminants in Irish catchments.

ACKNOWLEDGEMENTS

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MEASURES FOR MITIGATING POLLUTION FROM AGRICULTURAL SOURCES

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TREND REVERSAL OF NITRATE CONCENTRATIONS IN GROUNDWATER

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ABSTRACT

Time series from groundwater monitoring networks are requested to fulfil the obligations of the Groundwater directive. It is obligate to prove trend reversal when groundwater quality does not meet the required standards. In Denmark intense agricultural activities on 2/3 of the land area often gives rise to nitrate concentrations exceeding 50 mg/l. Regulation and technical improvements in the intensive farming in Denmark have succeeded in decreasing the N surplus by approximately 40% since the mid 1980s while at the same time maintaining crop yields and increasing the animal production of especially pigs. Dating of groundwater is an integrated and important part of the monitoring Danish strategy in order to make better use of the investments in monitoring. In this case groundwater dating was used to link agricultural N management and nitrate concentrations in groundwater. Two principal different methods were used to find an overall trend reversal for nitrate in groundwater that could be related to actions plans on nitrate leaching from agriculture. Only monitoring points where the groundwater was oxic were considered relevant. Firstly nitrate and CFC-recharge year for 194 individual monitoring points were used to prove trend reversal around 1980, when a two piece linear model was used. Secondly, the individual trends of 152 monitoring were found also by linear regression. These trend analyses prove that the youngest (0-15 years old) oxic groundwater shows more pronounced significant downward nitrate trends (44%) than the oldest (25-50 years old) oxic groundwater (9%). This amounts to clear evidence of the effect of reduced nitrate leaching on groundwater nitrate concentrations in Denmark (Hansen et al, 2011).

INTRODUCTION

A global challenge is to produce enough food for the ever-growing population and at the same time minimize the losses of N to the environment. Since the 1980s, agriculture in Western Europe has managed to reduce its nitrogen surpluses, owing to stringent national and European Community policies (Hansen et al., 2011; Fraters, 2011; Dalgaard et al., 2012). In the developing world it can be observed that regions in Africa continue to extract the nutrient capital of what were once highly fertile soils with low yields. In contrast intensive agricultural production in Northern China has a very high input of N to agricultural fields and high yields, but also a very high N loss to the environment where nitrogen losses today are at the same size as the most intensive parts of Western Europe were in the 1980ies. (Sutton, 2013)

In Denmark, public drinking water supplies entirely originate from groundwater and approximately 15% of the total area of Denmark has therefore been classified as nitrate-vulnerable abstraction areas (Hansen and Thorling, 2008) with many waterworks and wells having been turned off due to nitrate pollution. Groundwater protection is therefore a high priority and since 1985 it has been one of the most important drivers of regulation of the Danish agricultural sector through national action plans and EU policies. As for the Nitrates Directive the whole territory is designated nitrate vulnerable in the general sense of risk to freshwater and seawater.

The EU groundwater directive (EU, 2006) imply statutory requirements to identify and reverse trends presenting a risk of harm to the quality of aquatic ecosystems or terrestrial ecosystems, to human health or to the actual or potential legitimate use of the water environment through mitigation measures in order to progressively reduce the pollution and prevent deterioration of groundwater.

As a consequence this must be reflected in the related monitoring systems and the strategy for interpretation of the monitoring data. Specifically, for groundwater systems there is a methodological challenge in interpreting the impact of the measures due to the lack of concurrence between the observations of groundwater quality and the implementation of measures, which is a consequence of the often unknown distribution of residence time of groundwater at the monitoring points. Thus, dating of groundwater is very important in order to establish this link.

AGRICULTURAL PRACTISES, ACTION PLANS

Denmark is a rather small country with an area of 43.000 km^2 and a population of approx. 5.5 mill. people. 2/3 of all land area is used for agricultural activities incl. forestry and more than 20 % of the area is covered with cities and built up areas as roads, business areas etc. This leaves less than 10 % as uncultivated areas like lakes, dunes and wetlands. Denmark has a mild temperate coastal climate, though colder than Ireland. In general, the soils are sandy in the west and clayey in the east, which is reflected in a higher density of livestock in the west and mainly plant production without household animals in the east. Generally the agricultural practises are very intensive with high yields from crops and livestock. Most farmers are very well educated and the agricultural production gives an important contribution to the national NBP e.g. 21% of export (Danish Statistics, 2010).

The rising yields in agriculture in the 1960s and 70s was followed by an increased nitrogen surplus pr. acre farmland, figure 4, causing increased nitrate losses to groundwater and surface waters and incidents of severe eutrophication of the shallow coastal waters surrounding Denmark. In 1986 after a summer with severe algae bloom the newspapers and television flashed dead lobsters and fish suffering from oxygen depletion in the coastal waters. This initiated the first action plans to reduce nitrate losses from agriculture, and a national monitoring programme to measure the effectiveness of the measures.

The Danish Parliament agreed on the first Action Plan for the Aquatic Environment (APAE I) in 1987 and on APAE II in 1998, and thereby on fulfilment of the Nitrates Directive. In 2008 a midterm evaluation of APAE III showed that the nitrate leaching was not reduced as expected. As a consequence a new program ‘Green Growth’ has been adopted, the implementation, however, is still to be finalized. (Grant et al., 2011)

Measures

The Action Plans for the Aquatic Environment (APAEs) are comprehensive regulation regarding the aquatic environment. They precede the implementation of the Nitrates Directive, as the first plan was adopted in 1987. The action plans include the Danish code of good agricultural practise as mandatory measures and further restrictions in the use of nutrients. The action plans deal with nutrient-related measures e.g. mandatory fertilizer accounts, improved utilization of nitrogen in manure, reduced nitrogen standards for crops as compared to the economic optimum, and area-related measures e.g. reestablishment of wetlands and afforestation.(Grant et al, 2011) Some of the most effective environmental measures have been a reduction in the statutory and crop-specific N fertilisation standards and N utilization requirements of manures which has raised the overall N use efficiency from 27% in 1985 to 40% in 2008 (Dalgaard et al., 2011).

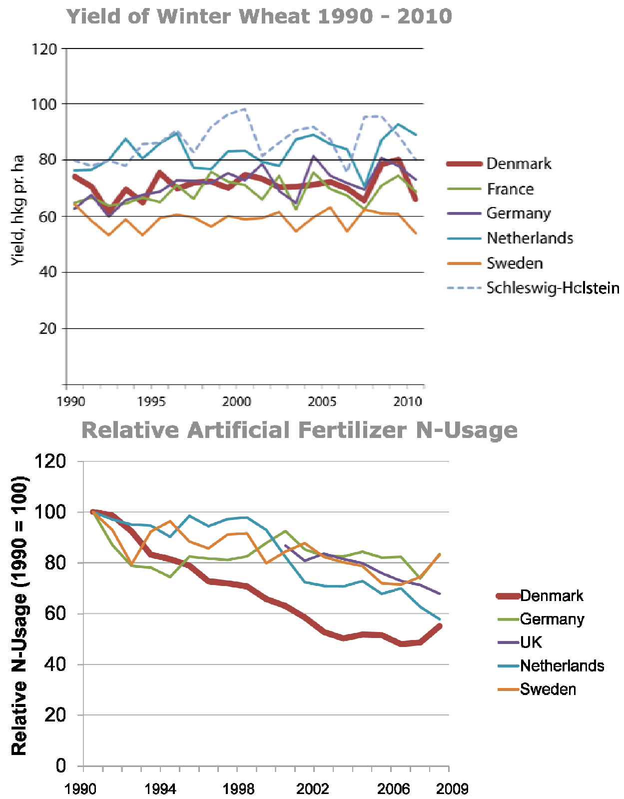

Figure 1. Maintenance of yield while reducing use of N-fertiliser. Data from Knowledge Centre for Agriculture DK, Leif Knudsen.

Since 1990, agriculture in Denmark has been able to reduce its N surplus by approximately 40% while maintaining crop yields, see figure 1&4. The result of the reduction in the agricultural N surplus is reflected in respective reductions in nitrate leaching of on average 33%, the N load in surface waters of approx. 29-32% (Grant et al., 2011) and groundwater nitrate concentrations of approx. 40% (Hansen et al., 2011).

NATIONAL MONITORING

The Danish National Monitoring Program for the Aquatic Environment was established in 1988, covering all elements of the environment (Jørgensen & Stockmarr, 2009). It has been revised regularly, the present program, NOVANA (national monitoring program for water and nature) is running from 2011-2015. The main structure of the program has been maintained since the establishment in 1988, thus providing long time series of measurements. The NOVANA program is directed by political and administrative demands, to monitor EU directives (including the Nitrates Directive), national regulations, conventions, etc. This means that all monitoring must relate to environmental goals. The NOVANA program is part of the strategic environmental planning. The monitoring serves to document if the state of the water and nature environment is developing in the right direction and whether the environmental goals are fulfilled. It also serves as the scientific basement to identify demand for new activities. (Grant, R. et al, 2011)

GROUNDWATER MONITORING

Groundwater monitoring in Denmark has until 2010 been based on information from 75 ground-water monitoring areas typically with 20-25 monitoring screens in each area and 5 agricultural catchments. Today a more distributed net of monitoring point is under establishment to fulfil the need of monitoring of the groundwater bodies, while monitoring points in groundwater older than 70 years is halted. In the original groundwater monitoring program about 75 % of the monitoring was targeted groundwater dated by CFC to be recharged after 1940. Approximately 17 % of the monitoring screens have nitrate concentrations above the maximum admissible concentration (MAC: 50 mg/l nitrate) for drinking water, and almost 50 % of the screens have nitrate concentrations above 5 mg/l. The rest of the screens are monitoring nitrate free, reduced groundwater. In the monitoring areas focus has turned towards the upper groundwater over the last 10 years, and about 250 new monitoring wells have already been established around 2005. The new screens are typically placed in the upper 5-10 m of the aquifer (10-20 m below surface).

STATE OF NITRATE IN GROUNDWATER DK

The easy question is: how is the state of nitrate in groundwater in Denmark? The difficult part is to give a clear answer. To do this a conceptual model of the understanding of the dynamics of nitrate in groundwater is prerequisite. Figure 2 shows a simple model of nitrate in groundwater. In the top nitrate is present in concentrations typically above 50 mg/l in oxic groundwater (O_2 > 1 mg/l). As the water infiltrates vertically oxygen is depleted before nitrate, and an anoxic zone generates where nitrate is reduced, before the groundwater reaches the reduced zone where no nitrate is present. The figure has no scale, and the actual sizes of the different zones depend strongly on the hydrogeology. In sandy regions nitrate can be found more than 100 m below surface and in some clayey regions nitrate is reduced already in the top soil. In these years intensive mapping of groundwater aquifers is taking place in areas with drinking water interest (40 % of DK) and a site specific scale is put on this model. This is done in order to find out the location of the nitrate vulnerable aquifers, and hence to efficiently delineate areas where implementation of measures to protect groundwater from nitrate and thus Danish drinking water resources are necessary.

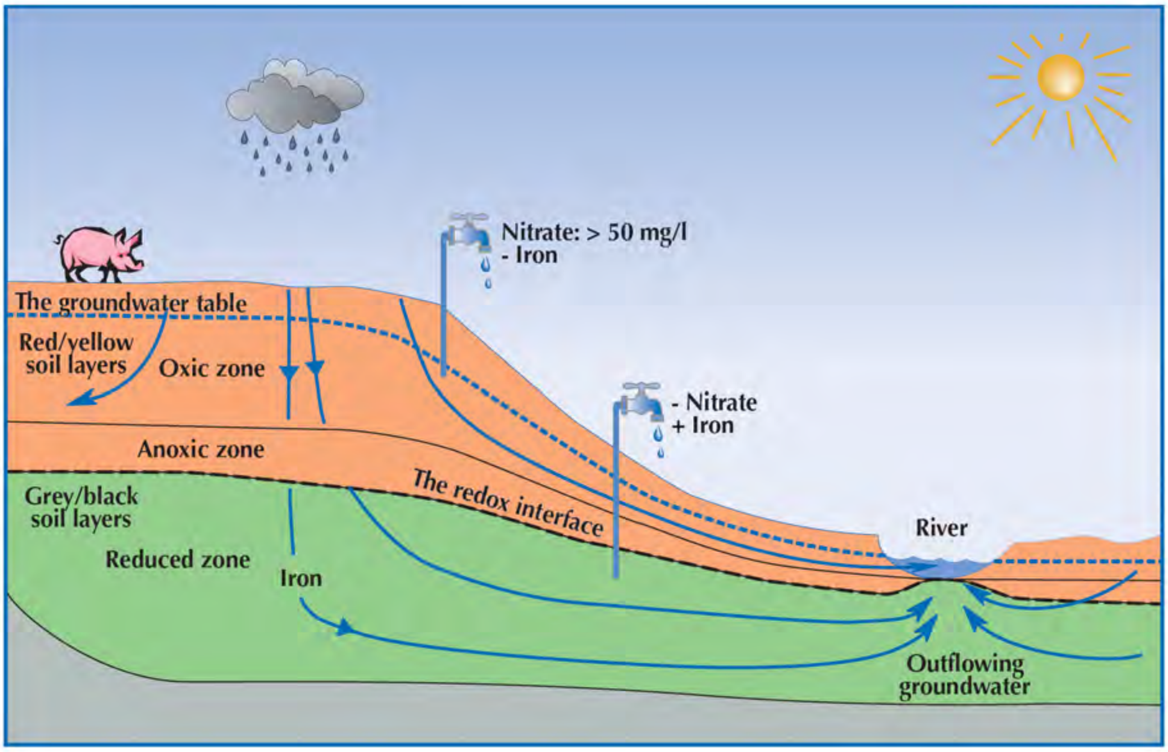

Figure 2. Conceptual model of nitrate in groundwater, note: no scale. (Hansen et al., 2012)

The implications of this model is that each sample from a monitoring well represents not only the point and time (x,y,z,t) where the water was abstracted but also the time of recharge, t_r, where the influence from surface activities were imbedded in the groundwater. The present state found in the monitoring network is thus a result of the nitrate leaching from agriculture over the last 70 years. The youngest groundwater in the monitoring programme is approx. 5 years due to the needed time for transport through the unsaturated zone and to layers where it is possible to pump water from.

Any map of nitrate state will thus show groundwater of different age, even when it was possible to take all samples the same date. If a map show data that are not properly sorted, it will show data from groundwater with and without nitrate, in principle showing a stochastic picture of the state. To give a better answer on how the state is, data from the different redox-zones must be presented alone, and the amount of groundwater in the different zone estimated. When understanding how much the action plans has effected groundwater quality, it is important to know whether the monitoring points with high nitrate concentrations represent the intense agricultural practises before or after 1985. In Denmark dating of groundwater is thus an important part of the monitoring activities. Until recently dating has taken place by the CFC method (Busenberg & Plummer, 2008). Due to the effectiveness of the Montreal protocol on control of ozone-depleting gasses, the method is not very useful for groundwater formed after 2000 and today new methods are implemented (^3H,^3He).

INTERPRETATION OF TIME SERIES

Interpretation of time series without any knowledge of the age of the groundwater is difficult. Figure 3 shows some examples of time series for nitrate from the monitoring programme. One with rising and the other with decreasing nitrate content. But do we observe effects of action plans or not? Dating of groundwater with CFC showed that both points monitor groundwater of an age of approx. 25 years, thus the observed time series represent agricultural practises from 1965-1990. The patterns do thus not reflect the last 25 years of action plans.

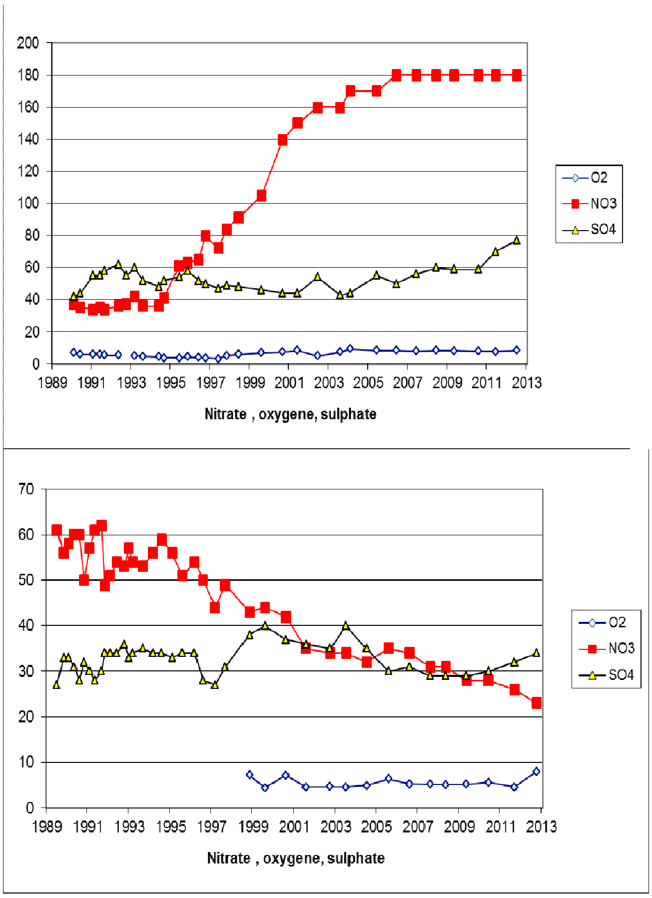

Figure 3. Examples of time series, from the national monitoring network

RESULTS

In order to interpret the data better a dataset with time series of groundwater samples from oxic groundwater was formed. Through a stepwise procedure:

Monitoring points with oxic CFC dated groundwater are included
Monitoring points with more than 8 years of data are included
Monitoring points with unstable redox conditions are excluded
Outliers, e.g. effects of establishment, are found and excluded.

Only monitoring points with oxic conditions were included because both nitrate and CFC gases used for dating are degraded in anoxic groundwater. The concentration levels of the redox sensitive parameters (NO_3^-, Fe^{++}, and O_2) were used to sort out 194 samplings points. Oxidised groundwater is defined as [NO_3^-] > 1 mg/l, [Fe^{++}] < 0.2 mg/l and [O_2] >1mg/l. This definition minimised the uncertainty in the determination of the groundwater redox state by giving third priority to the most uncertain parameter (i.e. oxygen). Iron in groundwater was thus used as an indication of complete nitrate reduction. The nitrate content from the year of sampling for CFC is illustrated as a function of the measured CFC-year for the 194 oxic monitoring points in figure 4. In the same figure a time series for the nitrogen surplus from agricultural areas is also shown (Hansen et al. 2011)

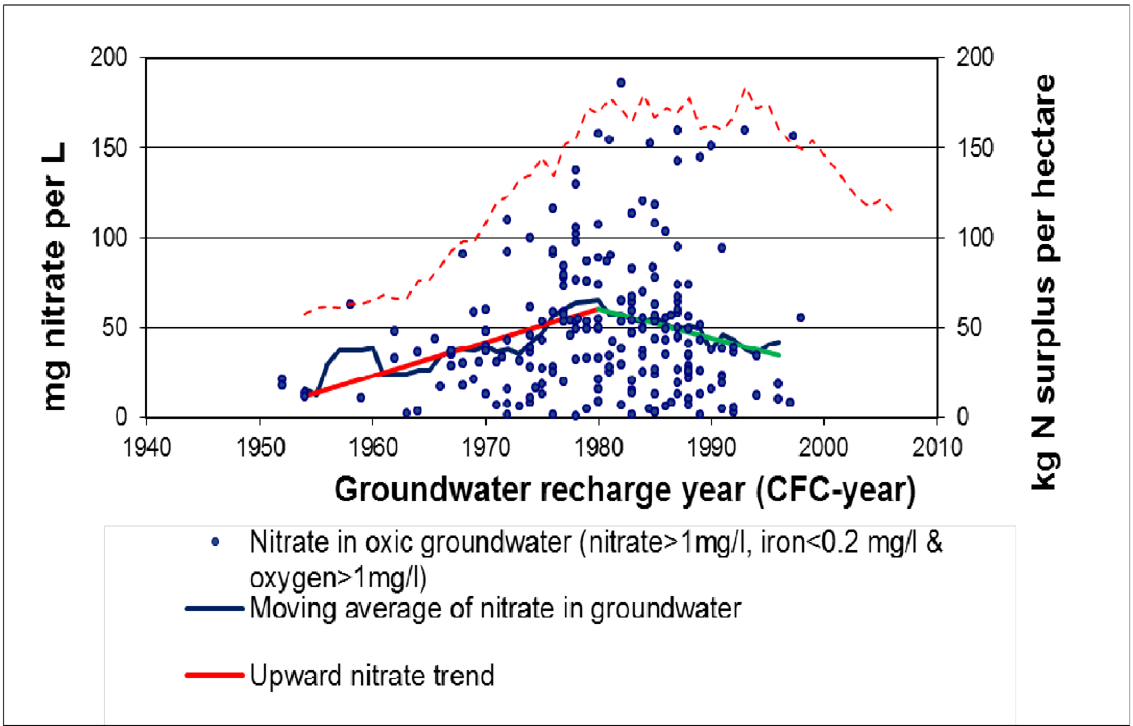

Figure 4. The national general nitrate trend based on 194 oxic groundwater monitoring points, compared to the national nitrogen surplus per ha. (Hansen et al., 2011)

In order to find a possible national trend reversal in the dataset in figure 4, the level of nitrate concentration at the year of groundwater recharge was described by a piece-wise linear regression line with one unknown change point, as required by the EU Water Framework Directive. A nitrate trend reversal was found at the year 1980 (± 3.4 years) with a significant upward trend before and a significant downward trend after 1980 (see Figure 4). The slopes of the upward (c. 1.83 mg/l/yr) and downward (c. -1.61 mg/l/yr) curves are significantly different from zero at the 0.05 probability level.

Next the 152 monitoring points with time series of more than 8 years were used to calculate the individual trend at each monitoring point with linear regression. The points with significant individual trends were sorted into three age groups and the fraction of upwards and downwards trends are shown on figure 5.

Consistently with the data analysis in Figure 4, the youngest oxic groundwater has more monitoring points with downward trends than the older oxic groundwater (Figure 5). However, comparison of the common trends in the three age groups demonstrated an only slight statistical significance (p=0.0394). Although, the general trend (figure 3) shows at trend reversal around 1980 the trends from the individual monitoring points show a more complex picture. A significant downward trend was demonstrated in approximately 44% of the youngest oxic groundwater (0-15 years old), 27% of the medium old oxic groundwater (15-25 years old) and 9% of the oldest oxic groundwater (25-50 years old). In comparison, a significant upward trend was found in approximately 18% of the youngest oxic groundwater (0-15 years old), 30% of the medium old oxic groundwater (15-25 years old), and 64% of the oldest oxic groundwater (25-50 years old) (Hansen et al., 2011).

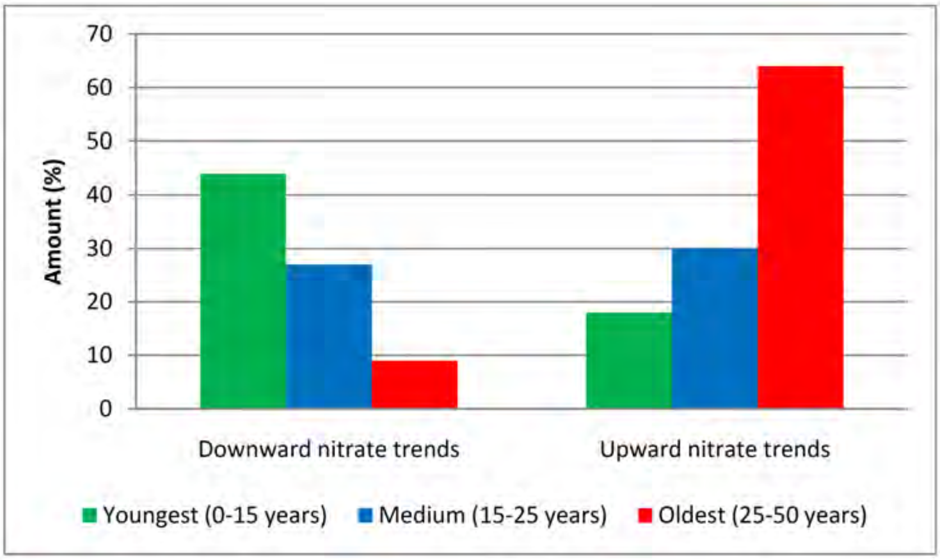

Figure 5. 3 age groups of nitrate trends based on 152 oxic monitoring points with significant trends over more than 8 years. (modified from Hansen et al., 2012)

DISCUSSION

Long-term groundwater quality monitoring with more than 20-year time-series provides optimal opportunities for investigating and understanding the impact of pressures and political action plans on groundwater quality. When addressing trends of pollutants in groundwater, it is fundamental to have a sufficient number of long-term time-series, thereby being able to combine general trends and trends for individual monitoring points as shown in this study. This requires a consistent national monitoring programme. Due to economic and political adjustments of the monitoring system, some time series are too short or abrupt, which reduces the payoff of monitoring investment.

This study demonstrates that groundwater recharge ages can be included as an essential component of groundwater trend investigations, and that their inclusion may help to correlate changes in land use and management practices with changes in groundwater quality. Groundwater recharge age determination allows concentrations of nitrate to be related to the time of recharge instead of the time of sampling, which, in turn, makes comparison between nitrate in groundwater and N loss from agriculture possible. Trend reversal was successfully described with a single change point using a two-section linear model. A statistically significant trend reversal was found in 1980 (±3.4 years) of the nitrate concentration of Danish oxic groundwater (Hansen et al. 2011). A trends reversal around 1980 in the N concentrations and loads at a hydrological catchment scale has also recently been documented in the Odense river in Denmark. (Larsen et al. 2008)

The trend reversal around 1980 of the nitrate concentrations in oxic groundwater coincided with the clear levelling out of the N surplus in agriculture after a period of strong increase, which actually occurred before the initiation of the first Danish environmental action plan in 1985. All these plans have focussed on the reduction of N-pollution from agriculture, being far the most important source for nitrate leaching in Denmark. Especially in the beginning of the action plan period, reduction of N-losses from point sources in the form of better waste water storage and treatment facilities in the rural areas, and reduced runoff from livestock houses, silage clamps and manure heaps had a significant effect (Hansen et al., 2011)

The Danish findings are comparable to the results from other EU countries (Fraters, B. et al 2011), although differences exist. Although this study shows clear evidence of an effect of reduced N leaching on the groundwater nitrate concentrations the last evaluation of the Danish action plans showed that the measures have not had the expected and required effect on all parts of the environment. For example, Danish coastal waters are still among the coastal water most frequently experiencing oxygen depletion, globally. In addition, groundwater nitrate concentrations still have to be lowered significantly in order to assure good ecological status of Danish estuaries and good chemical status of groundwater according to EU legislation.

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CATCHMENT MANAGEMENT – A LOCAL AUTHORITY APPROACH

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ABSTRACT

In 2002, Limerick County Council set up a farm inspections team under the Phosphorus Regulations to implement a catchment based approach to tackling the problem of eutrophication of surface waters. This team focused its efforts primarily on the Deel Catchment in West Limerick. In 1996 to 1999 report on water quality in Ireland this catchment was identified as having the second highest P export rates per km^2 in the Country (the Maigue in County Limerick being the highest).

The team operated in accordance with the policy document "Managing Ireland's Rivers and Lakes: A Catchment Based Approach to Eutrophication", with the aim of achieving the water quality objectives of the P regulations. Over the years the framework under which the team operated changed with the introduction of the Good Agricultural Practice Regulations, the River Basin Management Plans, the Surface Water Regulations (which subsumed the P regs) and the Groundwater Regulations. However, the fundamental approach with respect to tackling surface water pollution has not changed significantly. The approach has had significant success at reducing P levels in the Deel.

In relation to groundwater, the Council has been less proactive. There are a number of reasons for this: groundwater is conceptually more difficult and definite sources of pollution are more difficult to identify. However, progress has been made and continues to be made in this regard as the understanding of groundwater regimes grows and as the emphasis on groundwater quality increases, driven by both the WFD and the Drinking Water Regulations.

In this respect some specific and general measures which the council have taken to protect groundwater are discussed. These include policies aimed at protecting groundwater in areas of "poor" status, investigations of specific pollution issues and examination of set back distances.

Also, some of the problems associated with solving groundwater pollution problems are highlighted by reference to a specific case.

GROUNDWATER SAFEGUARD ZONES IN ENGLAND

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ABSTRACT

Safeguard Zones (SgZs) are non-statutory catchments around abstractions used to supply water intended for human consumption where measures are put in place to avoid the need for additional treatment. The ability to define SgZs comes from Article 7.3 of the Water Framework Directive. This paper explains how we are designating, investigating and delivering environmental objectives within SgZs in England.

BACKGROUND

INTRODUCTION

Groundwater Safeguard Zones (SgZs) are non-statutory catchments around abstractions used to supply water intended for human consumption where measures are put in place to avoid the need for additional treatment. Within England they form part of our strategy to improve water quality and are linked with investigations and actions developed as part of River Basin Management Plans (RBMPs). This paper explains how we are designating, investigating and delivering environmental objectives within SgZs in England.

WATER FRAMEWORK DIRECTIVE (2000/60/EC)

The Water Framework Directive (WFD) (Article 7.1) requires that the following be identified as Drinking Water Protected Areas (DrWPAs):

> *"all bodies of water used for the abstraction of water intended for human consumption providing more than 10m^3 a day as an average or serving more than 50 persons; and, those bodies intended for such use"*

Within England we have designated all groundwater bodies as Drinking Water Protected Areas.

Article 7.3 then gives the following requirements for DrWPAs:

> *"Member States shall ensure the necessary protection for the bodies of water identified with the aim of avoiding deterioration in their quality in order to reduce the level of purification treatment required in the production of drinking water. Member States may establish safeguard zones for those bodies of water."*

The WFD gives no further detail on the application of SgZs. However, there is the European Union Common Implementation Strategy guidance which covers this subject for groundwater (EU, 2007). Member States thus have flexibility in how they may apply SgZs.

AIM OF ARTICLE 7.3

Although the overall (long-term) aim of Article 7.3 of the WFD is to reduce the need for treatment of raw water used for potable purposes, the immediate requirement is to implement any necessary measures to avoid further deterioration in raw water quality and consequent additional water treatment. This is the current focus for our strategy for the implementation of SgZs.

PROTECTING DRINKING WATER ABSTRACTIONS IN ENGLAND

In England we have a tiered risk-based approach to the protection of drinking water abstractions and compliance with Article 7 of the WFD (see Table 1 below). For groundwater this is an extension of our existing approach using our Groundwater protection: Principles and practice (GP3) document and groundwater Source Protection Zones (SPZs). SgZs will occupy a middle tier between GP3 and Water Protection Zones (WPZs). In all cases the assessment of which tier of protection is appropriate will be preceded by a review of Environment Agency and water company data. This could include:

- conceptual models;
- monitoring data (for example groundwater quality data supplied by water companies to the Environment Agency, water company data supplied to the Environment Agency via the Drinking Water Inspectorate (DWI), and Environment Agency monitoring at abstractions used for human consumption);
- modelling data;
- chemical usage information;
- WFD characterisation and classification data;
- the results of the water company catchment risk assessments that are contained in Drinking Water Safety Plans; and
- a review of the actions and measures that have already been undertaken.

Table 1. Tiered approach to the protection of drinking water abstracted from groundwater

Tier	**Description**	**Controls / Tools**
1	General protection of the DrWPA (i.e. the whole groundwater body)	The Environment Agency will continue to apply the position statements in accordance with our Groundwater protection: Principles and practice (GP3) document. The groundwater protection hierarchy identifies progressively more sensitive locations with respect to the protection of groundwater resources, as follows: Unproductive strata → Secondary Aquifer → Principal Aquifer → SPZ3 → SPZ2 → SPZ1. Existing groundwater Source Protection Zones (SPZs) are a non-legislative tool to influence external parties and focus our position statements.
2	Safeguard Zones (non-statutory protection)	Environment Agency assessments indicate that certain abstractions are likely to require additional measures to avoid failing the Article 7.3 objective, the aim being to avoid deterioration in raw water quality in order to reduce the level of purification treatment. SgZs are areas where pollution originates and/or areas where pollution impacting an abstraction has been identified with high confidence. They are based upon existing groundwater SPZs, modified as necessary. SgZs may need to be revised and altered in size and shape if new information reveals that the source of the pollution extends outside of the designated SgZs.

		The Environment Agency is seeking to address the problems in SgZs by targeted use of existing powers and advice and incentive schemes; this will include voluntary agreements, campaigns and enforcement action to reinforce GP3.
3	Water Protection Zones (statutory protection)	Where there is a high degree of confidence that an abstraction is failing to meet Article 7.3 [or likely to if current trends continue] a WPZ may be defined as a 'last resort' if other mechanisms are unlikely to deliver the required objective. A WPZ in this context is a geographical area within the catchments of abstraction sources for drinking water to deal with specific point or diffuse source problems. It would be based on an existing groundwater SPZ, modified as necessary. In order to designate a WPZ we will need significant evidence that all other options have been adequately explored. We will also need support from internal and external partners. Finally, all WPZs will need to be approved by the Secretary of State for Environment, Food and Rural Affairs. Within WPZs, we are able to apply statutory measures to manage or prohibit activities which cause or could cause damage or pollution of water over and above existing statutory powers. A WPZ Order defines both the area and the specific measures designed to deal with identified water quality problems within it.

METHODOLOGY FOR DESIGNATING NEW SAFEGUARD ZONES

Within England we will identify new groundwater SgZs where the following criteria apply:

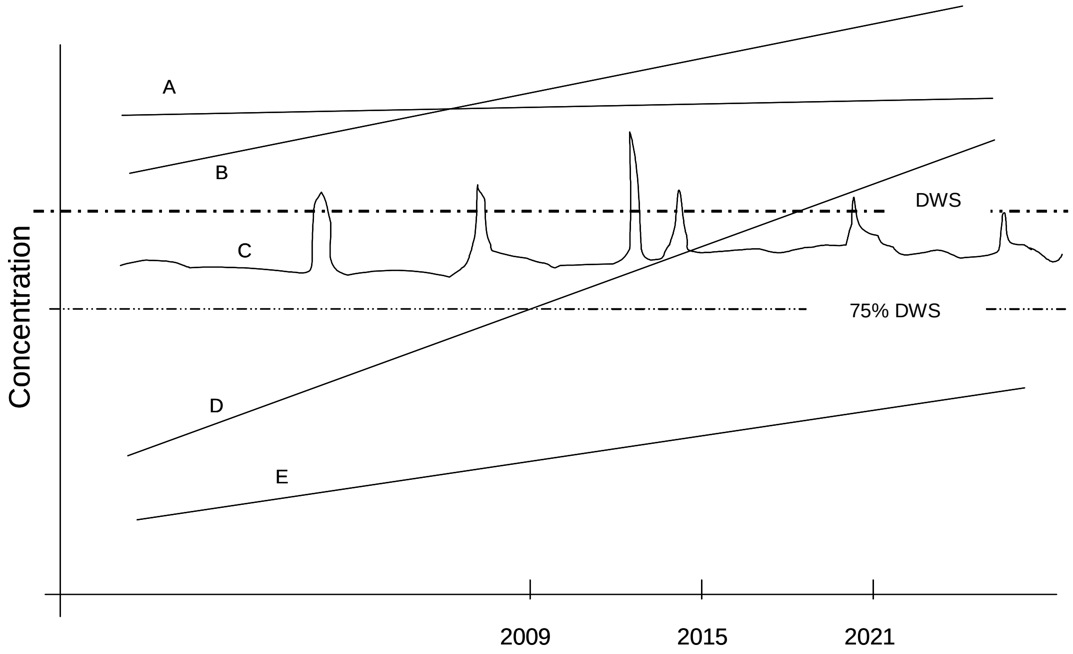
1. There is good evidence of:
    - An adverse trend in raw water quality such that without intervention additional water treatment would be required by or before 2021.
    - Any longer-term adverse trend in raw water quality which requires action in River Basin Cycles 1 or 2 to avoid problems developing after 2021.
    - Recurrent short-term deterioration in raw water quality (spiking) which could compromise existing treatment, for example lead to plant shut down or provides a real risk that water quality in distribution could breach the relevant potable water standards.

2. There is good evidence to identify the cause of the raw water impact.

3. Cost effective mitigation measures can be identified which would avoid or minimise the need for treatment or reduce risks of treatment failure.

The criteria for designating and de-designating SgZs are graphically presented in Figures 1 and 2 below.

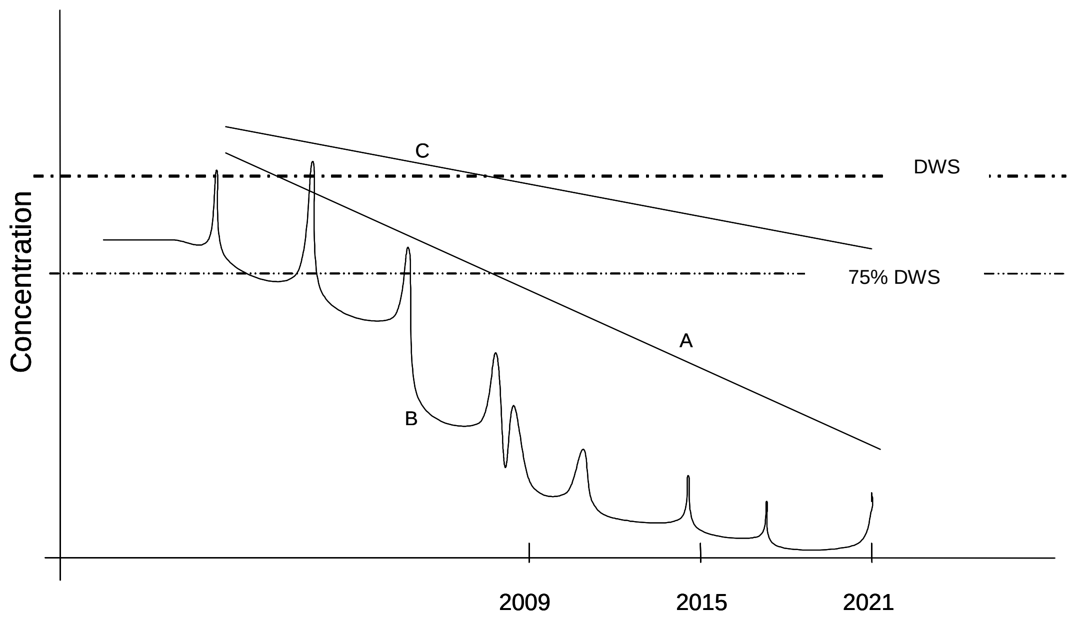
Figure 1. Example criteria for designating groundwater SgZs



Notes: DWS – Drinking Water Standard
Categorisation: Medium Priority = A, E High Priority = B, C, D

High priority abstractions are likely to be designated as SgZs. Medium priority abstractions may be designated as either SgZs or candidate SgZs. If a source is designated as a candidate SgZ it will be kept under review and may be formally designated in the future.

Figure 2. Example criteria for de-designating groundwater SgZs



Notes: DWS – Drinking Water Standard
Categorisation: Likely de-designation = A, B Do not de-designate yet = C

The process of identifying new SgZs is undertaken by the Environment Agency's regional hydrogeologists in partnership with the owner of the abstraction (usually a water company). We would not identify a new SgZ without the support of the abstraction owner.

Although this methodology is aimed at identifying SgZs around public water supply abstractions, it can be used on all abstractions that supply water intended for human consumption. This includes both abstractions for drink or food production and private drinking water abstractions.

DELINEATING GROUNDWATER SAFEGUARD ZONE BOUNDARIES

In the absence of better information the default zone boundary for a SgZ is Source Protection Zone 2 (SPZ2). SPZ2 is the 'outer protection zone' and is defined by a 400 day travel time from a point below the water table to the abstraction. Further details can be found in GP3. In some cases it may be necessary to define an alternative boundary. For example in high porosity aquifers SPZ2 may be small and the majority of the pollutant loading may be derived from an area outside SPZ2. An example of this is diffuse nitrate pollution in the Triassic Sandstone aquifer.

Due to the different manner in which surface water and groundwater bodies are delineated and the fundamental difference in flow regimes between these media, SgZs for surface water and groundwater will inevitably look very different.

USING GROUNDWATER SAFEGUARD ZONES

RIVER BASIN MANAGEMENT PLANS

In the first (2009) River Basin Management Plans (RBMPs) we designated 201 groundwater SgZs in England. As we move towards publishing the second RBMPs in December 2015 we are now reviewing our SgZs. As part of this review process we will:

- designate new groundwater SgZs;
- remove previously designated groundwater SgZs where appropriate;
- review the substances of concern; and
- revise the boundaries of existing groundwater SgZs where necessary.

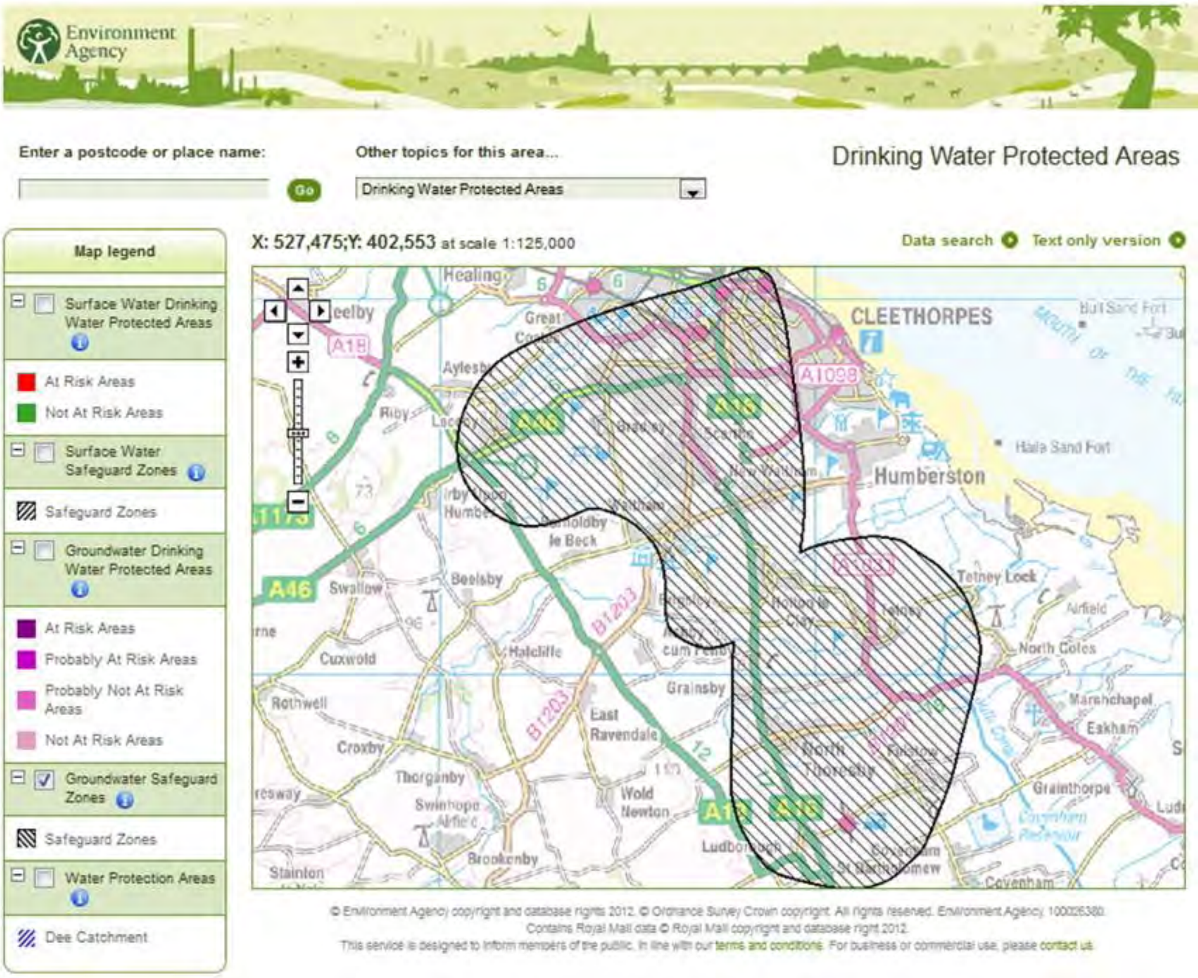
SAFEGUARD ZONE ACTION PLANS

A detailed action plan has been produced for each SgZ designated in the 2009 RBMPs. The action plan characterises in detail each SgZ. This includes assessing the sources of pollution and identifying the actions needed to meet the objective of Article 7.3. A wide variety of measures can be used within SgZs including awareness raising, pollution prevention campaigns, voluntary agreements, targeted enforcement, Catchment Sensitive Farming, agri-environment schemes, improvements to discharges and water company led catchment schemes.

PUBLICATION OF SAFEGUARD ZONES

In England, SgZs are published within RBMPs. They are also published on the Environment Agency's 'What's in your backyard?' website. As well as displaying all SgZs this website also displays the reason why each SgZ was designated.

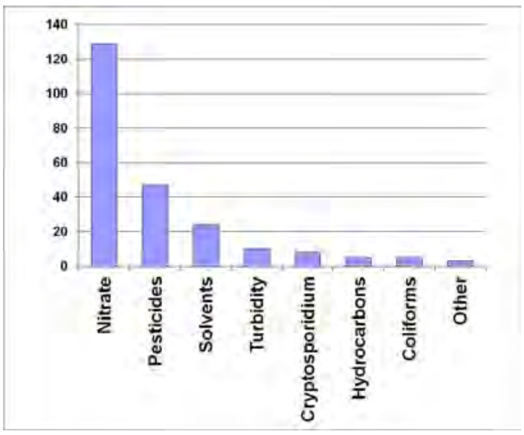
Figure 3. An example of a groundwater SgZ on the ‘What’s in your backyard?’ website



REASONS FOR DESIGNATING SAFEGUARD ZONES

The reasons for designating the original 201 groundwater SgZs in the 2009 RBMPs are presented in Figure 4. Some SgZs have more than one reason for being designated. Many public water supplies from groundwater within England are located in rural areas. This helps to avoid point source urban contamination such as from industry or historic contaminated land. Hence, a substantial proportion of the water quality problems found in public water supplies in England arise from rural land use issues. By far the most common reason for SgZ designation is nitrate. Our individual source apportionment investigations around SgZs have found that agriculture often provides a substantial contribution to the nitrate load at the borehole.

Figure 4. A summary of the reasons for designating groundwater SgZs



CASE STUDIES

SOUTH WEST REGION

The study area is focused on two small drinking water boreholes used by a water company in the Environment Agency's South West Region. The nitrate levels in these two boreholes have been increasing over many decades and there is a risk that the levels could exceed Drinking Water standards (DWS) in the future.

Most of the area adjacent to the boreholes and to the north is managed grassland with some woodland in the upper reaches of the catchment. The most common crops grown in this area are cereals (winter wheat and spring barley) with break crops of oilseed rape. Inorganic fertilisers are applied to arable land and the grassland receives organic fertilisers (manure) from dairy herds.

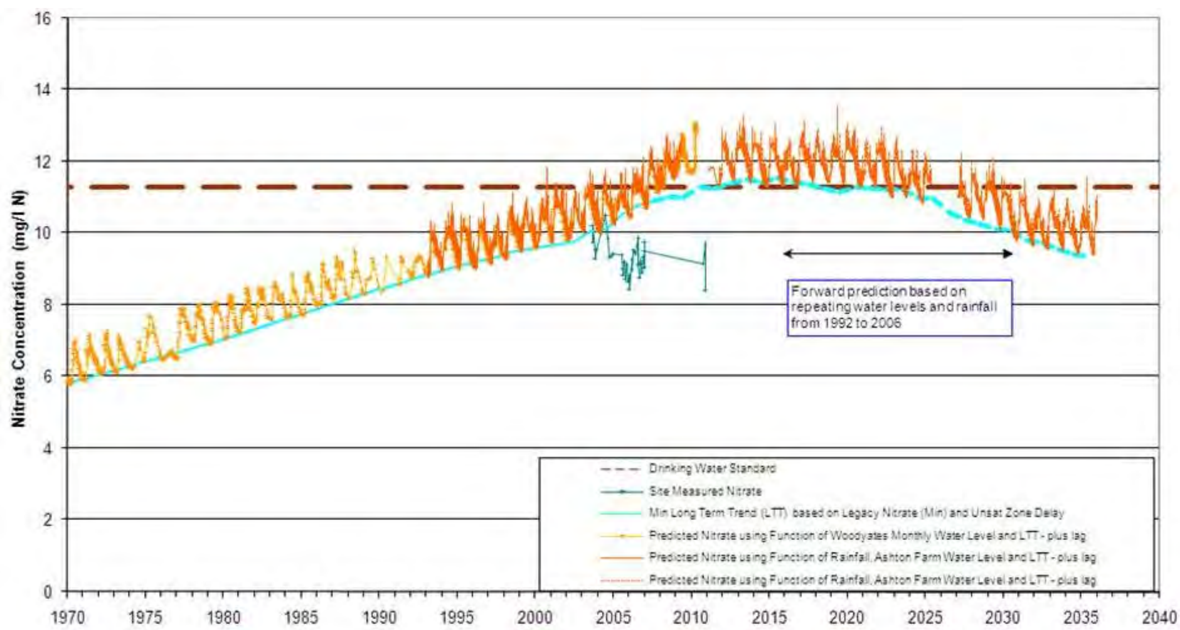
Source apportionment was undertaken to quantify the different sources of nitrate. In both catchments the majority of the nitrate load came from agricultural sources (92% in the first abstraction and 82% in the second). There was also a discharge from a sewage treatment works which was believed to contribute of the order of 7% and 14% of the loading at the first and second abstractions respectively.

Trend forecasts for each of the sources indicate that drinking water standards at the first abstraction may be breached at any time and at the second borehole, between 2020 and 2030.

A target water quality standard of 75% of DWS was set as the target standard for nitrate leaching across the catchment. This would be measured as an average across several years using porous pots. By using a value of 75% of the DWS, measured as an <u>average</u> over several years, the Environment Agency aims to ensure that the <u>peak</u> nitrate concentration at the drinking water abstraction will not exceed the DWS.

Modelling was undertaken (see Figure 5) to assess the impact of reducing nitrate leaching from agriculture to 75% of the DWS.

Figure 5. Predicted impact of reducing nitrate leaching to 75% of drinking water standard at the first study borehole.



An options appraisal and cost benefit analysis was carried out to assess the most cost beneficial way of meeting the drinking water standard. This analysis included the following range of options:

- alternative water supply or blending;
- point source improvements to the sewage treatment plant; and
- land management measures.

The analysis concluded that the most cost-beneficial option was to implement a specific set of land use change options. These options require the farming community to make relatively minor changes by moving to a rotation of winter oilseed rape (baling the straw); winter wheat (followed by cover crop), spring barley (not exceeding a specific nitrate application rate). These options allow the drinking water threshold to be met yet are both cost-beneficial and affordable. The local farming community has voluntarily implemented these land use change measures. Porous pots have been installed and the Environment Agency awaits the results over the coming years.

ANGLIAN REGION

A similar study was undertaken in the Northern Area of the Environment Agency's Anglian Region. The water company was concerned about rising nitrate concentrations and capacity for blending at three abstractions. The catchments of concern were identified as SgZs and action plans were developed. The investigation was similar to the South West project except that unsaturated zone coring was undertaken to investigate porewater nitrate concentrations. The porewater profiles showed good correlation with national fertiliser usage statistics and national nitrate leaching models as used in the WAgriCo investigation of nitrate leaching (UKWIR, 2009). These porewater concentrations were successfully used to predict historic nitrate leaching concentrations. The model predicted that nitrate concentrations will continue to exceed UK drinking water standards into the next River Basin Cycle at two of the abstractions and that concentrations at the third abstraction would continue to increase such that they will eventually exceed the standard. Modelled reductions of up to 50% of leached nitrate would reverse the trends at the first two abstractions by 2027, but even a 100% reduction at the third abstraction would not reverse the trend by this date. A 50% reduction in nitrate leaching would require a very substantial change in farming practice. Further discussions are taking place with landowners and Catchment Sensitive Farming colleagues regarding how we can meet the drinking water objective in these catchments.

As part of the source apportionment work the University of East Anglia also analysed water from several abstractions for nitrogen and oxygen isotopes. This analysis has suggested that artificial fertilisers applied to the land-surface form the main source of nitrate observed in the groundwater. This supports the results of our source apportionment work.

CONCLUSIONS

In the 2009 River Basin Management Plans 201 groundwater SgZs were designated within England. Action plans have been written for each of these SgZs. The actions identified within the action plans are now being implemented. It is too early to assess the overall effectiveness of these actions, but evidence suggests that they will make a contribution to reducing the level of treatment at abstractions used for human consumption. SgZs are likely to be most effective where relatively modest land use changes are required to deliver the Drinking Water Standard.

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WATER QUALITY AND SOURCE PROTECTION – A LOCAL AUTHORITY APPROACH

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ABSTRACT

In the last decade the role and responsibility of local authorities in the area of water management has expanded and now presents a complex and significant challenge at a time of restricted resources. The initial driving force to engage in a more proactive approach to address the county's water quality problems arose following the introduction of the Phosphorus Regulations in 1998. In 2002, a dedicated 'Phosphorus Team' (2 persons initially) with a small budget was set-up in Monaghan County Council to work on improving surface water quality.

The extent of Monaghan's impacted waters were confirmed when water quality status was later assigned in the River Basin Management Plans (2009-2015). In parallel with the need to protect and improve water quality generally, additional protection of our 20 surface water supply sources and groundwater supply sources for drinking water became evident.

Our catchment approach commenced with a review of local knowledge and available monitoring data, followed by additional biological monitoring and catchment surveys. Meetings took place with Teagasc/REPS Planners, Irish Farmers Association, Agricultural Contractors, licenced industry, Fisheries Board staff, the National Federation of Group Water Schemes and EPA Regional Laboratory staff to inform and promote engagement and to develop better working relationships. Catchment based information leaflets and best practice guidance was developed. This approach, combined with the use of developing GIS tools and the use of environmental consultants provided valuable information in a number of catchments. Environmental consultants were engaged from 2005 to carry out detailed surveys of farms and industrial and commercial premises with follow up visits by local authority staff where problems were identified. Major improvement works also took place in recent years under the Water Services Investment Programme.

This presentation focuses on the Proules River catchment in south County Monaghan. This is a complex catchment situated on a regionally important karst limestone aquifer supplying drinking water to Carrickmacross town. Two surface water supply sources are also present in the catchment supplying local group water schemes. The Proules catchment has point and diffuse pollution sources from agriculture, urban areas and miscellaneous activities. A suite of measures have been implemented in the catchment and in this presentation I will discuss our survey method and findings, progress to date, enforcement work, municipal improvement works, unresolved issues, water quality trends and future challenges.

TECHNICAL WORKSHOP

SIMPLIFIED APPROACH TO WETLAND MONITORING

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ABSTRACT

Wetland habitats are protected through national and international legislation and provide essential ecosystem services at global, national and local scales. In Ireland, the biodiversity value of wetlands has been estimated to be worth €385 million per year to the Irish economy. Irish wetlands are estimated to cover over 600,000 hectares and while extensive research has been conducted on the ecology of specific wetland habitats, there remains a limited understanding of the hydrology of the range of wetland habitats that occur throughout the border counties of the Republic of Ireland and Northern Ireland. A general paucity of baseline data for Irish wetlands, particularly with regard to wetlands without specific conservation designation, combined with a general mono-disciplinary approach to assessing wetlands, highlights the need for multidisciplinary studies to support conservation and management actions.

The geophysical and geochemical surveys of the Tellus and Tellus Border projects will result in seamless maps of key physical properties of soil and surface water chemistry across the border area of Ireland. These data will support research into the characterisation and management of border county wetlands.

The Tellus Border Wetland Project, a component of the larger Tellus Border Project, aims to combine the geophysical and geochemical Tellus Border survey data with data collected from five wetland sites that are representative wetland habitats of the border counties of the Republic of Ireland and Northern Ireland. This will allow the investigation of the sites' water delivery mechanisms and water requirements as well as determining the influence of underlying geology and soils on the surface and ground water being delivered to the wetland sites. Ecological monitoring of macroinvertebrates, zooplankton, phytoplankton and vegetation is also being undertaken at each site in addition to the hydrological investigations. The synthesis of hydrological and ecological data will inform conceptual models for each wetland site to guide conservation and management actions. This synthesis of methods is leading to a holistic understanding of ecosystem function at the five wetland sites that significantly improves the more frequent mono-disciplinary assessment of wetland ecology and hydrology.

One of the five representative wetland sites, Rockmarshall, County Louth (Figure 1), is a raised shingle beach where linear wetlands exist in the slacks between dry grassland ridges. Wetland habitats within the site include wet grassland, transition mire, reed swamp and scrub and a stream flows east to west across the northern end of the site before turning southwards and discharging into Dundalk Bay. The groundwater-dependent nature of this wetland site elevates its status as a result of legislative requirements for monitoring and understanding of groundwater-dependent terrestrial ecosystems through the Water Framework Directive.

In order to investigate the groundwater levels and water quality on the Rockmarshall wetland areas and to assess the influence of the stream on these parameters, a series of nine shallow piezometers were installed in the linear wetlands. This presentation will discuss the perils of installing piezometers within wetland environments and give details of costs and equipment required for the investigation, preliminary results and potential future installations to be performed to obtain additional understanding of this potentially internationally important wetland.

Figure 1: Rockmarshall wetland, County Louth

LOCATING HYDRAULICALLY ACTIVE INTERVALS USING DOWNHOLE METHODS IN LOW PERMEABILITY AQUIFERS

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ABSTRACT

Identifying hydraulically active intervals at depth in open boreholes is important for characterising aquifers, not just in terms of improving groundwater flow and contaminant transport models, but also for water quality sampling and targeted tracer testing. Poorly Productive Aquifers (PPA's) underlie approximately two-thirds of Ireland's landmass and consequently can play an important role in Irish groundwater flow regimes. Locating hydraulically active intervals in PPA's often proves challenging due to extremely low flow velocities in boreholes, which can render many of the conventional downhole flow characterisation methods unreliable. A research programme (Griffith Geoscience) sponsored research has examined the application of a range of downhole methods in boreholes installed in a number of catchments underlain by different PPA's types. Methods tested include temperature and conductivity logging, heatpulse flowmeter testing, and single well tracer tests. Results indicate that although not all downhole methods are suited to identifying hydraulically active intervals in the different aquifer types, application of a range of conventional and innovative methods can significantly improve current understanding in low productivity bedrock units. Of particular note, certain types of inexpensive single well tracer tests, employed by Griffith researchers have proven to be more successful than conventional heat pulse flow meter logging in detecting zones of groundwater flow.

INTRODUCTION

Low permeability, or poorly productive aquifers (PPA's), are classed by the Geological Survey of Ireland (GSI) as bedrock aquifers that are "generally unproductive" and embody typical transmissivity of less than 50 m^2/d (GSI 2006). PPA's underlie almost two-thirds of the total land area of Ireland (GSI 2006) and include bedrock types such as gneisses, granites, impure limestones and meta-sediments (EPA 2010). These low matrix porosity aquifer units, generally restrict groundwater flow to few poorly connected fractures and fissures (EPA 2010), whose low fracture permeability decreases with depth following a power law relationship (Comte et al. 2012). Boreholes drilled into these units may intersect relatively large numbers of fractures, yet only a small subset of these may be hydraulically active i.e. transmit groundwater through the rock mass (Berkowitz 2002). Boreholes intersecting two or more hydraulically active fractures or zones can give rise to strong vertical flow components (Berkowitz 2002). Consequently, measurable vertical flows can be used to identify and locate the depth of hydraulically active fractures in a well (Paillet 1995). Identification of these hydraulically active zones in boreholes is important for conceptualising groundwater flow and improving flow and contaminant transport models. In addition, knowing the depth of hydraulically active zones in a well allows for targeted groundwater quality sampling and provides predictable sampling locations during crosshole tracer tests (Maurice et al. 2011).

DOWHOLE METHODS

FRACTURE DETECTION AND CHARACTERISATION

A number of methods are applicable for fracture detection and aquifer characterisation in open bedrock boreholes. This may be achieved by examining undisturbed sampling using coring (Misstear et al. 2006). Here the core samples can be directly observed for joint or fracture characteristics. However, coring is expensive. A cheaper alternative to well coring, measuring aquifer parameters in-situ, is downhole geophysical logging (Misstear et al. 2006). Different aquifer parameters are measured by means of probes that are lowered into a borehole, while a record of the variations with depth is recorded as a continuous log at the surface (Chapellier 1992). The most commonly used probes for fracture characterisation include the caliper and acoustic televiewer. The caliper measures variation in well diameter with depth, by using two to four sprung arms that push against the borehole wall. Caliper logs can be used to identify wash-outs zones and give evidence of the presence of fractures at depth in open boreholes (Hearst et al. 2000). An acoustic televiewer measures the amplitude and travel time of sound wave pulses propagating through the borehole fluid and reflecting of the wall of the borehole (RG 2004). Acoustic logs of sound wave amplitude and travel time are displayed as 360 degrees image views of the borehole wall. The technique has the advantage that the character, relation and orientations of lithological features or fractures, including strike and dip, can be determined (Williams & Johnson 2004). Consequently, the caliper and acoustic televiewer provide crucial information on the structure and geometry of fractures intersecting the aquifer well, which in turn provide important inputs for groundwater flow and contaminant transport models.

Not all fractures intersecting a well will be hydraulically active (Berkowitz 2002). Downhole flow methods aimed at characterising flow regimes in a borehole can be applied to distinguish the hydraulically fractures from the overall fracture set. Commonly applied downhole flow methods include well fluid logs, borehole flowmeters and tracer tests.

WELL FLUID LOGS

Well fluid logs such as temperature and electrical conductivity logs measure changes of fluid properties with depth in a borehole. Sudden or step changes in one or both parameters with depth can be indicative of discrete water transmitting fractures, or zones intersecting the well (Figure 1). The well fluid logs can identify inflowing fractures whose water chemistry is different of that of the well column, but cannot identify outflowing fractures or inflowing fractures of similar water chemistry (Maurice et al. 2011). This means that the well fluid logs may not identify all representative hydraulically conductive zones in a borehole, and need to be used in conjunction with other downhole methods.

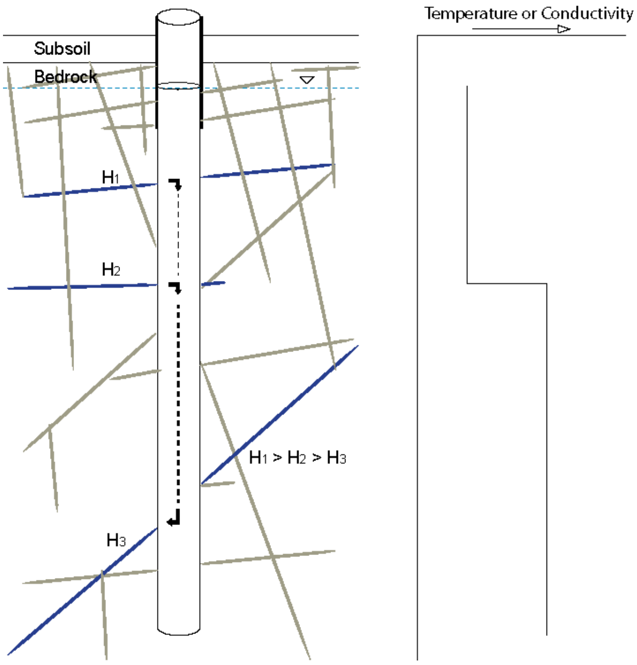

Figure 1: Temperature or conductivity log for conceptual model. Increase in parameter signifies location of hydraulically active fractures discharging water to the borehole (H_2). Note however, that not all hydraulically active fractures may be identified using this method; Water discharging to the borehole from H_1 displays no significant difference in water chemistry from the surrounding ambient well water chemistry, while although H_3 is hydraulic active, well water discharges to it. As a consequence no hydrochemical contrast is apparent.

HEATPULSE FLOWMETER

The Heatpulse Flowmeter is designed specifically for measuring well water velocities at low flow rates. The heatpulse flowmeter operates by generating a heated pulse of water that moves with the well water flow regime. Sensors detect and record response time and flow direction of the heatpulse, from which flow velocity are calculated for a borehole (Hess 1986). Typical flow velocities of the heatpulse flowmeter range from 0.1 to 5 m/min (Hearst et al. 2000). With specially designed flow diverters, reducing the lower limit to 0.01 l/min (Hess 1986). A conventional approach to heatpulse flowmeter logging involves taking stationary flow measurements at a number of depth locations. By examining changes in flow velocities from one measurement to the next, the locations of hydraulically conductive fractures can be identified (Figure 2). Flowmeter profiles can be collected under ambient and/or stressed (pumping or injection) conditions.

In fractured PPA wells, differences in head between fractures intersecting the same well must generate vertical flow rates above the flowmeter detection limit for the heatpulse to identify hydraulically conductive fractures effectively. This, in addition to the initial cost of this specialised tool and associated logging apparatus, restricts the application of the heatpulse flowmeter methods for identifying hydraulically active zones in PPA wells, despite its easy application and data interpretation.

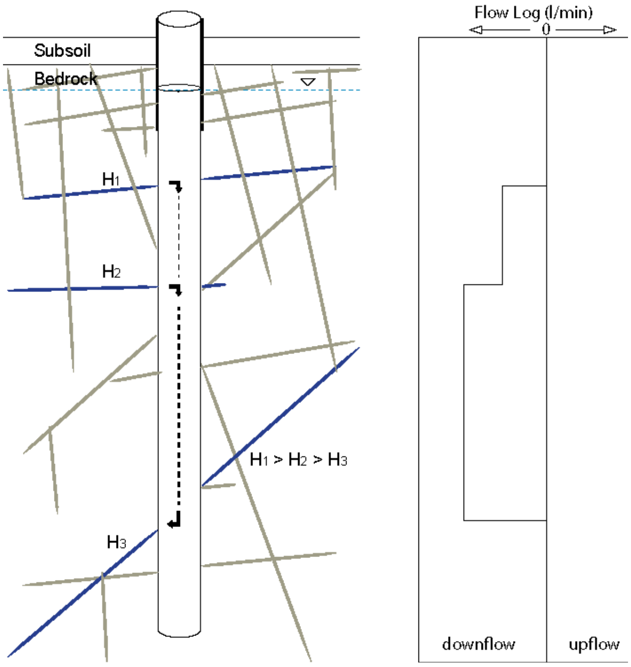

Figure 2: Flowmeter log for conceptual model under ambient conditions. Downflow is negative, upflow is positive.

SINGLE WELL TRACER TEST

Well tracer tests have also been applied to identify hydraulically active intervals and flow regimes within wells. Tracer tests can be multi-well or single well and conducted under natural flow conditions or forced flow conditions (Domenico & Schwartz 1998; Ward et al. 1998). Generally speaking, limited numbers of wells separated by significant distances, restrict the use of tracer tests to single well dilution methods. Single well dilution tests operate on the principle that groundwater from inflowing or crossflowing fractures in a well can cause a decrease in artificial tracer concentration around the depth location of that fracture (Maurice et al. 2011). The operating principle involves injecting an artificial tracer uniformly along the depth of an open or screened well and monitoring the dilution profiles over time. The depth location with the highest rate of dilution is indicative of the most hydraulically conductive fracture or zone (Figure 3). The single well dilution tests can be categorised into two types, depending on hydraulic conditions. “BoreHole Dilution Tests (BHDT)” are completed under natural gradient conditions while “Pump Back Dilution Tests (PBDT)” carried out under forced gradient conditions, generally at very low constant pumping rates (0.3 – 1 l/min) from the same well. In PPA boreholes, taking concentration depth profiles for BHDTs has shown to take days to weeks, to monitor the tracer dilution. An advantage of the PBDT is that the dilution is quicker, usually monitored over several hours, with similar results. To analyse flow scenarios in a well, a simple numerical spread-sheet dilution approach, generated by Maurice et al. (2011), can be applied. The dilution model predicts how different inflow and outflow scenarios produce a range of dilution patterns with time. This allows identification of hydraulically conductive zones with depth.

Single well tracer tests can be conducted using any one, of a large variety of tracers and measuring devices, to suit a range of budgets or site specific requirements. Its relatively low cost materials and simplistic approach (Hiscock 2005) makes it a suitable downhole test method for detecting active flow zones in wells with large open intervals, particularly in PPA boreholes.

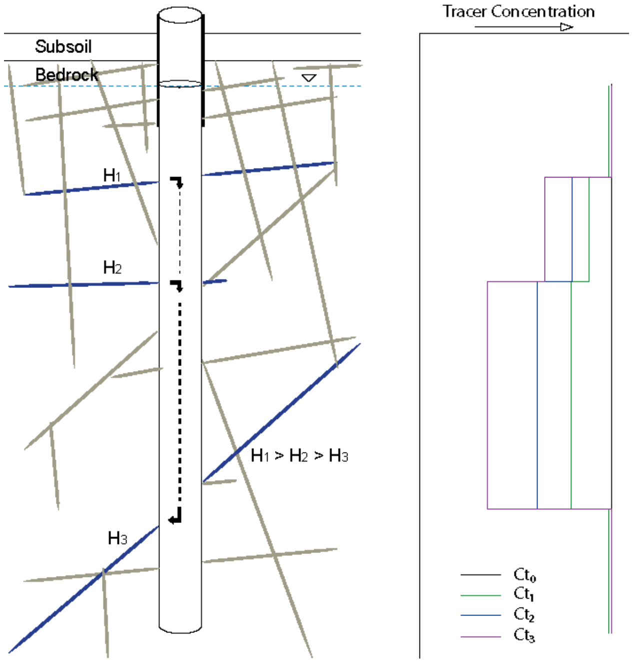

Figure 3: Artificial Tracer Dilution test under ambient flow conditions. Ct_X represents time after injection for each depth profile. Simulations generated using the approach of Maurice et al. (2011).

CONCLUSION & PERSPECTIVES

Geophysical logging methods provide a valuable means of characterising groundwater flow regimes in boreholes completed in bedrock aquifers. Caliper and particularly acoustic televiewer logs are necessary in identifying the geometry and structure of fractures. Well fluid, borehole flowmeter and tracer test methods are used to identify fractures that are hydraulically active. The interpretation of well fluid logs, however, can be ambiguous and may not identify all representative hydraulically active fractures intersecting a borehole, especially when no notable contrasts in hydrochemistry exist. In such cases, flowmeter logs can be employed to detect hydraulically active intervals. However, flowmeter methods are typically applied in productive hydrogeological units, and have more limited scope in PPA's

Single well tracer tests provide a cheap alternative to flowmeter logs for identifying hydraulically active fractures at depth in PPA boreholes. Furthermore, the methods are simple, require non-specialist equipment and data can be analysed by simple numerical spread-sheet models. Tests work effectively once there is some, albeit small, inflow component into the well.

Identification of hydraulically active fractures and their geometry in a borehole is an important element in terms of aquifer contributions and flow pathways. The information is essential in providing higher levels of confidence in estimations of groundwater flow and contaminant transport models.

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